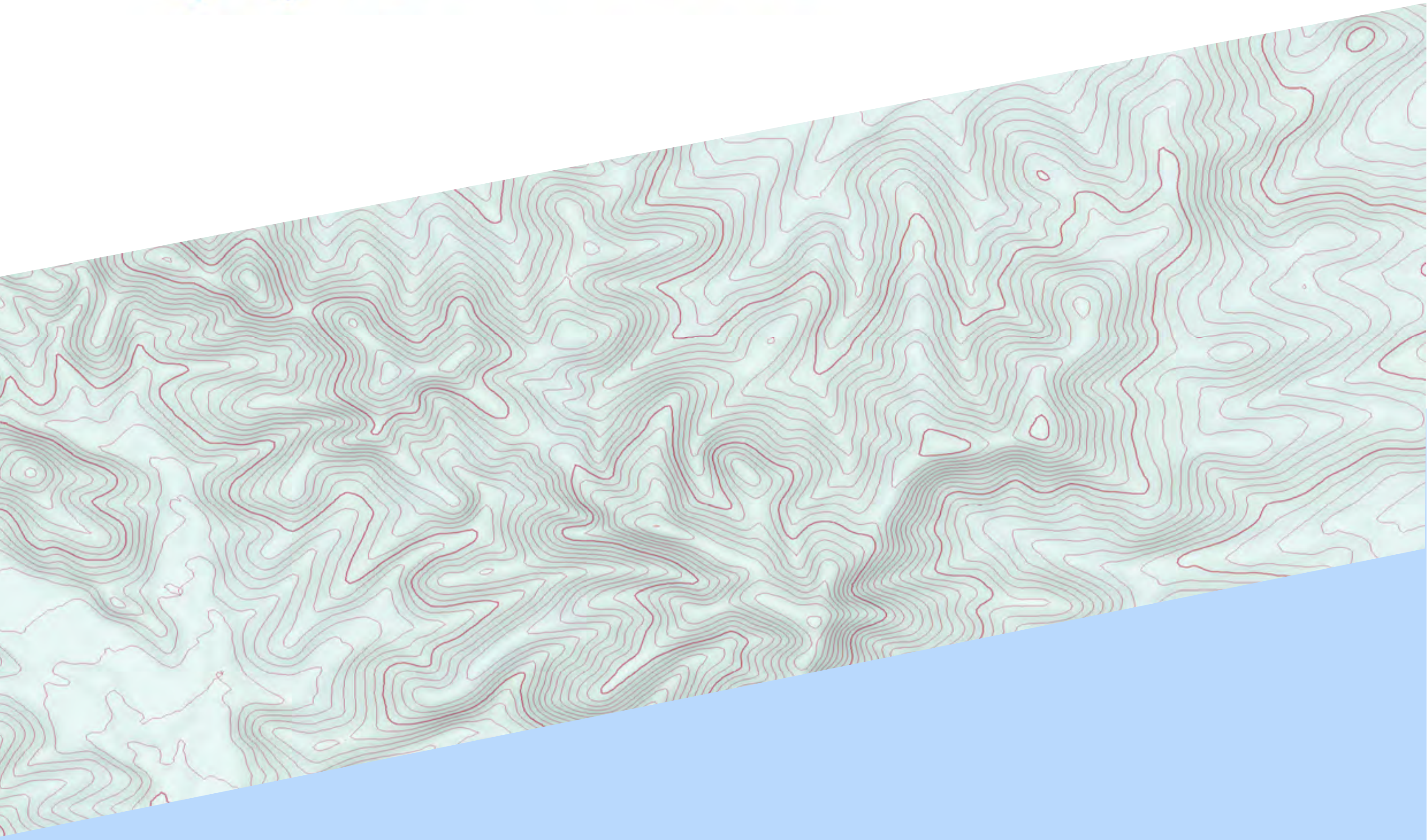
Attachment B – Groundwater Assessment

WATERSHED HYDROGEO



South32 Illawarra Metallurgical Coal

Dendrobium Area 3C

Longwall 22 and 23 Groundwater Assessment

June 2021

DOCUMENT REGISTER

Rev/Issue	Date	Comments
1	25 August 2020	Draft for comment
2	30 August 2020	Incorporating IMC comments
3	31 August 2020	Incorporating latest inflow data, monitoring details
4	16 April 2021	Updated following minor revision to longwall footprint
5	10 May 2021	Incorporating IMC comments, including possible TARP structure
6	11 May 2021	Incorporating IMC comments
7	18 May 2021	Corrected labelling on Figure 7-1.
8	02 June 2021	Corrected typographical errors

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QUALITY CONTROL

Function	Staff	Signature	Date
Authors	Will Minchin	[signature]	02/06/2021
Approved	Will Minchin		

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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
DPIE	NSW Department of Planning, Industry and Environment
EPA	NSW Environment Protection Authority
IAPUM	Independent Advisory Panel for Underground Mining (advising DPIE, succeeding IEPMC)
ICEFT	Illawarra 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 (50th percentile) flow at a gauge for a specified period
WaterNSW	Bulk water supply and source protection authority for Greater Sydney

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 16 longwalls at Dendrobium from Areas 1, 2, 3A and the current domain, Area 3B.

IMC is seeking Department of Planning, Industry and Environment (DPIE) approval to extract proposed Longwalls 22 and 23 within Area 3C. 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 these longwalls (Section 1.5). Watershed HydroGeo ("WatershedHG") was engaged by IMC to prepare an assessment of groundwater-related impacts to inform the SMP application.

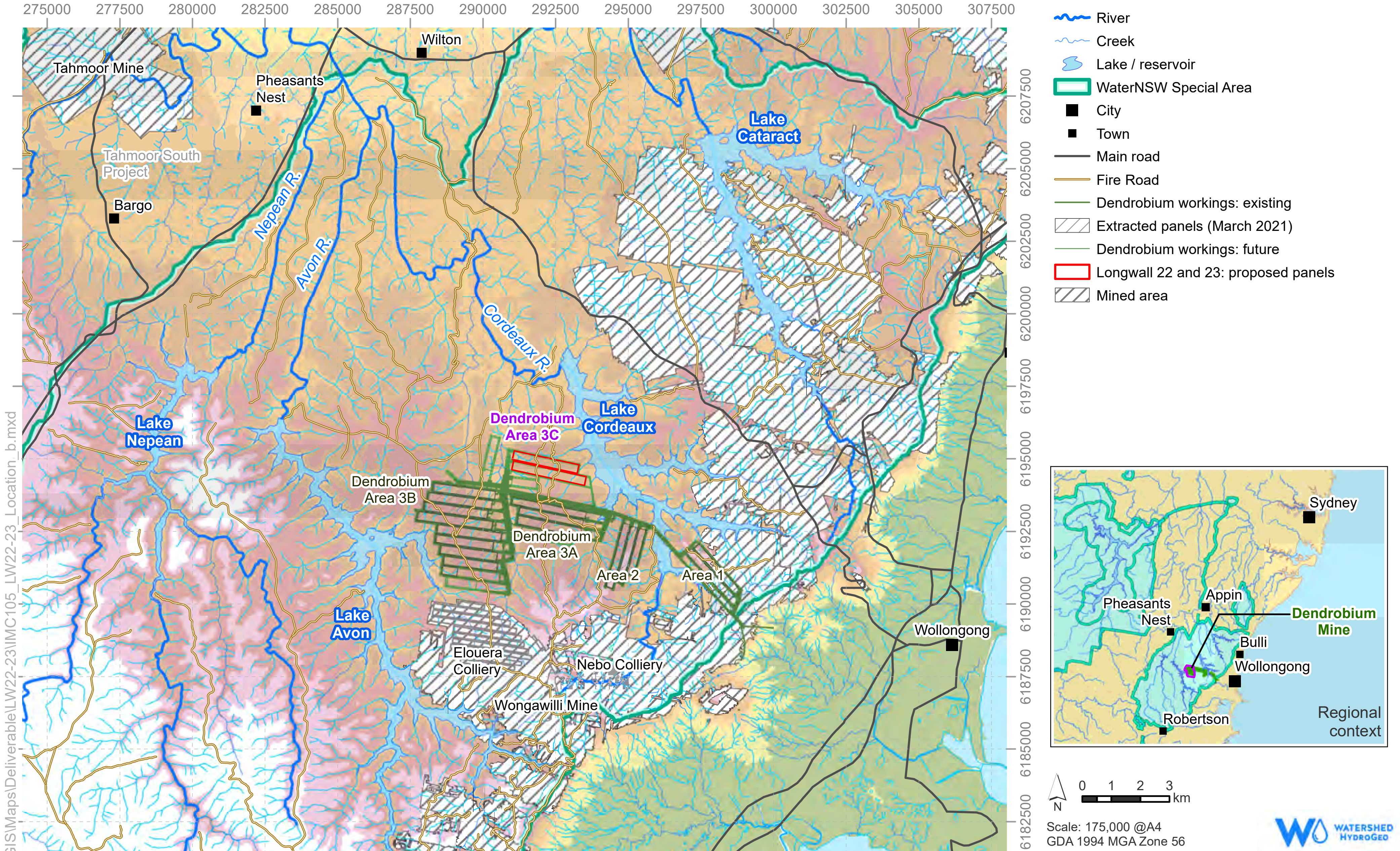
An earlier version of this document was provided to meet the requirements of the Area 3C SMP approval, Condition 15, Schedule 3. This current document has been updated with recent data (e.g. investigation of geological structures, groundwater levels and inflow data, surface water losses) and with an 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) completed in 2007.
- Area 2 (Longwalls 3, 4, and 5) completed in 2009.
- Area 3A (Longwalls 6, 7 and 8) extracted between 2010 and 2012. Longwall 19 has SMP approval and will be extracted following Area 3B.
- Area 3B has been active since February 2013. Eight longwalls have been completed (Longwalls 9, 10, 11, 12, 13, 14, 15 and 16), Longwall 17 is currently being extracted, Longwall 18 has SMP approval.

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. Recent SMP approvals require that Longwalls 14 to 18 must have a maximum cutting height of no more than 3.9 m.



IMC | Dendrobium Mine

Dendrobium Mine and Area 3B location plan

Figure 1-1

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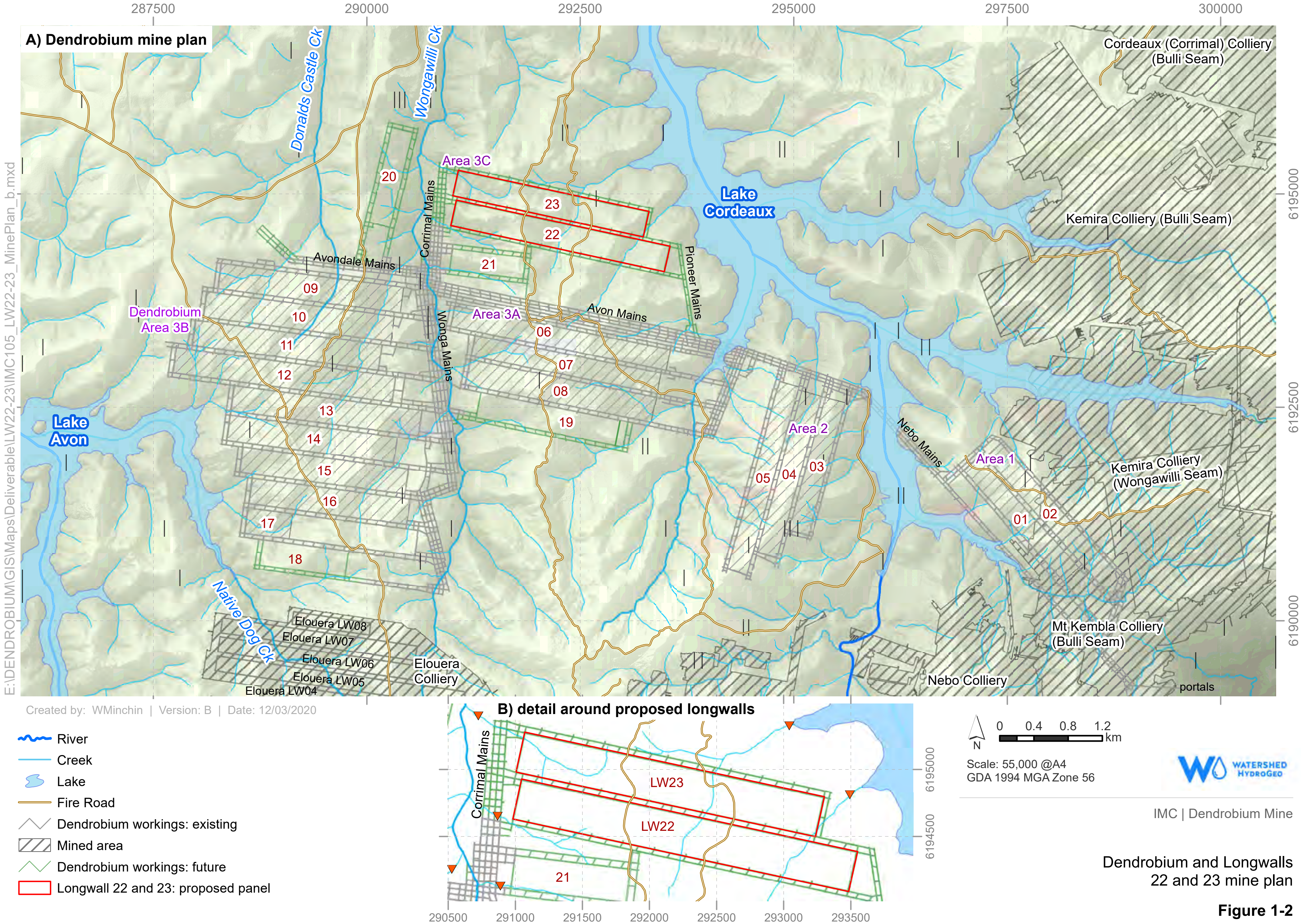

A) Dendrobium mine plan
287500
290000
292500
295000
297500
300000
6195000
6192500
6190000
Donalds Castle Ck
Wongawilli Ck
Area 3C
20
23
22
21
Corrimal Mains
Avondale Mains
Lake Cordeaux
Cordeaux (Corrimal) Colliery (Bulli Seam)
Kemira Colliery (Bulli Seam)
Pioneer Mains
Avon Mains
Dendrobium Area 3B
Area 3A
Wonga Mains
09
10
11
12
13
14
15
16
17
18
06
07
08
19
Lake Avon
Area 2
05
04
03
Nebo Mains
Area 1
01
02
Kemira Colliery (Wongawilli Seam)
Native Dog Ck
Elouera LW08
Elouera LW07
Elouera LW06
Elouera LW05
Elouera LW04
Elouera Colliery
Nebo Colliery
Mt Kembla Colliery (Bulli Seam)
portals
E:\DENDROBIUM\GIS\Maps\Deliverable\LW22-23\IMC105_LW22-23_MinePlan_b.mxd
Created by: WMinchin | Version: B | Date: 12/03/2020
River
Creek
Lake
Fire Road
Dendrobium workings: existing
Mined area
Dendrobium workings: future
Longwall 22 and 23: proposed panel
B) detail around proposed longwalls
Corrimal Mains
LW23
LW22
21
290500
291000
291500
292000
292500
293000
293500
6195000
6194500
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 Longwalls 22 and 23 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	Current	12/12/2020	*Sep-2021	243	2014	295	305		3.9	279	345	385
3B	18	Approved	*Oct-2021	*Mar-2022	155	1018	295	305		3.9	300	332	370
3A	19	Approved	*Apr-2022	*Dec-2022	220	1500	295	305		3.6	287	331	369
3C	21	Approved	*Jan-2023	*Apr-2023	100	872	245	256		3.9	310	340	382
3C	22	Proposed	*June-2023	*June-	330	2561	295	305		3.9	305	345	380
3C	23	Proposed	*July-2024	*July-2025	300	2283	295	305		3.9	290	340	395
3C	20	Proposed	*Sep-2025	*Jan-2026	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 3B as well as 3A and 3C (**Figure 1-2**) that is relevant to this SMP application are outlined in the following sections.

1.2.1 Area 3B (Longwall 18)

This longwall would extend into the Dams Safety NSW Avon Notification Area, and is proposed to be setback at least 300 m from the Lake Avon Full Storage Level (FSL), in accordance with Schedule 4, Condition 8 of the 3B SMP Approval. This longwall has been shortened at its eastern end to avoid mining through geological structures, and is 1 km from Wongawilli Creek.

There are no historical workings overlying Longwall 18. Longwall 18 would be 450-500 m north of old workings at Elouera Colliery (Section 1.3), including Elouera Longwall 8. More detail regarding Longwall 18 is available in WatershedHG (2020a).

1.2.2 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 19.

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

1.2.3 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 DPIE, while additional groundwater modelling and assessment, was requested by DPIE prior to further consideration of Longwall 20. **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.

Longwall 20 is 120 m west of Wongawilli Creek, and 570 m east of Donalds Castle Creek at their closest points. Longwall 21 is 240 m east of Wongawilli Creek at its closest point.

Longwalls 22 and 23 are to be located to the north of Longwall 21, and east of Wongawilli Creek. The details of these are presented in **Table 1-1** and **Figure 1-2**. Longwalls 22 and 23 are proposed to be 300 m from the Lake Cordeaux FSL and are both more than 3 km distant from Lake Avon. Wongawilli Creek is 320 m west of Longwall 22 and 340 m west of Longwall 23 at its closest point.

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.

1.3 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 (DPIE-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 DPIE-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 DPIE in the assessment of the SMP. This assessment focuses on the potential impacts of Longwalls 22 and 23, 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 DPIE; and
- Recommendations made by the Independent Expert Panel for Mining in the Catchment (IEPMC) and Independent Advisory Panel for Underground Mining (IAPUM) and other agencies or advisory groups.

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. IEPMC comments and recommendations 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.

An updated groundwater model was developed for the *Dendrobium Mine – Plan for the Future: Coal for Steelmaking EIS* which proposed mining in Areas 5 and 6 (HydroSimulations, 2019c). A modified version of that model, developed by Watershed and SLR and incorporating new field data and with modifications to meet requirements by agencies, 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 7.4.5).
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: - Lake Avon leakage (Section 7.4.3); - Lake Cordeaux leakage (Section 7.4.3); - loss from watercourses (surface water take) (Section 7.4.5); and - losses from water supply catchments (Sections 7.4.6).
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. Description of local modelling in HGEO (2019b).
		(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;	Groundwater 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. HGEO (2017b and 2019b) documents investigation into interaction with and losses from Avon Reservoir.
		(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, 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.	Modelling and assessment previously reviewed by Kalf and Associates.

Additional requirements have been set via the SMP Approval for Area 3B, the latest of which is dated 8 December 2020. Those relevant to this groundwater assessment are set out in **Table 1-3**.

Table 1-3 Area 3B SMP requirements relevant to Groundwater Assessments (08/12/2020)

Condition		Detail	Where dealt with
Schedule 3			
Groundwater Model			
18	The Applicant must regularly review and update the Area 3B Groundwater Model to the satisfaction of the Secretary. The model must:	(a) include detailed consideration of surficial aquifers, swamps and watercourses;	Section 5.2.3 outlines the stratigraphic units included in the groundwater model. This includes a representation of swamps. Section 5.3.4 describes the representation of watercourses.
		(b) include all available data on groundwater levels;	Groundwater level targets and calibration (Section 6.4)
		(c) model baseflow contributions for all sub-catchments from baseline (i.e. prior to the extraction of Longwall 9) until 30 years post-mining, using 5-yearly increments;	Predictions of surface water losses in watercourses (surface water take) (Section 7.4.5).
		(d) provide adequate water table contour plots, drawdown plots and pore pressure vertical section plots for predicted and observed conditions;	Section 7.3 presents contour groundwater levels, depth to water (in line with IEPMC's request of 28/11/2019), and hydrographs for observations and predictions.
		(e) take into consideration the findings of any independent report on groundwater commissioned by the Department, or advice from the Independent Expert Panel, and the report required under condition 19(c) of this approval; and	We have reviewed advice from PSM (2017) and the reviewers of that and considered IEPMC (2019a,b). See Sections 1.5.1, 1.5.2 and then through out relevant sections of this report.
		(f) be peer reviewed by a suitably qualified, experienced and independent expert, who is approved by the Secretary.	Modelling reviewed by Kalf and Associates (KA) [KA, 2019]. Comments made by KA are incorporated into this report.
Groundwater Monitoring and Height of Cracking			
19	The Applicant must undertake a comprehensive program of groundwater monitoring and assessment, including:	Undertake a comprehensive program of… investigations of the height of connective cracking.	HGEO (2020c) and Hebblewhite (2020), summarised in Section 3.6.
Schedule 4			
13	Prior to the extraction of Longwall 17, the Applicant must undertake additional investigations into:	(a) geological structures near bore S2436 to clarify the nature, extent and significance of monitoring data reported from that bore;	Details provided separately.
		(b) the location and nature of the Elouera Fault, including additional surface drilling and subsequent geotechnical, geophysical and hydrogeological testing; and	Provided separately. A summary is presented in Section 2.5.1.
		(c) report the results of these investigations to the Secretary, WaterNSW and the DSC, to the satisfaction of the Secretary.	Provided separately.

Table 1-4 Area 3C SMP requirements relevant to Groundwater Assessments (19/12/2019)

Condition		Detail	Where dealt with
Schedule 3			
15	Groundwater Model The Applicant must submit to the Secretary revised groundwater modelling for Area 3C that:	(a) include cell dimensions of 50 x 50 m within the footprint of all proposed longwalls;	Section 5.2.2 describes the cell sizes for Area 3C longwall areas.
		(b) adequately justifies any continued use of the 'stacked drain' method as accurately reflecting groundwater drainage above the goaf.	Sections 5.4 and 5.4.5 describe the methods currently used to simulate connected fracturing, including TVM and stacked drains. Section 6.4.2 and **Appendix F** present the modelled heads, including hydrographs showing representation of depressurisation above and adjacent to longwalls, including near Wongawilli Creek and Avon Reservoir.

1.5.2 Summary of independent advice to regulators

IEPMC advice regarding Area 3C groundwater modelling (HS, 2019b) has been incorporated by DPIE into Schedule 3, Condition 15 of the Area 3C Approval. This condition was relevant to model cell sizes within longwall areas (Condition 15a) and to the use and justification of Stacked Drains to simulate connected fracturing (Condition 15b). These are addressed in Sections 5.2.2 and 5.4.5 respectively.

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 1-5**.

Table 1-5 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.	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 (WatershedHG, 2019a). 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 Area 3C is increasing. 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 Longwalls 22 and 23. 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 taken place and been reviewed. These have confirmed that deformation occurs through to the surface.	Field investigations presented in Sections 2.6 and 3.6. Subsequent model representation of fracturing is presented in Section 5.4.

IEPMC recommendation			Response	Reference
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 0 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) We do not agree that specific software should be specified. Both SURFACT and USG have advantages and disadvantages and have been verified to give essentially the same results. 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 (2020a) 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 LW 16 to LW 18.	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 and Longwall 19 SMP Groundwater Assessments. A summary of the key comments and responses is presented in **Table 1-6**.

Table 1-6 Summary of IAPUM comments on Longwall 18 and Longwall 19 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 is consistent with IMC's stated option of sealing the mine with material that returns average permeability to the permeability of undisturbed coal (or lower). Section 3.7.2 discusses observations of groundwater re-pressurisation or recovery occurring above longwalls in Areas 3A and 3B while dewatering of the underlying workings is ongoing. This occurs in the upper Bulgo Sandstone and lower Hawkesbury Sandstone, and suggests that recovery in these units will occur to some degree, no matter what closure plan is enacted (i.e. sealed or unsealed). A sealed or unsealed mine would mainly affect groundwater pressure recovery in the deeper strata and mined seam, especially in Areas 1 and 2.	HGEO, 2020h and 2021b and Section 3.7.2.
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 were initially based on core testing results, with model calibration to achieve appropriate head separation between layers at nested sites. The model parameters compare well against harmonic mean of packer test results (now shown in Section 3.5.1) 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**

IAPUM comment			Response	Reference
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 will be 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 DPIE-commissioned study into the Height of Connected Fracturing (PSM, 2017) for recent SMP application groundwater assessments (HS, 2019a and 2019b; SLR, 2020a) have been described in detail in previous assessments. Most of these recommendations have been retained for the groundwater model utilised in this assessment. A summary is presented in **Table 1-7**.

Table 1-7 Summary of recommendations from PSM (2017) relevant to groundwater modelling

#	Issue / recommendation	Action	How and where addressed
1	Accounting for structures, specifically Elouera Fault	South32 maps structures in the mining area (e.g. IMC, 2020) and has commissioned multiple studies to investigate the role of structures (e.g. MSEC, 2019, SRK, 2020). Specific studies on the Elouera Fault are continuing, but include HGEO (2019b, 2020) and SCT (2020).	There is discussion of geological structures in Section 2.5.1. Elouera Fault investigations are not relevant to Area 3C, and are described in SMP documentation for Longwall 18 (e.g. HGEO, 2020d; WatershedHG, 2020a).
2	Valley-bulging (valley-closure) around lakes	This process is incorporated in groundwater modelling by increasing the hydraulic conductivity of the strata along valley walls and beneath valley floors. See response to #4, below.	Measured and modelled increases in hydraulic conductivity (Sections 3.6.3 and 5.4.4).
3	Accounting for basal shears	Basal shears have the potential to act as conduits between longwalls/goaves and to connect to Lake Avon. Based on advice from SCT, and the PSM study, these occur around the claystones (BHCS and SPCS). PSM stated that "based on its general experience in sedimentary rock geological terrains, this shearing is likely to be continuous throughout the Dendrobium Mine region."	Basal shears are not modelled explicitly as discrete features, as the evidence from packer testing around Area 3B and Lake Avon (HGEO, 2019b; SCT, 2017) and near Sandy Creek (SCT, 2019a) does not support these being the primary potential groundwater pathways in off-goaf areas. Broader deformation or valley closure is represented in the modelling as outlined in the response to #2 and #4.
4	Off-goaf fracturing	The groundwater model simulates off-goaf Kh enhancement, although this may be accounted for via the 'valley-bulging' mechanism described in #2. Enhancement has been represented as occurring up to 600 m from longwalls and being applied as declining with distance.	Sections 3.6.3 and 5.4.4.
5	Representation of fracturing through to surface in Area 3B	Neither the Tammetta (2013) or Ditton (Ditton and Merrick, 2014; DGS, 2016) models were supported by the PSM study or reviews, although IEPMC (2019a) consider the Tammetta method to be an appropriate tool for assessments, in the absence of other more site-specific data. There is clearly some form of fracturing from the seam to the surface above Area 3B and 3A panels (HGEO, 2020c). PSM assert there is vertical connection from seam to surface above Area 3B (based on their review of the Longwall 9 investigations by PB, 2015); however, we do not consider that data from water budgets, groundwater levels and inflow chemistry consistently support this conceptual model.	The revised modelling in this study began with PSM's conservative assumption, and then worked to calibrate the model to inflow and groundwater levels (drawdown) while holding to the constraints and soft evidence of recent centre-line bore investigations. As described in HGEO, 2020h (Section 3.7.2), recovery of groundwater pressures is observed in centre-line monitoring bores in Area 3A and 3B, above workings that are currently being dewatered. This is strong evidence for a poorly connected fracture network.
6	Geotechnical modelling	Geotechnical modelling could be done prior to groundwater modelling (e.g. FLAC) or coupled (e.g. COSFLOW). Geotechnical (FLAC) modelling has been carried out by SCT for longwalls in other parts of Dendrobium Mine. HydroSimulations (2019c) and then SLR (2020a) used a method to incorporate the outputs of such modelling in the groundwater model, chiefly around up-scaling from the fine detail of local-scale geotechnical models to regional groundwater models). However, this approach is not used in this study.	This update to the model does not rely on the geomechanical modelling by SCT, which had been previously used in HydroSimulations (2019c) and SLR (2020a). This study has concentrated on constraining the model, where possible, using the recently acquired field data by simulating enhanced bulk properties via the TVM package (Section 5.4).

1.5.3 Report structure

The structure of this report is outlined in **Table 1-8**. 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;
- HS, 2014;
- HS, 2016a;
- HS, 2016b;
- HS, 2018;
- HS, 2019a;
- HS, 2019b;
- HS, 2019c;
- SLR, 2020a; and
- WatershedHG, 2020.

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

- Groundwater: e.g. HydroSimulations 2012-2016 and HGEO, 2017-2021; and
- Surface Water and Shallow Groundwater, e.g. HGEO, 2017-2021.

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 1-8 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 is located.
3	Hydrogeology	A summary and discussion of key facets of the groundwater system, including discussion of relevant points from PSM (2017) and IEPMC (2018 and 2019a;b).
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 18 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. Bargo and Yanderra which are 15 km northwest of Longwall 23, and Wilton which is approximately 14 km north of Longwall 23.

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 these Area 3C longwalls, ground elevation ranges between 290 mAHD (northeast corner) to 420 mAHD in the centre of the area, averaging about 360 mAHD. Topographic elevation in the centre of Longwall 20 is approximately 350 mAHD, 380 mAHD in the centre of Longwall 21 and 390 mAHD in the centre of Longwalls 22 and 23. Topography declines to the east of Longwalls 21, 22 and 23, toward Lake Cordeaux. Topography also declines to the west of those panels, toward Wongawilli Creek.

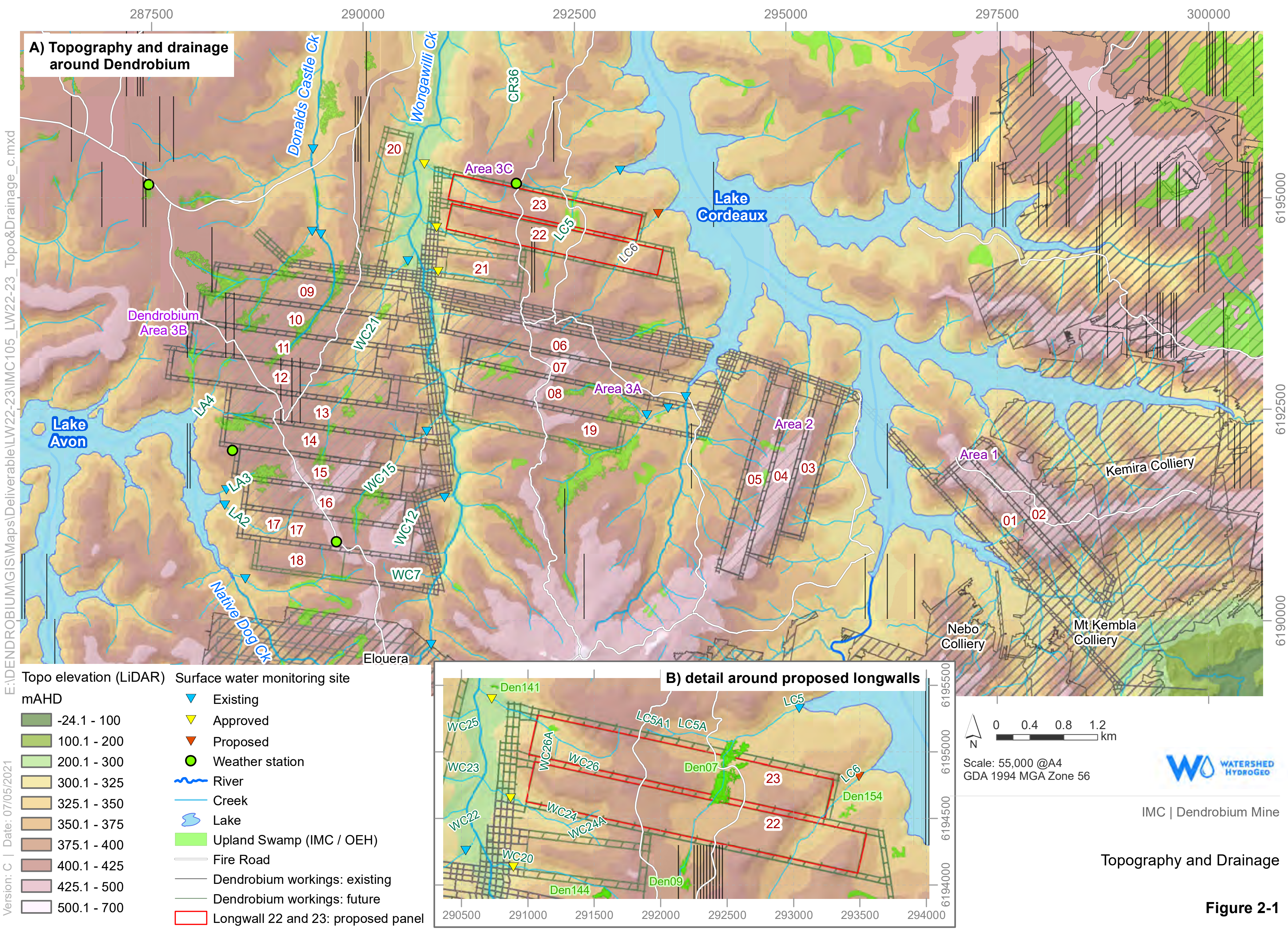
The reach of Wongawilli Creek closest to Longwalls 20 to 23 is at 285 mAHD (south/upstream end) to 270 mAHD (north/downstream end).

Review of WaterNSW's bathymetry data directly to the east of Longwalls 22 and 23 indicates that the deepest floor elevation in this part of Lake Cordeaux is approximately 268 mAHD. The Wongawilli Coal seam is at approximately 40 mAHD at the eastern end of Longwalls 22 and 23, meaning there is 220 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

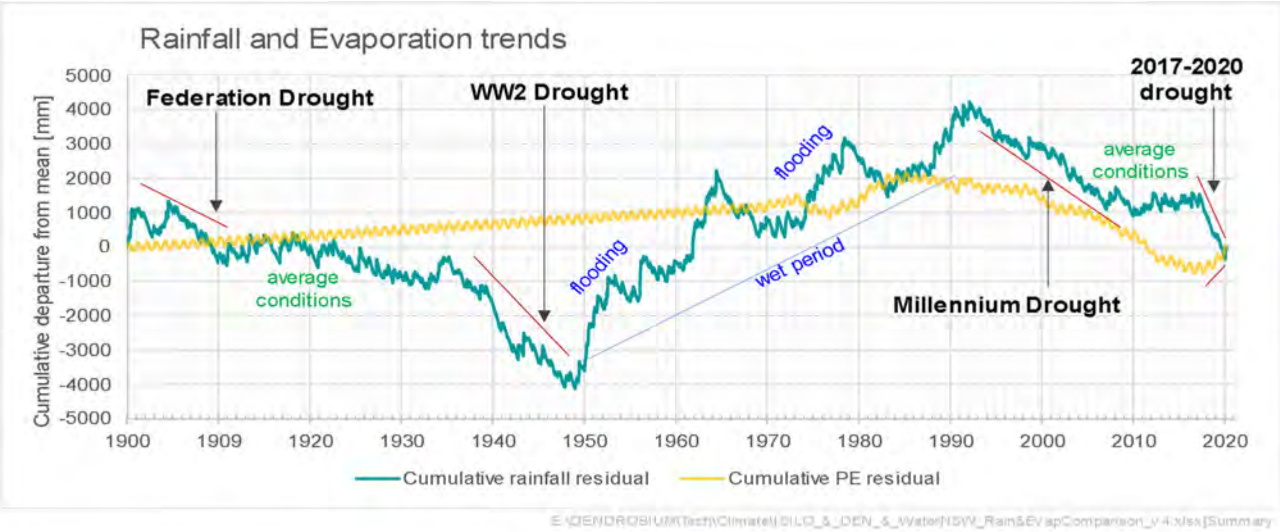


Figure 2-2 Rainfall and evaporation trends

Figure 2-2 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).

The low rainfall totals during the 2-3 years to February 2020 and the slope of the trend curve are indicative of rainfall deficits assessed by BoM (2020) 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. 2020 included significant rainfall events in February and August and then another in March-2021.

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 2-2**).

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 3C are (**Figure 2-1**):

- Donalds Castle Creek flows north from above Longwalls 9 to 12 of Area 3B. It is 500 m or more west of Longwall 20, but approximately 1.5 km west of Longwalls 21, 22 and 23.
- 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 320-400 m west of Longwalls 22 and 23 (the thalweg of the creek is 345 m and 320 m from the finishing ends of LW22 and LW23, respectively, at its closest points). This is slightly further then

[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.

Longwalls 21 (240 m west) and Longwall 20 (120 m east). Longwalls 22 and 23 are at similar distances from Wongawilli Creek as some of the recent Area 3B panels, which are typically 300-600 m from the creek.

Multiple tributaries to these watercourses and to the reservoirs are identified immediately around Longwall 22 and 23 (**Figure 2-1**).

LC5 and LC6 flow into Cordeaux Reservoir. LC5 would pass directly above the centre of Longwalls 22 and 23, with a 770 m length of that tributary above the panels and pillars (44% of the total length of LC5). LC6 would cross the eastern end of Longwall 22 and then skirt the eastern edge of Longwall 23.

WC24 and WC26 are tributaries to Wongawilli Creek. WC24's headwater tributary (WC24A flows from above Longwall 22, and WC24 would cross the southwestern corner of Longwall 22. WC26 would flow for about 930 m (68% of its length) above the panel and pillars of Longwall 23.

Longwalls 20 and 21 would underlie several tributaries (**Figure 2-1**). Longwall 20 directly underlies the small tributaries WC23 and WC25. Longwall 21 is close to the headwaters of WC24, would underlie approximately 400 m of WC20 (a tributary of Wongawilli Creek), and would underlie a small fraction of the LC5 catchment, although it is about 290 m from the watercourse itself.

2.4.1 Monitoring

IMC has been monitoring stream level and flow around Areas 3A and 3B since late 2007. HGEO (2021c, in-prep) and the *Watercourse Impact Monitoring, Management and Contingency Plan* (WIMMCP) have more detail on surface water monitoring around Area 3C. Monitoring sites are shown in **Figure 2-1**. Of note are recently installed gauging stations near to Longwalls 20-23:

- LC5S1 on LC5: commenced monitoring 4/04/2019. This watercourse could be affected slightly by Longwall 21, and likely to be affected by Longwalls 22 and 23.
- CR36S1 on CR36: commenced monitoring 5/09/2019. This watercourse could be affected slightly by Longwall 23.

IMC has received approval for additional surface water monitoring gauges around Area 3C on WC20, WC24, WC26, and are investigating a site on LC6 near Longwalls 22 and 23 (**Figure 2-1**).

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), Longwalls 22 and 23 are proposed to be 300 m from the Cordeaux Reservoir FSL, but this distance increases to 500 m for the south-eastern corners of both panels. The reservoir is 1.8 km and 2.5 km east of Longwalls 21 and 20 respectively. Avon Reservoir is on the other side of the Area 3B mining domain and distant from Area 3C.

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 (Moffit 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.

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).

Structures, typically faults and dykes and lineaments, have been mapped and described by IMC geologists (e.g. IMC, 2013). As mining approaches an area, knowledge of local structure and geological conditions improve, due primarily to the ability to conduct inseam drilling i.e. the mapping shown in **Figure 2-3** is from March-2021. At that time, inseam drilling had been conducted through the footprint of Longwall 22, and through most of Longwall 23. The knowledge of structures near Longwall 23 will improve further as adjacent workings are developed and inseam drilling can investigate further.

Structural features around Area 3C are shown on **Figure 2-3B**, with a selection of these listed below, with some information from IMC geologists. Lineaments detected at surface may reveal the presence of faults (IESC, 2021) or dykes. As noted below, near Longwall 22, lineaments are primarily correlated with a group of east-west trending dykes.

- East-west trending dykes and faults (detected in the Wongawilli Seam), mainly lying to the south or within the southern end of Longwall 20 or to the immediate north of Longwall 21, and to the immediate south of Longwall 22:
  - Dyke "DD9": is a long feature running from near Area 2, 170 m north of Longwall 21, through the southwestern corner of Longwall 22, and through the southern quarter of Longwall 20. It is noted to be a thick and persistent dyke zone.

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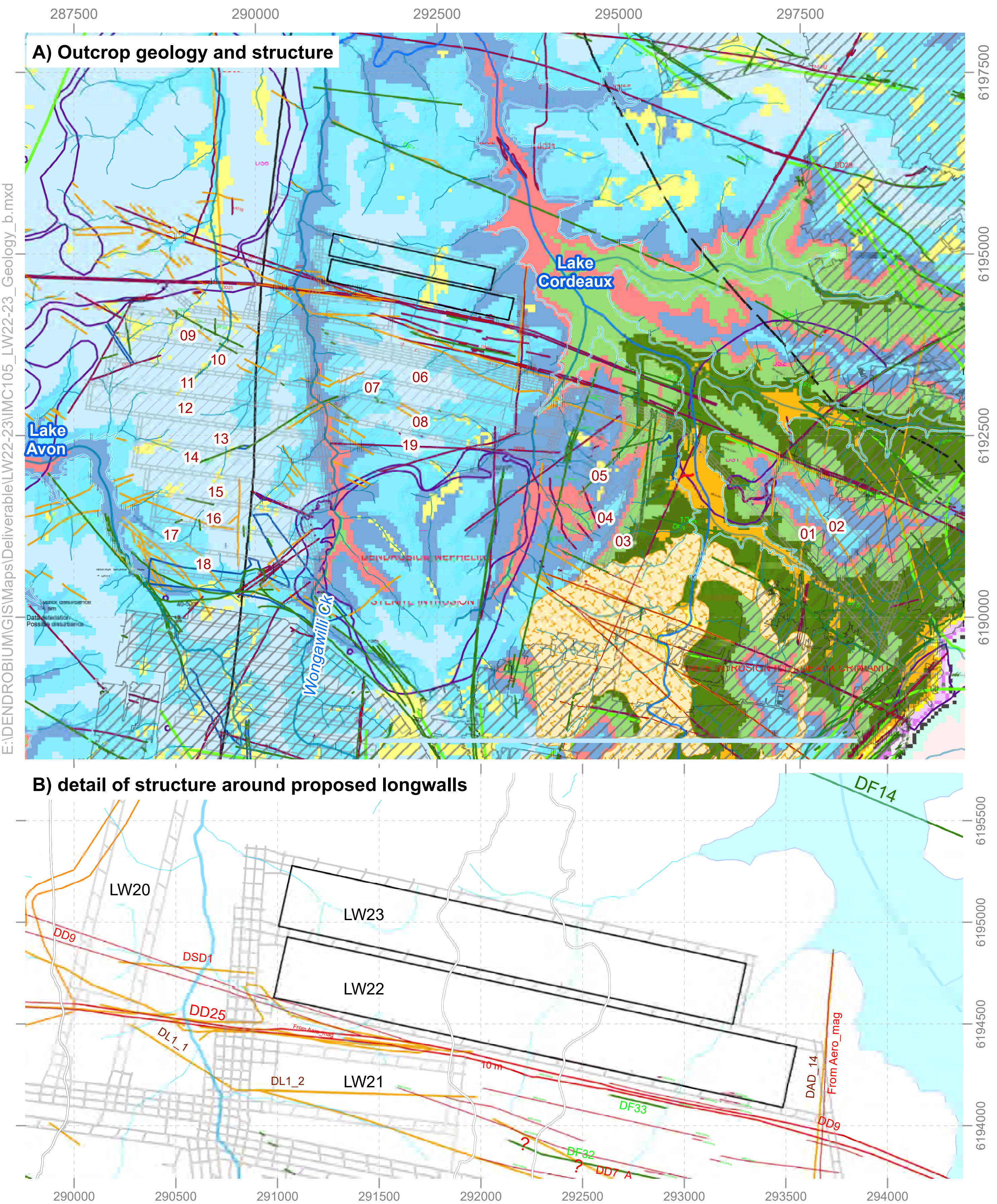
[2] If necessary, refer to the original: www.resourcesandenergy.nsw.gov.au/__data/assets/image/0004/352858/Southern_Coalfield_regional_100K_Geology_Map_1st_ed_1999.jpg



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
Southern CF: fault
Southern CF: fold
Southern CF: structure

Geological structure (IMC mapping)

Fault
Dyke
Lineament
Disturbed ground

0 0.5 1 1.5 km
N

Scale: 25,000 @A4
GDA 1994 MGA Zone 56

Created by: WMinchin | Version: B | Date: 02/04/2021

WATERSHED HYDROGEO

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Geological setting

Figure 2-3

  - ▷ Dyke “DD25”: starts about 90 m north of the north-western corner of Longwall 21 and then runs westward, passing about 75 m south of Longwall 20.
  - ▷ DD9 and DD25 merge into one another between Longwalls 21 and 22. There are hard and soft phases present within this zone.
- Faults “DF32” and “DF33”: are small faults located to the east of Longwall 21 and south of Longwall 22 and are part of the DD9 dyke zone. Drilling shows a displacement of up to 1.5 m.
- A number of lineaments have been detected in this area, some broadly correlated with the position of dykes (rather than faults) mapped at seam level:
  - ▷ “DSD1” is interpreted as being an indication that the dykes mapped at seam level in the DD9-DD25 dyke zone extend to surface.
  - ▷ “DL_1” and “DL_2” are lineaments interpreted from aeromagnetic survey. These broadly align with the wider dyke zone and support the general structural trend in this area.
  - ▷ “DAD_14” is a north-south trending feature from aeromagnetic survey. Based on experience elsewhere at Dendrobium, this is likely to be a narrow dyke feature.

Further discussion of the likely behaviour of these structures in relation to extraction of Longwalls 22 and 23 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 effects to significant distances, leading the transmission of effects out to hundreds of metres or a kilometre or so 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.*”.

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** (from HS, 2019c). 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 Coal Measures, coal seams, to significant depth (>400-500 m).

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.

Figure 2-3A shows that around Area 3C, 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.

The incised nature of the (now flooded) Cordeaux River valley means that to the east of Area 3C the base of the Cordeaux Reservoir is hosted within the Bulgo Sandstone and Bald Hill Claystone (**Figure**

2-3A), while the Hawkesbury Sandstone forms the flanks or sides of the reservoir. Further to the north, due to the northward dip of strata, the Bulgo Sandstone and Bald Hill Claystone deepens to beneath the floor of the reservoir and the reservoir is hosted almost entirely within the Hawkesbury Sandstone with the Bald Hill Claystone present only along the valley thalweg.

Table 2-2 Summary of the stratigraphic sequence

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

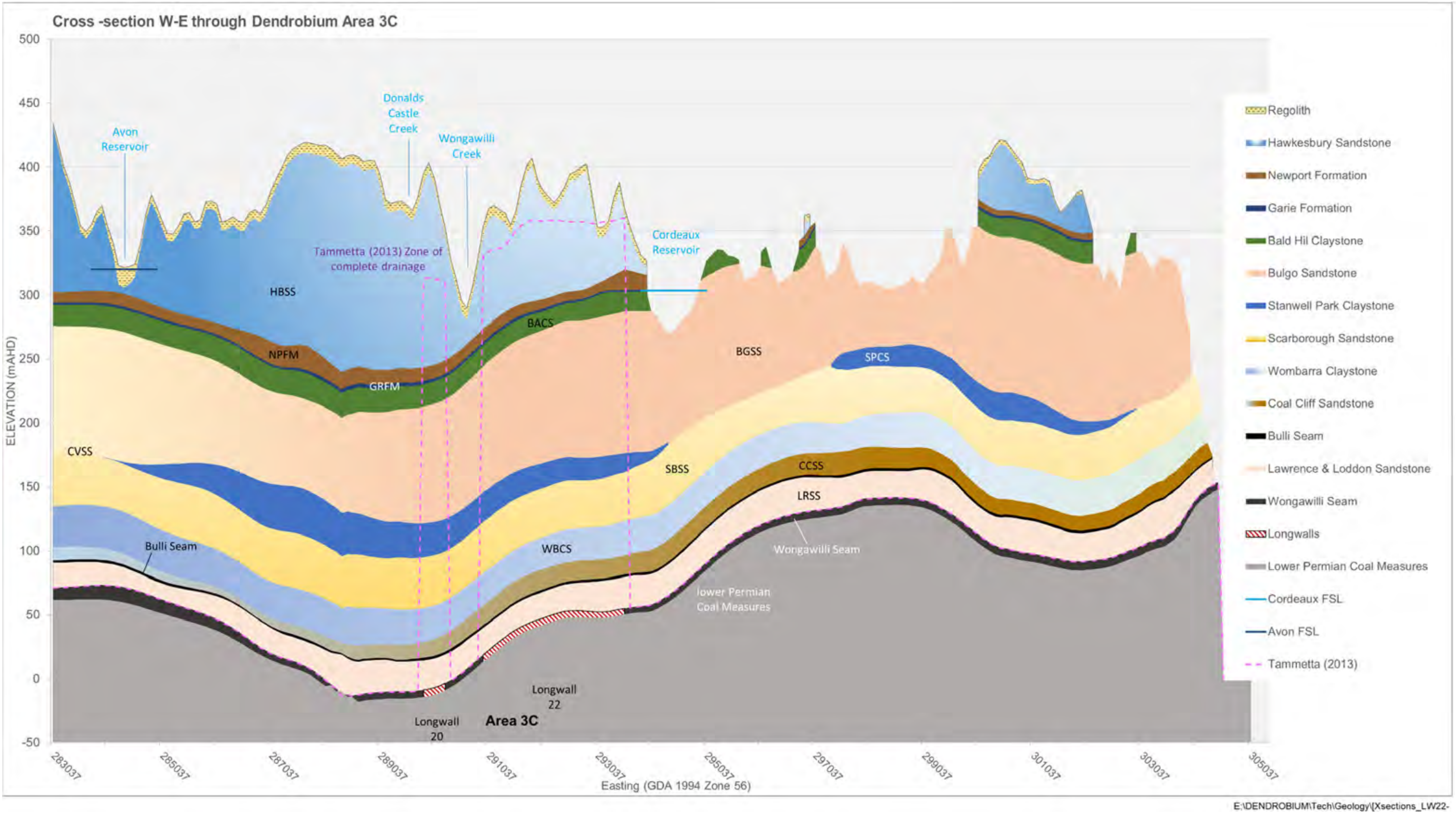


Figure 2-4 Cross-section through A3C Longwalls 20 and 22

The cross-section (**Figure 2-4**) illustrates the main units and geometry of the sequence around Area 3C. The section shows that the Wongawilli Seam is approximately 290 to 400 m deep through Longwalls 22, being 320-340 m deep at the centre of the panel. Outside of the panel footprint, depth of cover declines, mainly associated with variable ground topography but also because of the syncline to the west, to 250 m near Wongawilli Creek and to 240 m at the edge of Cordeaux Reservoir.

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.

Fracturing is most intense and vertically connected immediately above the collapsed longwall (goaf) (the 'caved zone'), and within the 'fracture zone' the intensity of fracturing grades upwards through to less fractured strata (Booth, 2002). 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).

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).

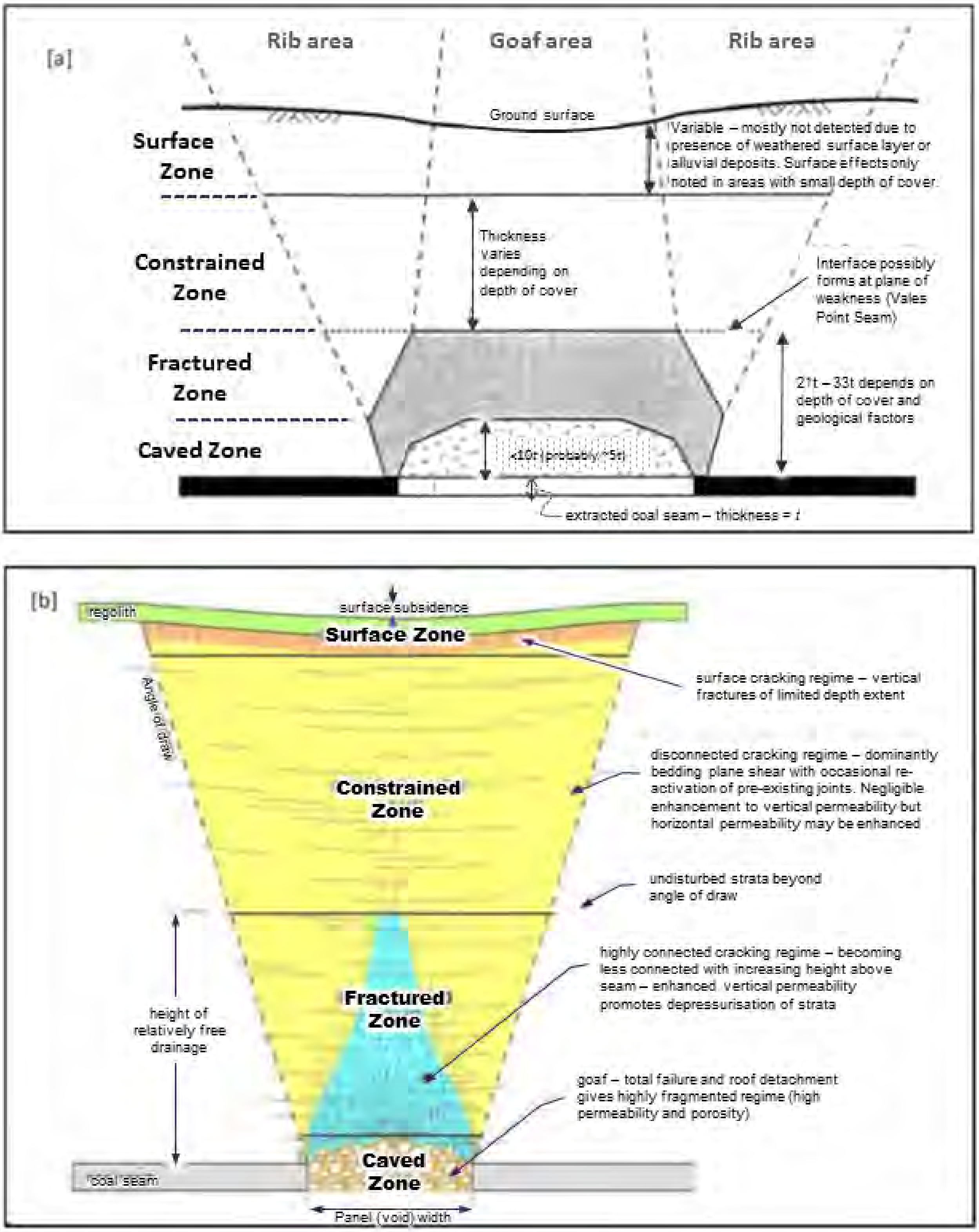
At the surface, subsidence and tension across the subsidence trough combine to cause 'surface cracking'. This is significant with respect to impacts on surface water features, such as watercourses and swamps, that may overlie or be adjacent to longwalls.

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

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 (most significantly, the analysis of HGEO, 2020c), are presented later, in Sections 3.6.1.

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.



(source Forster & Enever, 1992 and Department of Planning, 2008)

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 groundwater works that are considered 'water supply works', as per the AIP, are summarised in **Table 3-1**. All other Groundwater Works are further from Longwalls 22 and 23, and most of them are along the coastal plain, and stratigraphically separated from the coal measures.

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

GW work ID	Distance from Dendrobium Mine	Distance from Area 3C	Description
GW112386	1.9 km north of Area 3A, 0.5 km northeast of Longwall 23.	0.5 km to the NE of Longwall 23	Monitoring bore installed by WaterNSW on western edge of Lake Cordeaux.
GW040945	7.2 km WNW of Area 3B	9.7 km to the W of Longwall 23	WaterNSW test bore drilled to investigate groundwater supply near Avon Dam.
GW068119 and others	4.5 km south of Areas 1-2	8.7 km to the SE of Longwall 22	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	9.7 km to the N of Longwall 23	Domestic/stock bore completed in the Hawkesbury Sandstone, just south of Wilton.

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 to the north of Longwall 23. Given the distance involved, these features are therefore not at risk from the extraction of Longwalls 22 or 23.

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 Longwalls 22 and 23 are:

- Den07: a broad swamp along LC5, mainly located directly above Longwall 23 and, approximately 5% lies above Longwall 22.
- Den09: a narrow swamp along the headwater reach of LC5, located 90 m south of Longwall 22 and 300 m east of Longwall 21.

The Surface Water assessment (HGEO, 2021c [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 mapped on the GDE Atlas within 3 km of Longwalls 22 and 23 (the nearest such feature being Cordeaux River), while the mapping of potential *terrestrial* GDEs shows several features within 400 m of Longwalls 22 and 23 (**Figure 3-2**).

Cross-referencing against swamp and vegetation mapping (Niche, 2021 and NPWS, 2003) indicates that none of the features mapped on the GDE Atlas, which are based on national or regional studies, correspond to the mapped and ground-truthed Upland Swamp areas (Section 3.2.2). The BOM GDE Atlas includes attributes describing the relevant vegetation communities, and these are labelled on **Figure 3-2**. These include:

- CSGF = Coastal Sandstone Gully Forest – the areas mapped by the GDE Atlas as being potential GDEs are approximately 1% of the overall area of 'Exposed Sandstone Scribbly Gum Woodland' mapped by NPWS (2003) and included in the assessment by Niche (2021).
- CSRW = Coastal Sandstone Ridgetop Woodland – the areas mapped by the GDE Atlas as being potential GDEs are <0.5% of the overall area of 'Sandstone Gully Peppermint Forest' mapped by NPWS (2003) included in the assessment by Niche (2021).
- SRS = Sandstone Riparian Scrub – the areas mapped by the GDE Atlas along Wongawilli Creek as being potential GDEs are approximately 1% of the overall area of 'Sandstone Gully Peppermint Forest' mapped by NPWS (2003) included in the assessment by Niche (2021).

In discussion with Niche, we note that the attribution of vegetation communities in the GDE Atlas appears to be incorrect, with the ''gully" forest of NPWS differing in location to the 'gully' forest of BOM, and the 'ridgetop' woodland of NPWS differing in location to the 'exposed' woodland of BOM.

Based on advice from Niche, the vegetation communities described in the first two bullet points (above) are not sensitive to changes in groundwater level.

The last of these, the Sandstone Riparian Scrub, is located along Wongawilli Creek, and therefore are in a location where groundwater discharge would occur. Niche advised that the aquatic ecology, rather than the terrestrial ecology (i.e. vegetation), is considered more significant in locations like this, however the GDE Atlas did not map any *aquatic* potential GDEs in this area.

Niche (2021) 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. Upland swamps, on the other hand are prone to groundwater changes as a result of subsidence and associated fracturing, and are therefore the focus of the ecological impact assessment (Niche, 2021).

3.3 Monitoring

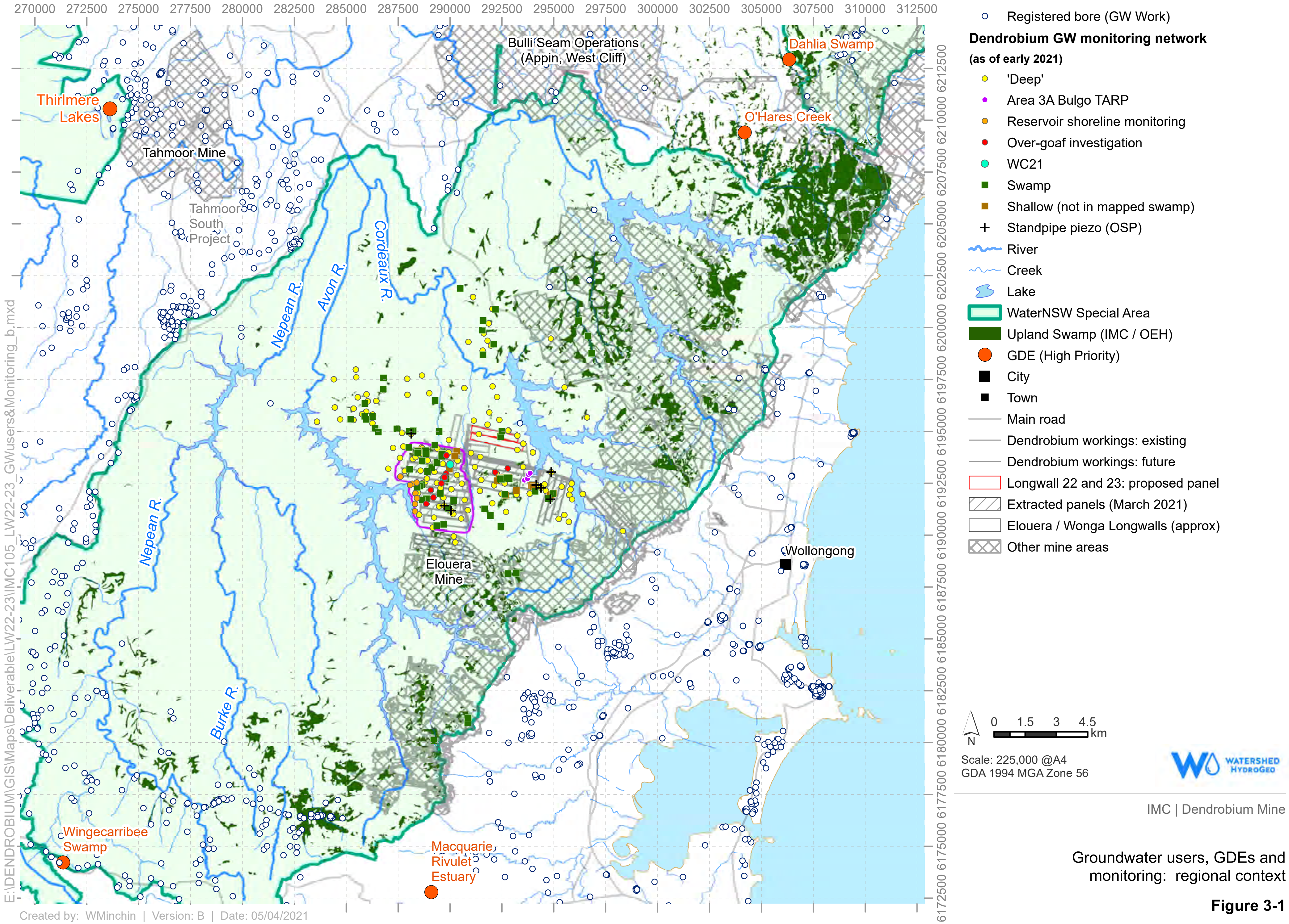
Groundwater monitoring locations are described in the following section. Surface water monitoring sites are presented in Section 2.4.1.

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 3C (**Figure 3-2**). Groundwater level monitoring is typically conducted via:

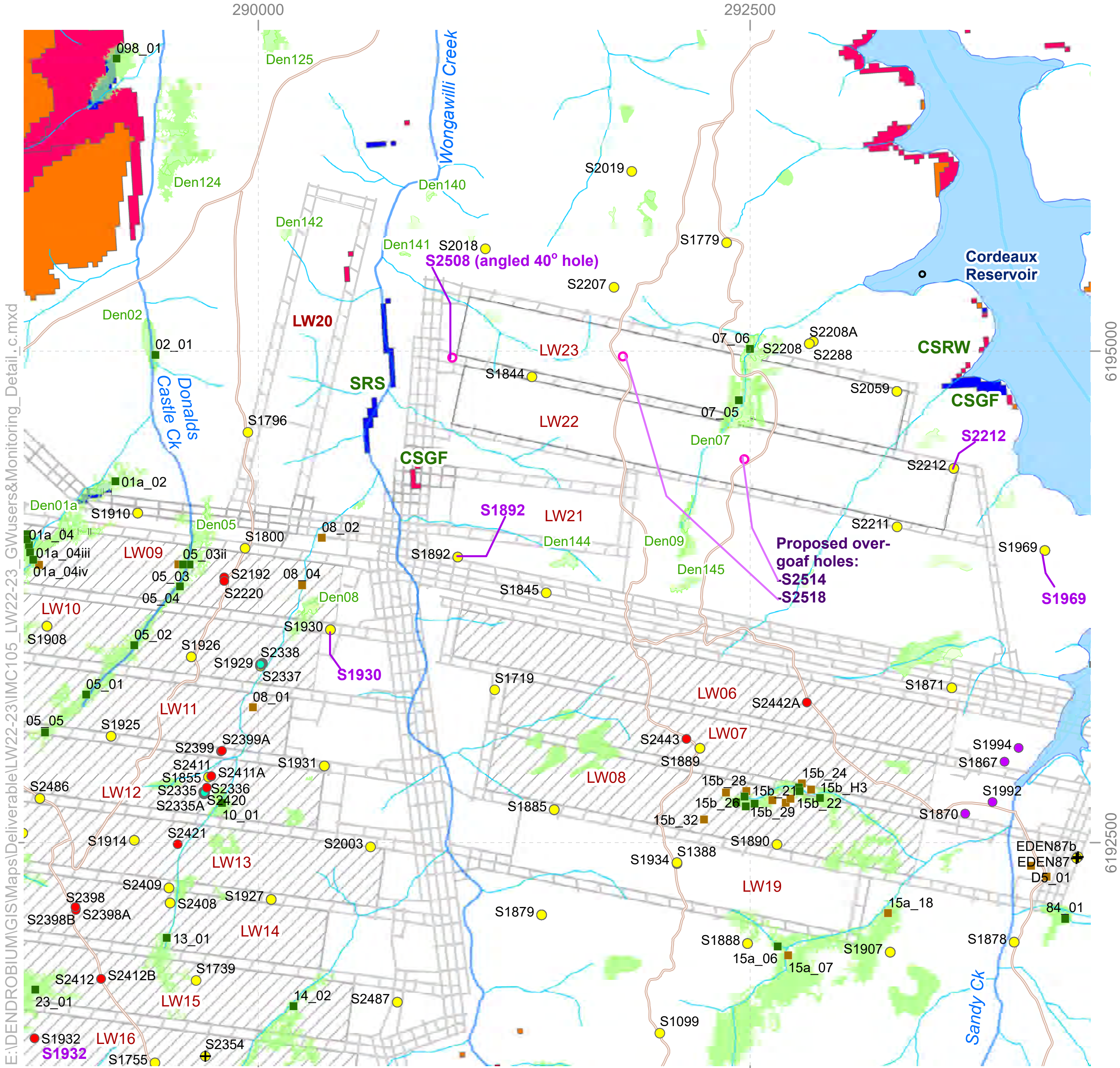
- Multi-level vibrating wire piezometers (VWPs) installed within 'deep' bores. While there are questions about the absolute accuracy of VWPs, they do allow monitoring at multiple levels within a single bore, meaning they maximise the ability to monitor groundwater pressures in 3-dimensions and allow 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 once a suitable baseline of data has been established.
- 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 (PB, 2015) and then a number of bores more recently above Longwalls 6, 7, 12, 13, 14, 15, 16 and 17 (HGEO, 2020c). 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.

Drilling of a pre-mining over-goaf borehole is planned for Longwall 21, and bores S2514 and S2518 are planned for Longwalls 22 and 23 respectively. Other monitoring sites (e.g. S2508 near to Longwalls 22 and 23, as labelled on **Figure 3-2**) have been drilled or are being planned. S2508 is an angled bore, inclined 40-degree to the west, with piezometers monitoring the lower HBSS, close to and essentially at the level of Wongawilli Creek.



Groundwater users, GDEs and monitoring: regional context

Figure 3-1



Registered GW Work

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
- Lake
- Upland Swamp, Area 3C (IMC)
- Upland Swamp (IMC / OEH)
- GDE (High Priority)
- Main road
- Dendrobium workings: existing
- Dendrobium workings: future
- Longwall 22 and 23: proposed panel
- Fire Road
- Mined area

Terrestrial GDE mapping: BoM GDE Atlas

- High potential GDE - national assessment
- High potential GDE - regional studies
- Moderate potential GDE - national assessment
- Moderate potential GDE - regional studies
- Low potential GDE - national assessment
- Low potential GDE - regional studies

CSGF = Coastal Sandstone Gully Forest
CSRW = Coastal Sandstone Ridgetop Woodland
SRS = Sandstone Riparian Scrub

N 0 0.2 0.4 0.6 km

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

WATERSHED HYDROGEO

IMC | Dendrobium Mine

Groundwater users, GDEs and monitoring around Area 3C

Figure 3-2

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 DPIE-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 Geotechnics (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).

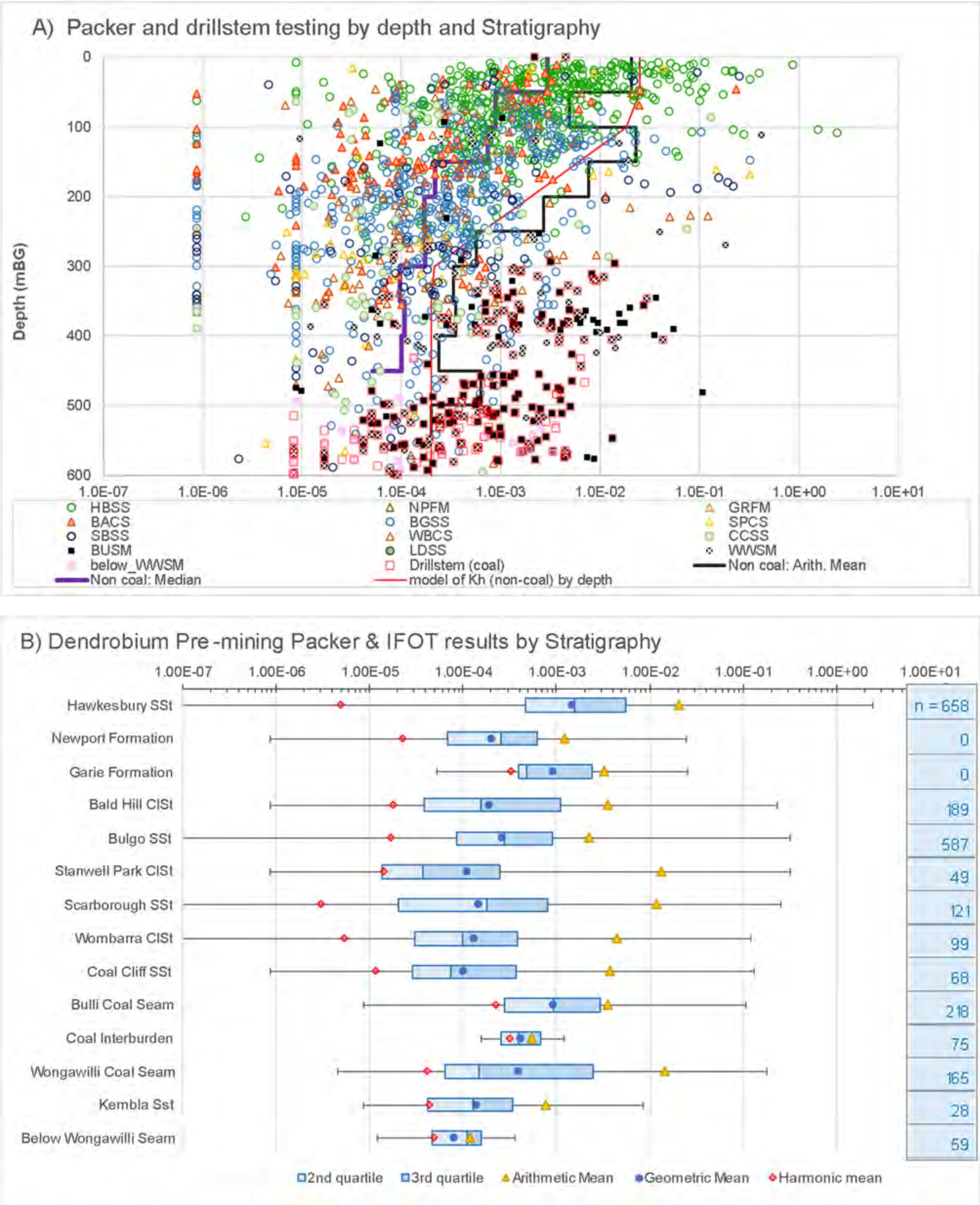


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Figure 3-3 Summary of horizontal hydraulic conductivity (Kh) by depth and stratigraphy

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**.

At Dendrobium, core testing of the Hawkesbury Sandstone, Newport Formation, Bald Hill Claystone and Colo Vale Sandstone has been carried out, and the results are summarised in **Figure 3-4A**, along with the calculated harmonic mean of the packer and drillstem tests conducted at Dendrobium, noting that the harmonic mean is the recommended method for characterising the effective or representative Kv of a hydrostratigraphic unit (Domenico and Schwartz, 1998). This dataset has been augmented with a summary of similar core testing at BSO (from Heritage Computing, 2010), presented as the harmonic mean and the minimum and maximum range in vertical hydraulic conductivity. **Figure 3-4B** presents the extensive core testing dataset from the Tahmoor Mine.

Vertical hydraulic conductivity (Kv) is difficult to measure in the field, and laboratory measurements on core samples are the most-often used method of characterising Kv. These values may be somewhat lower than field or *in situ* values because of much smaller sample volume available from core samples, i.e. this technique may not capture hydraulic conductivity due to secondary porosity, which is why the harmonic mean from the packer tests has been added to **Figure 3-4A** (**Table 1-6**).

The extensive datasets, compiled from available data from Dendrobium as well as from neighbouring operations (Tahmoor and BSO), 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).

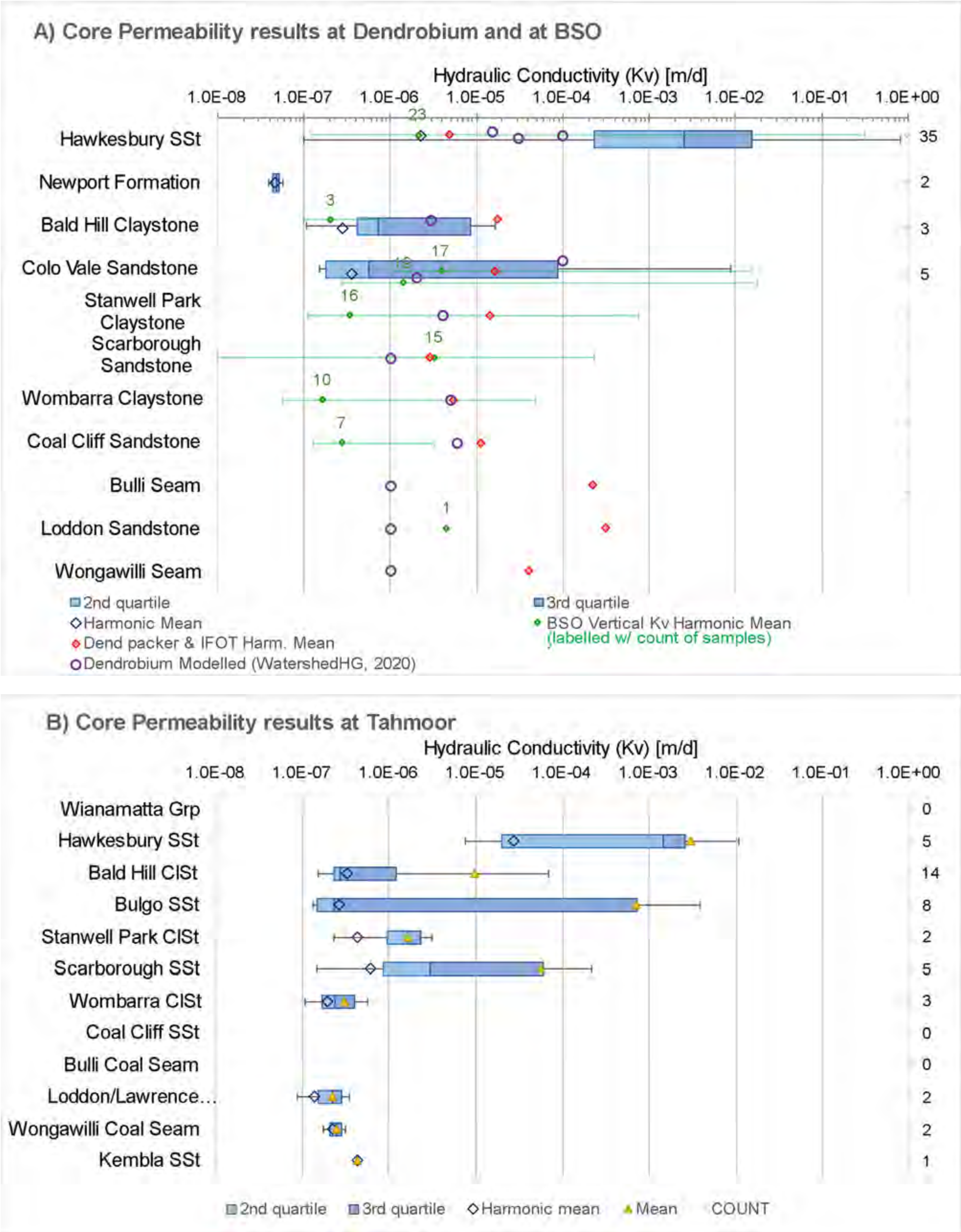

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Figure 3-4 Summary of vertical hydraulic conductivity (Kv)

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 3-2** provides total and effective porosity results from laboratory testing of core samples, based on a dataset from Dendrobium and from BSO (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 3-2 Summary of porosity (%) determined from Dendrobium and BSO core samples

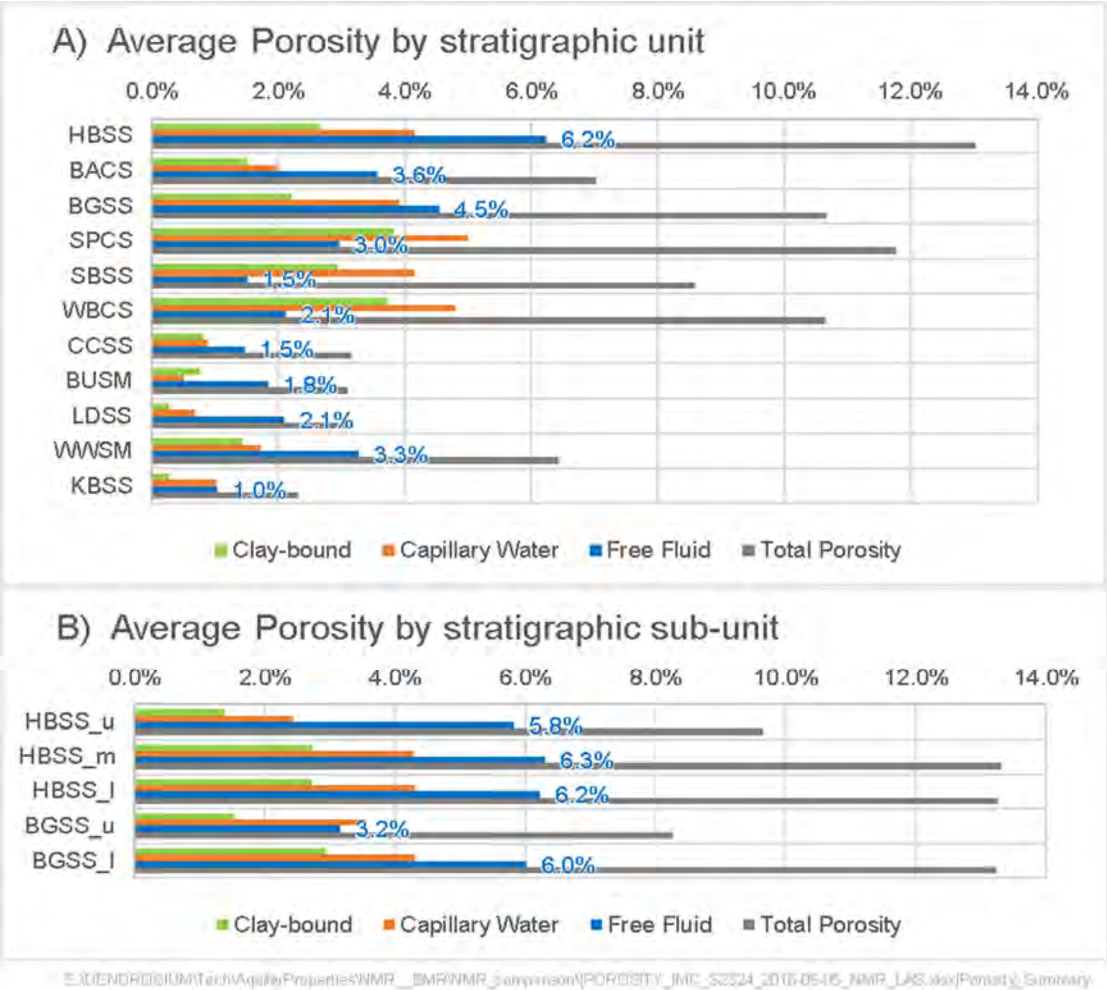
Geological Unit	Total Porosity (%)				Effective Porosity (%)	
	Min	Mean	Max	Count	Mean	Count
Hawkesbury Sandstone	3.8	15.4 (14.9)	23.6	68 (4)	11.2	2
Newport Formation	2	2.4	2.6	3		
Bald Hill Claystone	4.1	6.1	9.9	6		
Colo Vale Sandstone	3.7	9.4	18.1	10		
upper Bulgo Sandstone		(8.2)		(5)	3.3	5
lower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

Total porosity data in parentheses () is from BSO. All Effective Porosity measurements are from BSO.
Source: E:\DENDROBIUM\Tech\AquiferProperties\Packer\Dendrobium_AquiferPropertiesDatabase_20161219.xlsx

IMC has also used Borehole Magnetic Resonance (BMR) imaging in selected drillholes to provide continuous logging of density, gamma count, porosity and hydraulic conductivity. More analysis of downhole BMR traces was presented in HS (2019c), and a summary of that is as follows. 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 3-5A 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 3-5B** 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 3-2**). The BMR free water values for Narrabeen Group (i.e. BGSS, SPCS, SBSS) are typically higher than the effective porosity values in **Table 3-2**.



(from HS, 2019c)

Figure 3-5 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 BSO, are higher than those suggested for specific yield in studies conducted in the Sydney metropolitan area and elsewhere, which indicate a specific yield of between 0.01 and 0.02 is reasonable for typical 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.

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 *et al.,* 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 *et al*., 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 at depth steadily decreasing the 'elastic storage' of the rock formation.

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 the nature of these changes is provided earlier, in Section 2.6.

On-going research by IMC, some 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 – this is not the stated focus of work at Dendrobium, however recent investigations at Dendrobium and other Southern Coalfield Mines have provided useful information.

3.6.1 Fracturing within and immediately adjacent to longwall panels

HGEO (2020c) presents comparisons of pre- and post-mining conditions at a number of bores in Areas 3A and 3B. The field investigations included packer testing, downhole camera and acoustic televiewer surveys, core logging and water level monitoring.

Most of the boreholes drilled and tested as part of this investigation were within the longwall footprint, and deliberately located along the centreline. However, two bores at Longwall 12 were located off-centre and above a chain pillar to investigate any differences in the pattern and character of fracturing.

Figure 3-6 is an example of HGEO's logs illustrating (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.

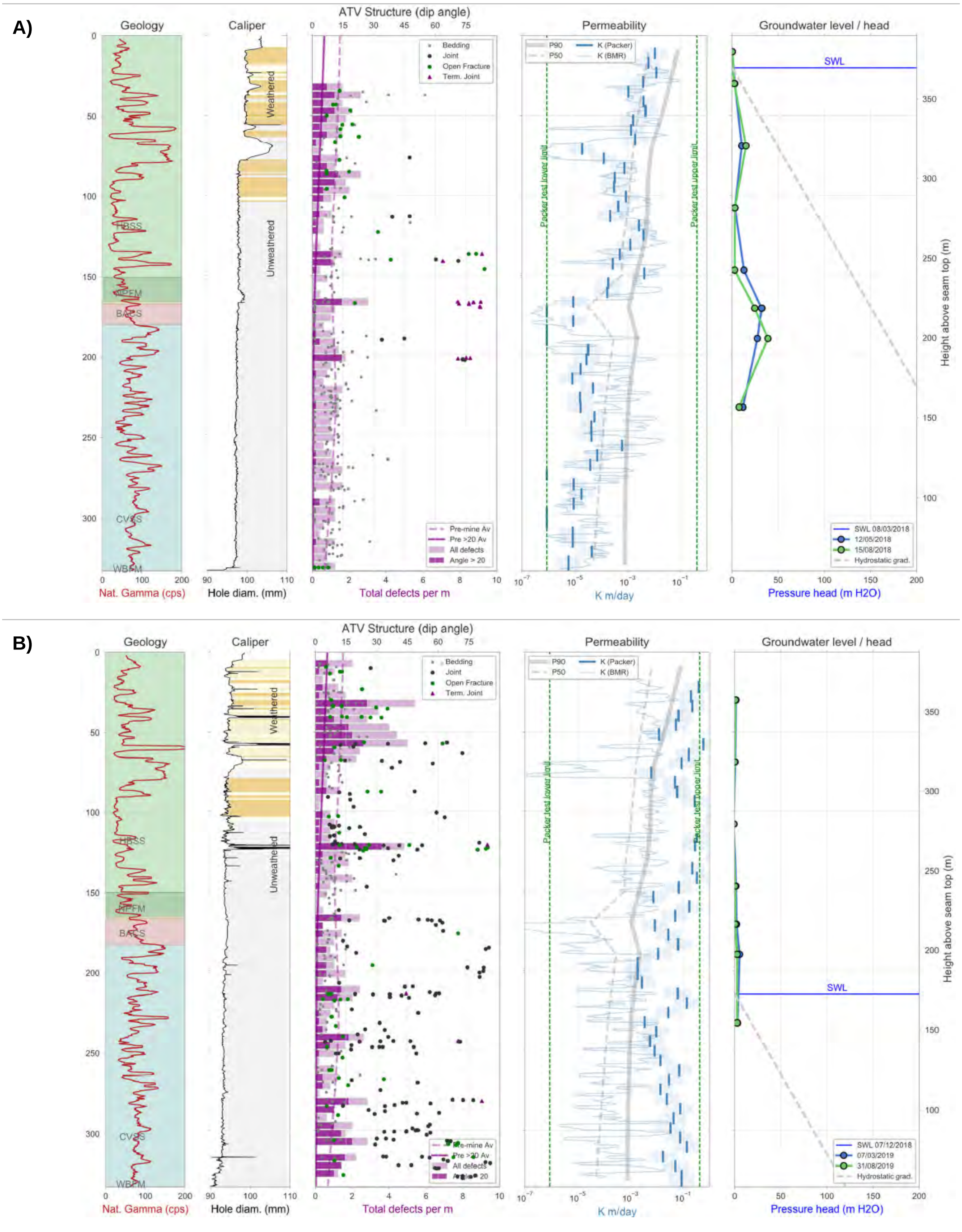


Figure 3-6 Pre- and post-mining conditions above Longwall 14 (boreholes S2398 and S2398A)

The findings from HGEO (2020c) are listed in **Table 3-3**, with some discussion based on our review and consideration of how to represent processes in numerical modelling. The reference # applied in the table is for convenience in referencing here, and is not from HGEO (2020c)

Table 3-3 Summary of findings from longwall fracturing investigations

#	Finding from HGEO (2020a)	Comment
Fracturing:		
1	In both areas, mining-induced fracturing, including high -angle fracturing is highly variable but appears to extend to the surface, or into the pre-longwall surface fracturing zone (<50 m depth). There is a lower density of fracturing above the narrower (249 m) longwalls in Area 3A than the wider (305 m) longwalls in Area 3B.	Agreed. The concept of mine-related fracturing extending to the surface is adopted. The nuance to this is what mode or orientation this fracture is (see #2 and #3). Agreed. The wider panels appear to cause more intense fracturing.
2	In both areas and for both longwall widths, there is a general trend of decreasing fracture density with height above the goaf and a distinctly lower fracture density in the HBSS *[Hawkesbury Sandstone*] than in the underlying CVSS [*Colo Vale Sandstone*]. There is a high fracture density anomaly associated with the BACS [*Bald Hill Claystone*], particularly in Area 3A. There is also an apparent increase in high angle fractures at heights above the goaf of less than ~120 m.	Agreed. Post-mining fracture density appears to decline with height above the goaf. Agreed. BACS is more prone to failure than adjacent strata, possibly because of brittle failure. Agreed – see response to #3.
3	In most over-goaf holes, fractures display a weak preferred orientation parallel to the longwall face within 100 to 200 m above the goaf, <u>transitioning upward to lower-angle or bedding plane fractures</u> with little or no preferred orientation. 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.	Agreed. The point about the general transition from more high angle fractures near the goaf to a greater proportion of low-angle fractures at greater height is significant.
Permeability:		
4	All holes drilled above extracted longwalls in both Areas 3A and 3B show significant increases in permeability throughout the profile. Packer tests indicate an increase in permeability of 2 to 3 orders of magnitude relative to pre-mining conditions. At the centreline of Longwall 12 (S2420) there is a zone of apparently unaffected (near median) permeability in the upper CVSS and BACS; however, this is anomalous compared with other over-goaf holes.	Agreed. Packer testing clearly shows Kh increased throughout the sequence above longwalls.
5	Packer tests in the hole above the pillar zone between Longwalls 11 and 12 (S2399) indicate distinctly lower permeability throughout all strata, with only one quarter of tests plotting above the pre-longwall P90. The lower permeability in strata over the pillar zone is consistent with observations of low defect densities over the pillar zone compared with over the goaf.	Agreed. Strata within the footprint is significantly more disturbed than that above the pillars. Comparison of the three bores at Longwall 12 (S2420/S2411/S2399) and other centre-line bores suggests that the centreline is more affected than the off-centre positions, which is again more affected than the strata over pillars.
Groundwater conditions:		
6	Holes drilled above the goaf centrelines in both Areas 3A and 3B have standing water levels that are significantly (>100 m) below the estimated pre-mining water table or are dry to the base of the hole. The low SWL reflects strongly depressurised strata conditions, downward head gradients and water losses from the holes through open fractures.	Agreed. Simulating the differential drawdowns through the strata (i.e. large drawdowns closer to the seam, lesser drawdowns at distance above it) will be important. Note however that depressurisation may be caused by increased horizontal permeability, especially in the upper horizons and/or increased porosity or void space, not just by vertical drainage, though it is likely a varying combination of both.

		This is further supported by subsequent analysis (HGEO, 2020h) showing groundwater recovery above longwalls that are currently being dewatered.
7	VWPs installed after longwall extraction indicate significant depressurisation throughout all strata, with near-zero pressure heads recorded on most piezometers. Holes in both areas show positive pressure heads in some sensors in the upper CVSS and BACS, indicating localised perching or incomplete drainage of fractured rock domains. Minor perching has been observed in post-longwall holes drilled above Longwall 9. The post-longwall hole above Longwall 14 (S2398) shows depressurisation of all strata above the goaf.	Agreed. See response to #6.
Overarching findings:		
8	There are no clear and consistent step-changes in fracture density associated with any of the predicted heights of fracturing. Rather the data are interpreted to show decreasing fracturing with height above the goaf…	Agreed. Note however that it is easier for conceptual description and assigning model parameters to describe 'zones', even though deformation appears to broadly occur as a continuum.
	… and with anomalous fracturing within the BACS and below 120 m above the goaf.	This is consistent with above findings and will be incorporated in modelling.

The analysis and data presented in HGEO (2020c) provides useful information for setting up and parameterising the groundwater model and are therefore directly relevant to the modelling work to address Condition 15b.

The following section describes key points in applying the findings to a groundwater model, noting that the observations around fracturing and deformation are important to inform inputs to a groundwater model (e.g. "does the geometry and permeability appropriately match observations in the field?"), while observations about depressurisation are important with respect to subsequent outputs of the groundwater model ("does the model appropriately match the observations of depressurisation and inflow?").

Horizontal hydraulic conductivity (Kh) is increased throughout the sequence, from seam to surface, within the longwall footprint. This concept is clearly supported by the count of **low-angle defects** which have clearly and consistently increased from pre- to post-mining throughout the profile. The packer test data constrains the modelled post-mining **Kh**, i.e.:

Post-mining Kh is well constrained

- typically 1E^{-2} to 1E^{-3} m/d in the Bulgo or Colo Vale Sandstone;
- Slightly higher, 5E^{-2} to 5E^{-1} in the Hawkesbury Sandstone; and
- which are approximately 2-3 orders of magnitude greater than the host or pre-mining Kh).

The presence of **high angle defects** is not as uniform and appears more intense at depth (closer to the goaf), and then again at the BACS. It is also potentially more intense again in the upper or mid-HBSS, although this last observation is not consistent across all centreline bores, and seems mainly related to natural weathering.

Logs give a clear indication of where high angle fracturing occurs

There is no **Kv** data directly available from field investigations. However, the packer tests constrains the possible Kv (i.e. it must be equal to or lower than the packer test K), because a Kv higher than that would influence the overall K measured by the packer tests.

Kv is unknown, but has an upper bound

However, the logs showing the density of high-angle defects (HGEO, 2020c) provide useful soft-evidence for specifying where Kv is enhanced to a greater or less degree.

Groundwater level response can give some indication of Kv increases, but drainage of groundwater may be related to Kh.

Kv will be calibrated considering Kh and defect count, inflow and groundwater level response

However, with respect to that last point, the **initial position is to assume that above a longwall, Kv = Kh,** thus beginning model re-calibration from the position of **seam-to-surface connection** (consistent with the presence of some fracturing to the surface) with parameters set by the available packer testing data. If the modelling is unable to match head and inflow responses, this representation will change, while being constrained by field data.

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 (2020c), 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 (2020c), 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.

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 any future longwalls in Area 3C that are located near Cordeaux Reservoir or near to the Wongawilli Creek valley.

SCT (2015) presented discussion on the presence and behaviour of horizontal planar feature’ basal shears associated with the Bald Hill Claystone 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**.

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 and S2331	150 m from LW12	2.9E-03 to 5.00E-03	x 2	
AD2	S2314 and S2314A	210 m from LW13	3.04E-02 to 2.10E-01	x 7	
AD3	S2377 and S2377B	104 m from LW14	1.20E-02 to 1.50E-01	x 12	Post-mining re-drill in Dec-2017
AD3	S2377 and 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 and S2378B	105 m from LW15	2.80E-03 to 1.30E-02	x 5	
AD4	S2378 and 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 and S2376	10 m from LW13	3.04E-02 to 2.90E-02	x 1	
AD7	S2314 and S2435	320 m from LW14	3.04E-02 to 3.10E-01	x 10	
AD8	S2436A, B,C and S2436D	310 m from LW16	5.10E-03 to 1.60E-01	x 30*	*Different test intervals mean this is not reliable. No change in Kh below single shallowest interval.
	General	Not specified		"larger"	PSM, 2017. No data cited.
	General	Hawkesbury Sandstone within 200 m		→ 5E-2 m/d	HGEO, 2018b

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

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 (2020g). Based on this, 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) that has been inferred or measured in some boreholes could be ignored.
- Enhancement of horizontal permeability can 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, this, and specifically 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.

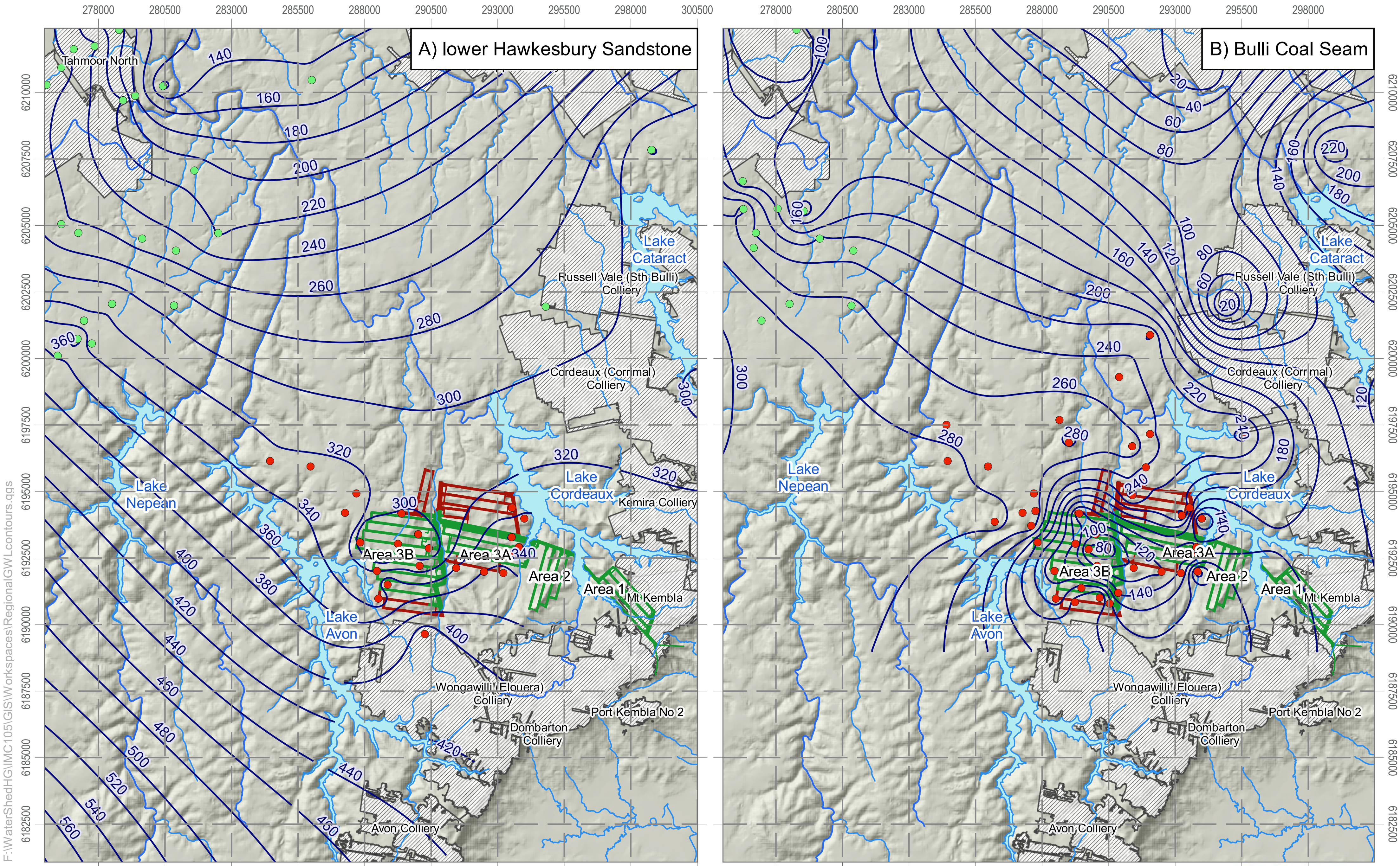
3.7 Groundwater level analysis

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 HS, 2019c) is presented on **Figure 3-7**. This shows the water levels from the lower Hawkesbury Sandstone 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-Hawkesbury Sandstone 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, BSO and Tahmoor (**Figure 3-7**).



0 1 2 3 km
N
Map Scale: 1:180,000 @ A4
GDA 1994 MGA Zone 56

- River
- Creek
- Lake / reservoir
- Dendrobium - Existing Workings
- Dendrobium - Future Workings
- Mined area
- IMC bore locations
- Other mine bore locations
- Groundwater level contour (mAHD)

WATERSHED HYDROGEO

IMC | Dendrobium

Interpolated groundwater levels. lower Hawkesbury Sandstone and Bulli Coal Seam

Figure 3-7

3.7.2 Temporal trends

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

Bore S1892 (**Figure 3-8**) is located just north of Longwall 6 and near to proposed Longwall 21, and 270 m east of Wongawilli Creek[3]. S1930 is located on the western side of Wongawilli Creek (**Figure 3-9**), near Area 3B longwalls. These two hydrographs illustrate effects at or beneath the creek, which are relevant to future longwalls in Areas 3A, 3B 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 in S1892 and S1930 (due to missing data, depressurisation due to Longwall 6 can only be inferred in the SBSS piezometers in S1892, although they do show signs of compression effects at this time). At S1892, the upper HBSS piezometer (labelled “8m: HBSS” on **Figure 3-8**) shows no drawdown, while the 49m piezometer shows about 8 m drawdown, due to both mining and rainfall deficits.

In S1930 (**Figure 3-9**), depressurisation of the BGSS and lower HBSS continues as mining in Area 3A progressed, and then sudden changes in pressure in these units as Area 3B Longwall 9 approached (at the end of Longwall 9). The upward spike in pressure in early 2014 is a result of strata compression as the longwall approached, followed by a decline. After Longwall 10 was extracted, the lower piezometers failed completely, but prior to this the decline in groundwater level had accelerated. Since then, water levels in the lower HBSS have remained consistently 5-10 m below the level of the creek. Water levels in the upper HBSS have remained unaffected (in the 9.3 m deep piezometer) or unaffected/mildly affected (the 45.6 m piezometer). This has been described elsewhere (HGEO, 2020b; WatershedHG, 2018), and similar behaviour is expected to occur along the length of Wongawilli Creek between Areas 3A and 3B.

Bore S1932 (Figure **3-10**) is located within Area 3B Longwall 16, which was extracted in 2020. Although distant from Area 3C, this bore has been shown here because it had a very long record. Depressurisation has occurred in the deeper units since 2009 (especially noticeable in the more permeable coal seams), but has increased since 2018 as Longwall 14 was extracted, and then with a step change in pressures with the passage of neighbouring Longwall 15. Groundwater pressures within the coal seams have declined by approximately 150-200 m since 2008, while the uppermost Bulgo Sandstone water levels have drawn down a total of 40 m. As with S1930, the shallowest piezometer did not show any obvious decline in water levels, and the second piezometer (48 m-HBSS) indicates a slow downward trend, having declined from a pressure head of 18 m (367 mAHD) in 2008 to 10 m (359 mAHD) in early 2020.

Bore S1969 (**Figure 3-11**) is 900 m north of Longwall 6 and 700 m from proposed Longwall 22. It is 240 m from Cordeaux Reservoir. The early time groundwater pressures in the deepest units (LRSS and KBSS) appear to be incorrect, but reasonable from mid-2010. The WBCS, LRSS and KBSS piezometers show depressurisation in response to Area 2 extraction. The SBSS also appears to show depressurisation of about 10-20 m since 2010, and have declined from being approximately equal to lake stage to being persistently below lake levels. The BGSS pressures have remained in approximate equilibrium with lake levels, usually slightly below but sometimes above lake stage. Groundwater levels in the younger strata (BHCS and HBSS) have not been affected by mining, remaining 50 m or more above lake stage.

[3] Note: we have identified an error in piezometers S1892-113m and -257m from 2017 – this to be corrected in the field.

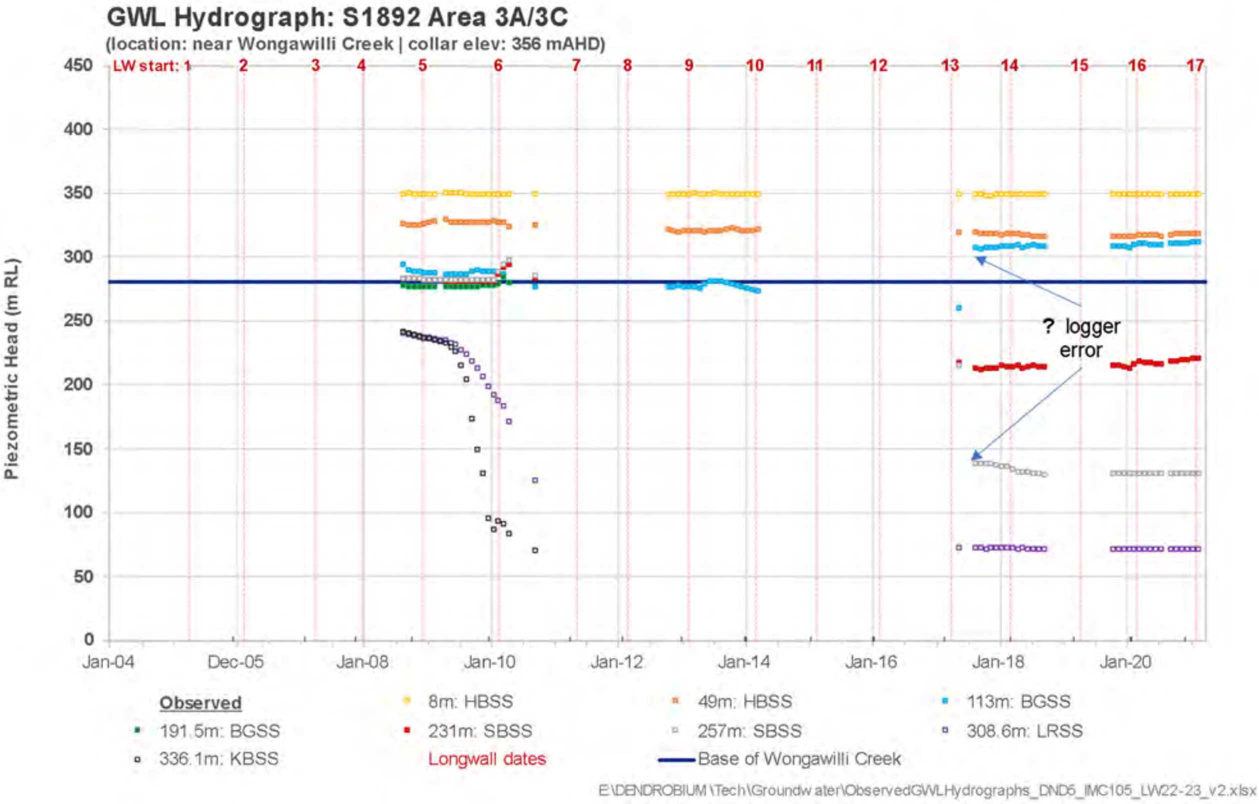


Figure 3-8 Groundwater level trends at bore S1892 (Area 3A/3C and near Wongawilli Creek)

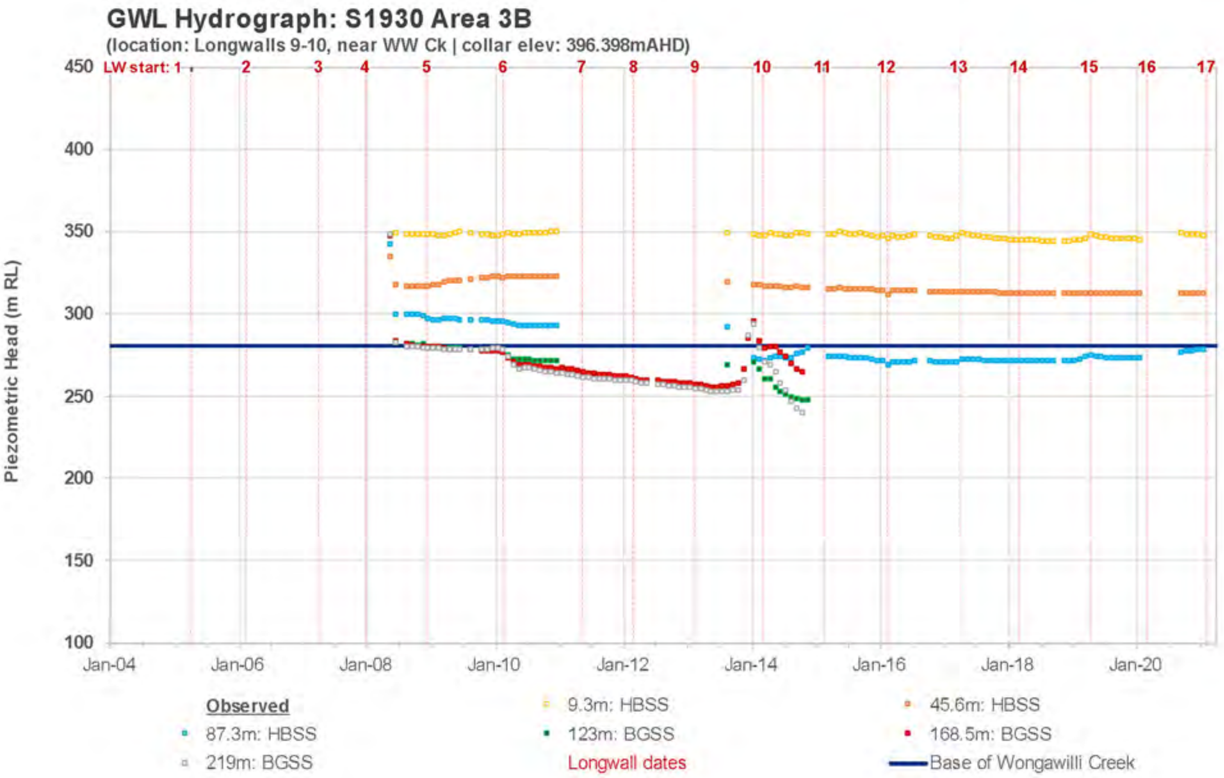


Figure 3-9 Groundwater level trends at bore S1930 (Area 3B), near Wongawilli Creek)

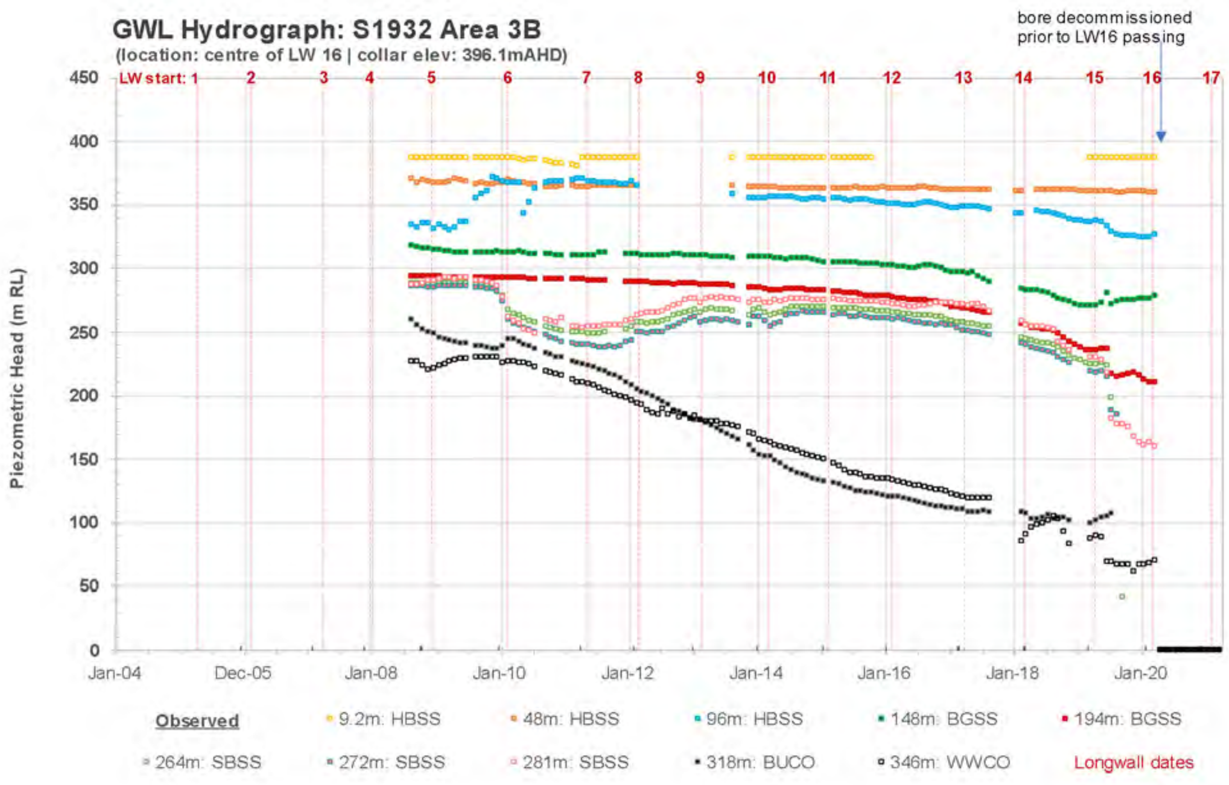


Figure 3-10 Groundwater level trends at bore S1932 (Area 3B, Longwall 16)

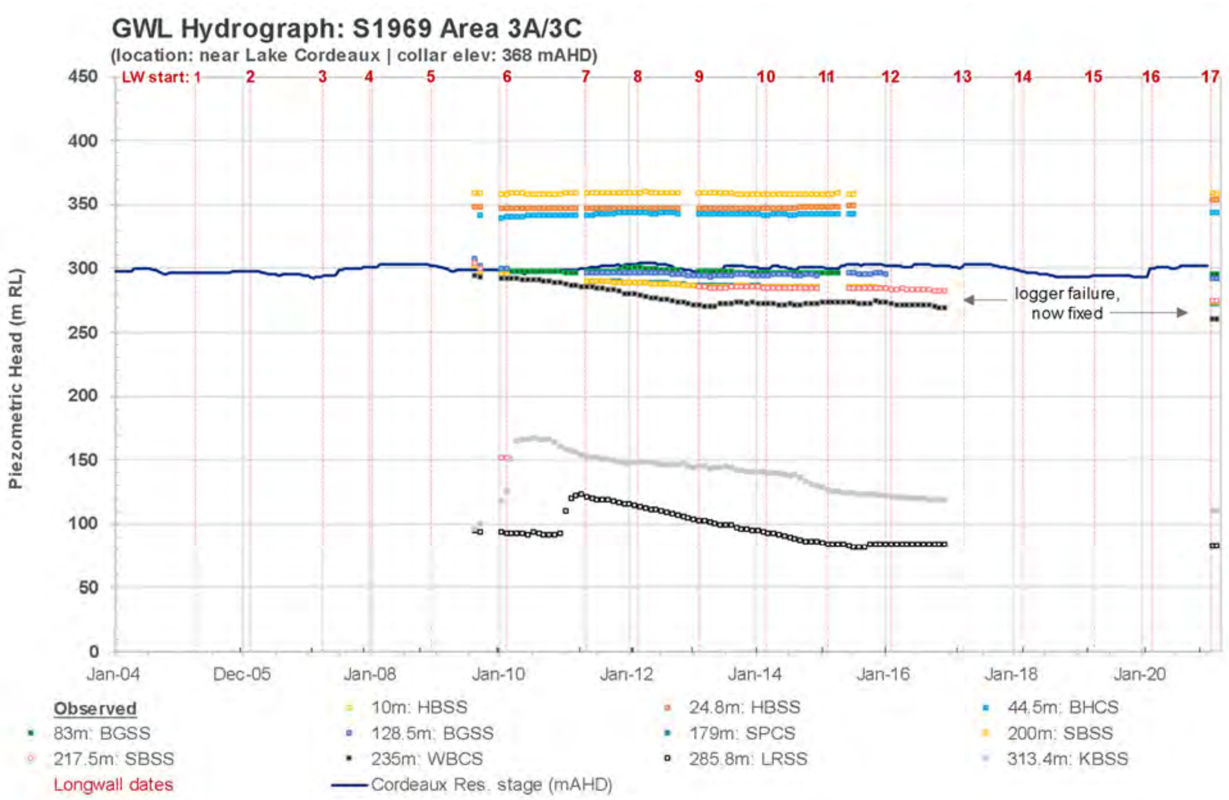


Figure 3-11 Groundwater level trends at bore S1969 (Area 3A/3C, near Cordeaux Reservoir)

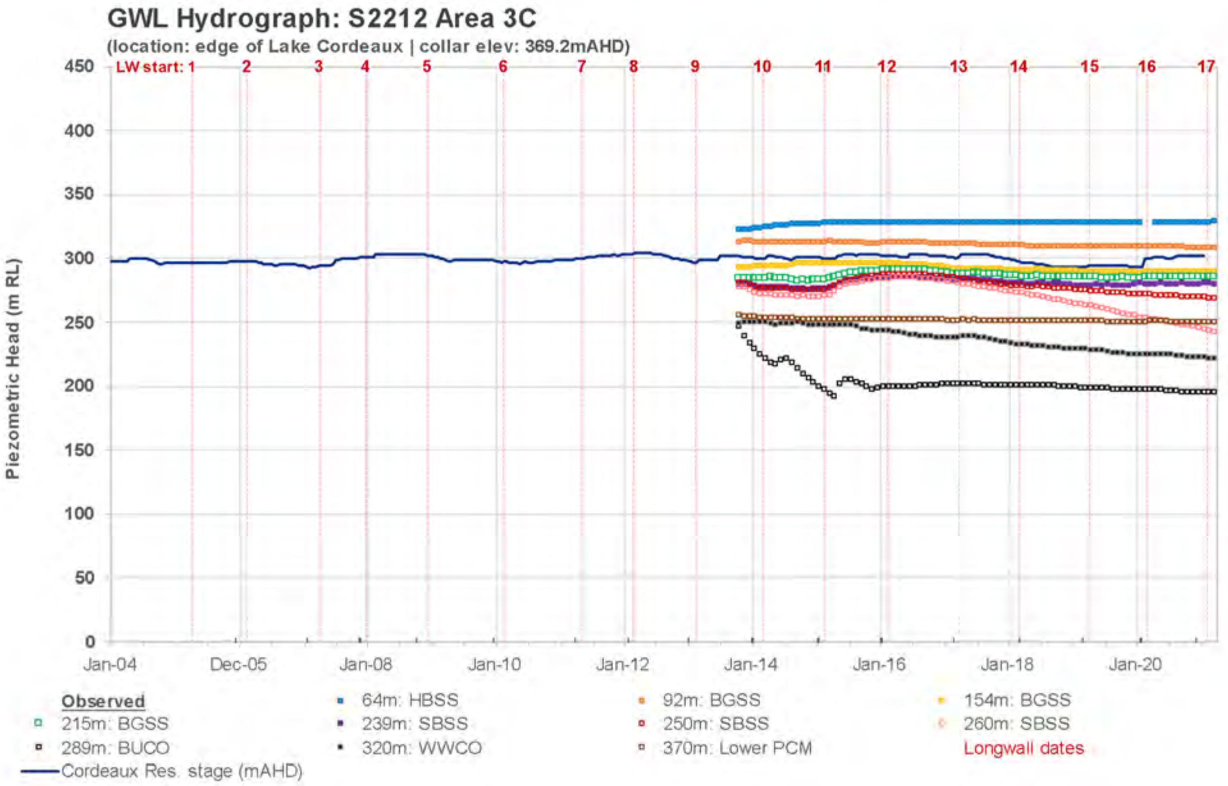


Figure 3-12 Groundwater level trends at bore S2212 (between A3C Longwall 22 and Cordeaux Res.)

Bore S2212 (**Figure 3-12**) is located 100 m east of the edge of proposed Longwall 22 and 300 m from Cordeaux Reservoir. The data on **Figure 3-12** suggests that after the mining of Area 3A, HBSS and upper horizons of the BGSS are consistently 25 and 10 m (respectively) above lake stage and contributing groundwater flow toward the reservoir, but the pre-mining condition is unknown (refer to S1969, above). Groundwater pressures in the lower BGSS have been consistently below recorded lake stage, e.g. were 7-15 m below the lake stage recorded in mid-2018. Pressures in the Bulli and Wongawilli coal seams (BUCO and WWCO) have declined over time, due to mining effects.

Groundwater level monitoring in longwall centre-line holes has allowed observation of 'perching' of groundwater levels at sites in Areas 3A and 3B. That is, pressures in all strata declined following longwall extraction. This decline has been followed by groundwater recovery, commencing 2-3 years after longwall extraction, in the upper BGSS (or Colo Vale Sandstone, CVSS), BHCS or into the lower HBSS (HGEO, 2020h and 2021b). 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).

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 (e.g. HGEO, 2017d; HGEO, 2020f), 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, 2020f).

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 immediately south of Longwall 20 is 1800-2100 µS/cm, and slightly higher in the roadways near Longwall 21 (1800-3200 µS/cm). Extrapolating the trend from **Figure 3-13** suggests increasing salinity in the deep groundwater system to the north toward Longwalls 22 and 23.

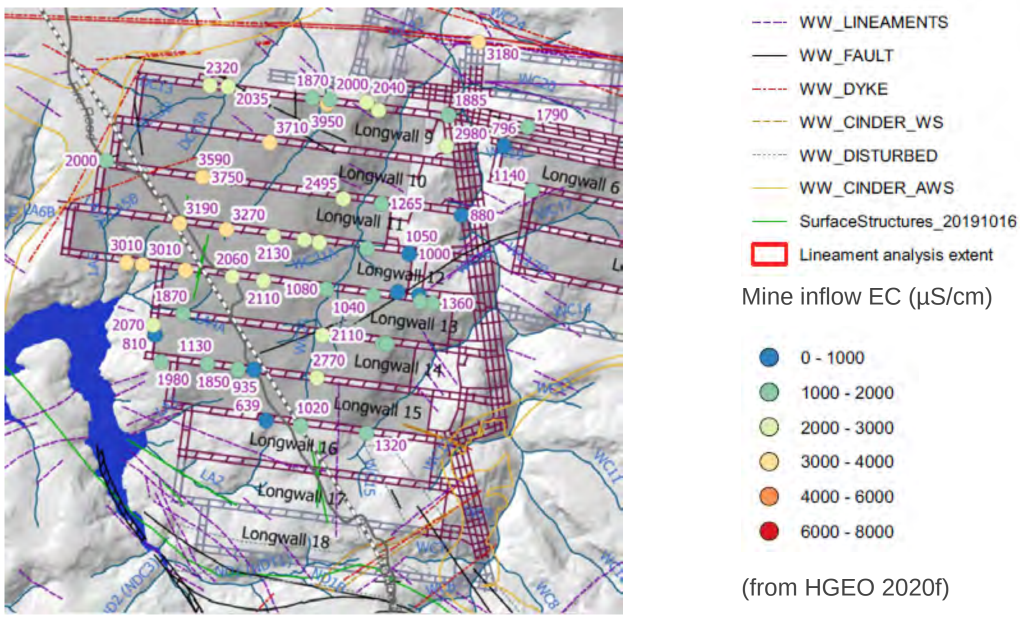


Figure 3-13 Distribution of EC in inflow to mine workings

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, 2020f).

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.

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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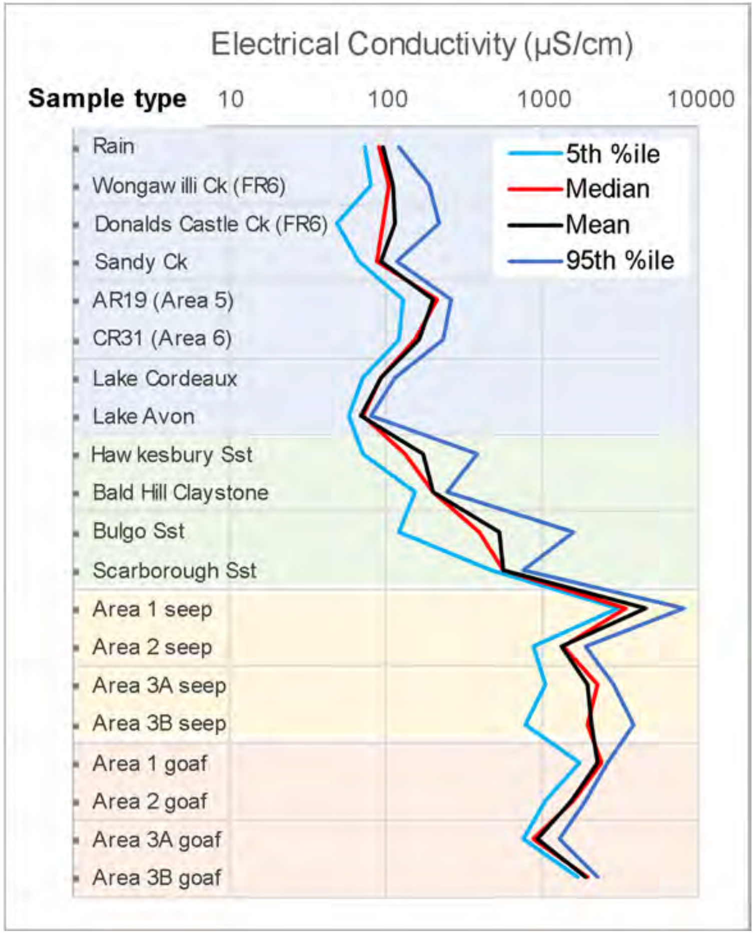


Figure 3-14 Electrical Conductivity (EC) Variation in surface water and groundwater

Groundwater within the Hawkesbury Sandstone 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 Hawkesbury Sandstone is the main outcropping geology, **Figure 2-3**). Groundwater in older stratigraphic units (such as the Bulgo Sandstone, which is present at outcrop to the southeast of Area 3C, and Scarborough Sandstone) is generally more saline. Groundwater EC in the workings, even in goafed areas, is reflective of 'deep' groundwater, such as the Scarborough and Bulgo Sandstones 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.

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). The most useful indicators are:

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

Of these, tritium, EC and Na/Cl are identified as the most useful indicators for routine monitoring and reporting. In addition, the Li/Cl ratios allow discrimination of some deep groundwater sources. Tritium typically identifies waters derived from rain within the last ~50 to 70 years (or mixing with a young source). IMC has investigated other isotopic tracers (e.g. ^{14}C, $^{7}Li/^{6}Li$ and $^{87}Sr/^{86}Sr$) to better understand mine inflow pathways and water-rock interactions. The investigation is currently being finalised, and IMC are in the process of modifying their isotope monitoring program to sample for ^{14}C, tritium, ^{13}C and $\delta^{2}H/\delta^{18}O$).

Analysis of these indicators shows that deeper groundwaters have distinctly different characteristics in terms of dissolved metal ions. The deeper groundwater (i.e. as sampled at seeps in the workings) is characteristically higher in minor ions such as Li, Ba and Sr compared to surface water and shallow groundwater (when normalised to chloride). These characteristics reflect long residence times and equilibrium established with the host groundwater minerals. Furthermore, different mine areas can be distinguished using water fingerprinting. Mine seepage and goaf drainage from Areas 3A and 3B have distinctly higher Li/Cl ratios than seepage and goaf water from Areas 1 and 2. This suggests that groundwater parameters within the coal measures are spatially variable and that variability is reflected initially in seepage samples, and subsequently in goaf water compositions.

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

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
DPI, 2011	unknown	6%	n/a
Coffey, 2012a,b	Baseflow separation, WTF	2.7 or 6%	n/a
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
HS, 2016b	Chloride mass balance baseflow separation, WTF	6.5%	65
BoM, 2020	AWRA-L model (2005 to Mar-2021)	7.6%	90
This study	Soil moisture balance model (2005 to Mar-2021)	6.6%	78

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 (2016b and 2019c). 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 7% of long-term average rainfall, which matches well with independent estimates made by BoM's AWRA-L model to Mar-2021 (7.6%).

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.

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**.

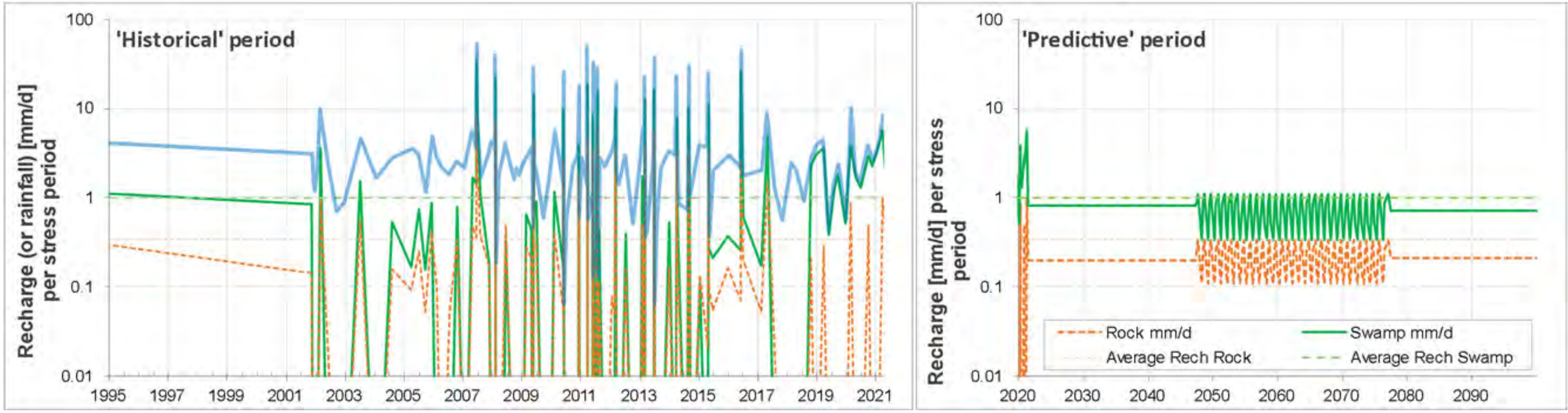
Of note from **Figure 3-15B** is the increase in PE and the resultant increase in potential evaporation demand on shallow groundwater during 2017 to early 2020. This was caused by both a lack of rainfall, and an increase in the PE.

Evapotranspiration by vegetation is governed by rooting depth. A review of literature, including Canadell *et al.* (1996), Florabank[4], Lamontagne *et al.* (2005), Allen *et al.* (2006) 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. Recent field work by SMI Environment Centres (2019) found that the vertical extent of roots within swamp deposits was 0.4-0.8 m.

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

A) Modelled rainfall recharge



B) Modelled potential evapotranspiration from groundwater

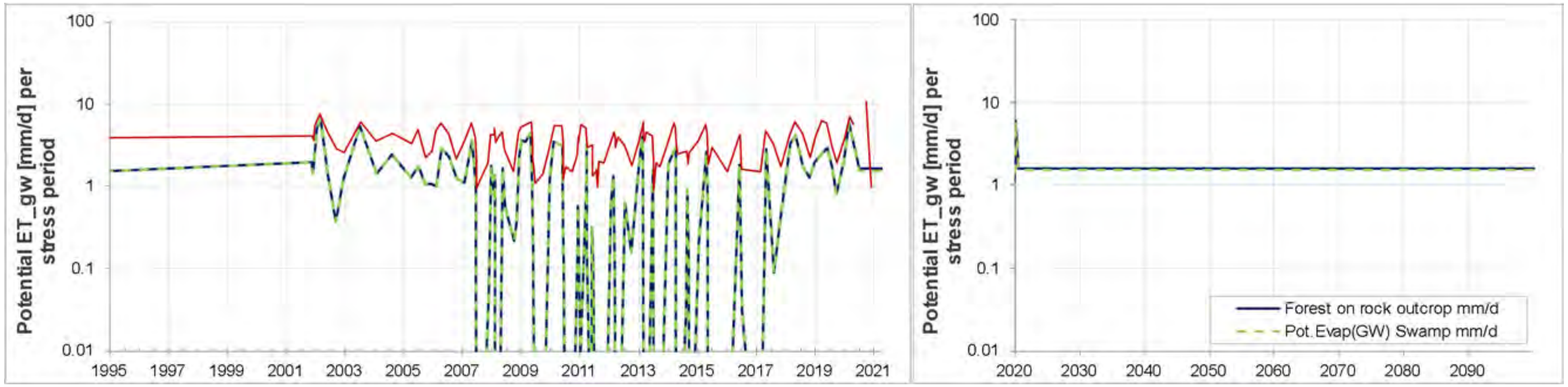


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Figure 3-15 Modelled recharge and evaporation timeseries

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[5]. 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 March 2021. This now includes a record for Area 3C, where first workings commenced in May 2020. 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 April-2020 to March-2021

Statistic	Area 1*	Area 2	Area 3A	Area 3B	Area3C	Dendrobium Total
Minimum	--	0.09	0.09	0.23	0.00	1.14
Average	0.33	1.22	0.86	4.24	0.04	6.10
Maximum	--	3.82	6.99	6.81	0.23	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 Longwall 9 total groundwater inflow to Dendrobium Mine has ranged between about 4,000-12,000 m3/d (i.e. 4-12 ML/d) (averaging 6.7 ML/d). The highest water-year total was 3,040 ML in 2016-17.

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.

Area 3B increased consistently with newly-extracted area until 2017 (Longwall 13), and has plateaued since then, even declining since late 2017 (counter to the trend of increasing inflow with longwall area). This decline could be due to either (or both) persistent dry conditions since 2017 (Section 2.3.1) and declining groundwater levels or storage in and around additional Area 3B longwalls leading to lower inflow.

[5] IMC Procedure DENP0049 – Mine Water Balance v4.0.

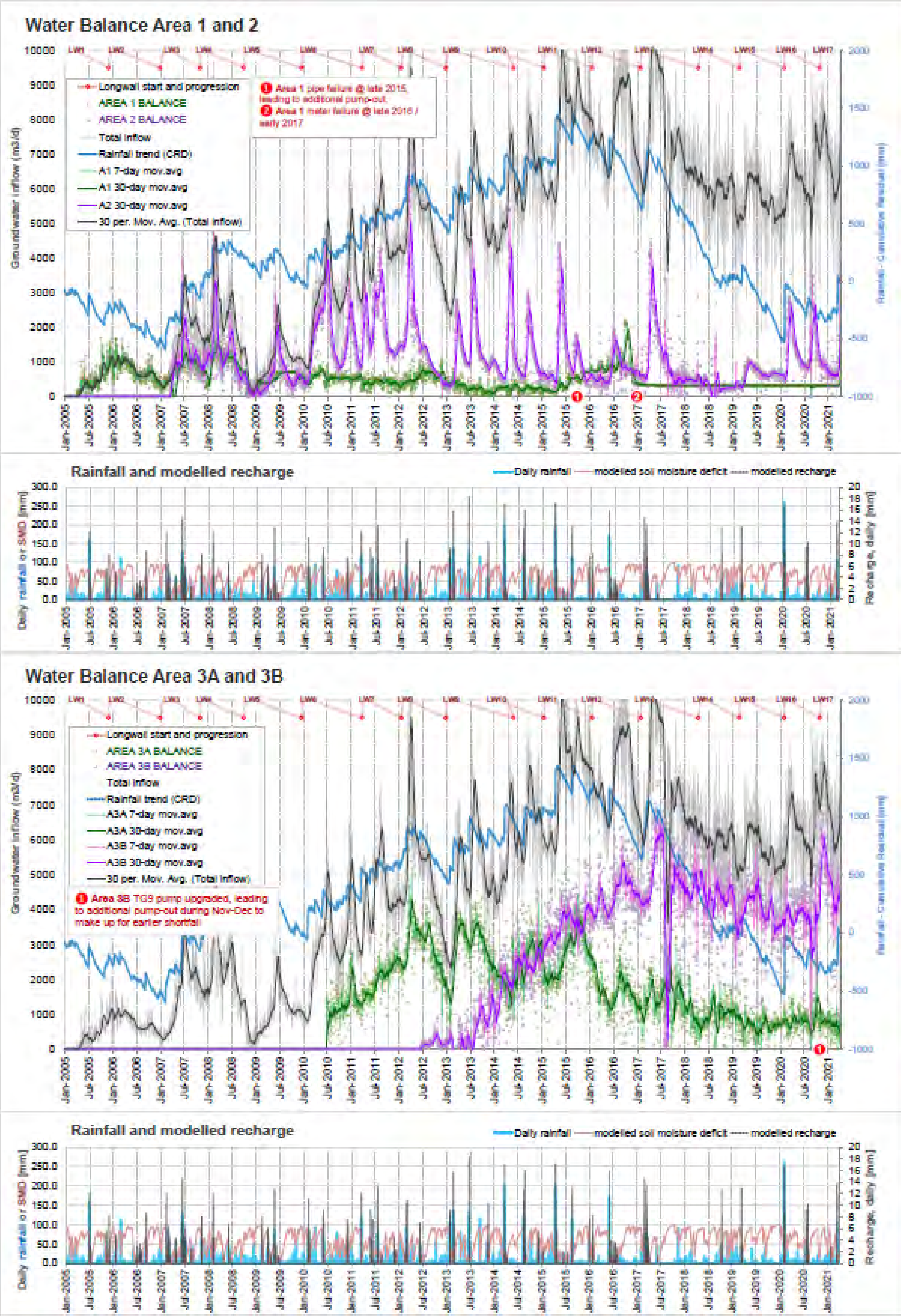


Figure 3-16 Historical mine inflow at Dendrobium

HGEO (2020b) 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 = 13% 90%ile = 25%
Area 3B		13% (8-17)%	Median = 1% 90%ile = 6%
Source	Mackie, 2016	HGEO, 2020b	HGEO, pers.comm (2021)

Using a baseflow separation method, HGEO (2020b) 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). Eight years after commencement, approximately 1% of Area 3B inflow is considered to be modern water. 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/d since then. Area 3A does not show any response to rainfall that appears to be the result of those events, while Area 3B has a spike coincident with the rainfall event, but this increase is no different to other spikes that have occurred during the preceding drought period.

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.

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 (HS, 2019c). 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%

E:\DENDROBIUM\Tech\SurfaceWater\Baseflow\Summary.xlsx

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 HS (2016a,b) and McMahon (2015) discussed that, while the loss of surface flow in undermined headwaters streams such as WC21, DC13S1, DCS2 is discernible on hydrographs for those streams (HS, 2016c; HGEO, 2017), 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' (WatershedHG, 2019b). The latest End of Panel Reports (HGEO, 2020a and 2021a) 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, 2020a and 2021a). At the end of Longwall 15 and after Longwall 16, 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. In the case of WWL, this 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 2018c, 2019a, 2020a, 2021a) 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 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 (WatershedHG, 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 (e.g. Mclean *et al*., 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).

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 Department 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 and 2002; Holla and Barclay, 2000; Guo et al., 2007; Mills, 2011; Tammetta, 2012; Ditton and Merrick, 2014), as well as analysis of data from Dendrobium, and discussion between hydrogeologists (e.g. HGEO, HS, WatershedHG), geotechnical engineers (SCT) and mine geologists (IMC), 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 (2020c) (Section 3.6.1) and recent End of Panel reports (e.g. HGEO, 2020b).

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 (2017) calculated subsidence of 0.8 m (above pillars) and 2.5 m (along the longwall centreline) for the End of Panel report for Longwall 12, 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).

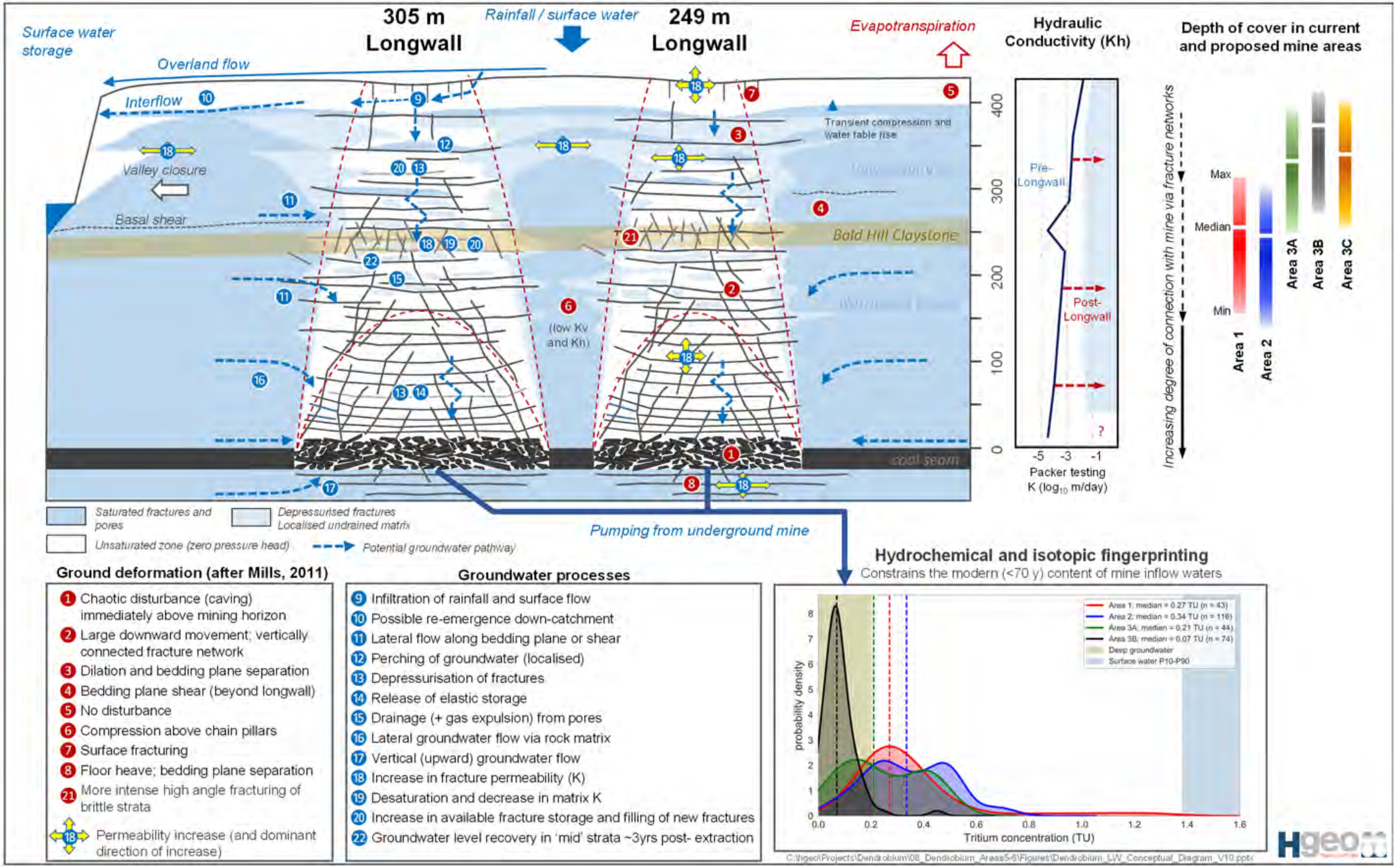


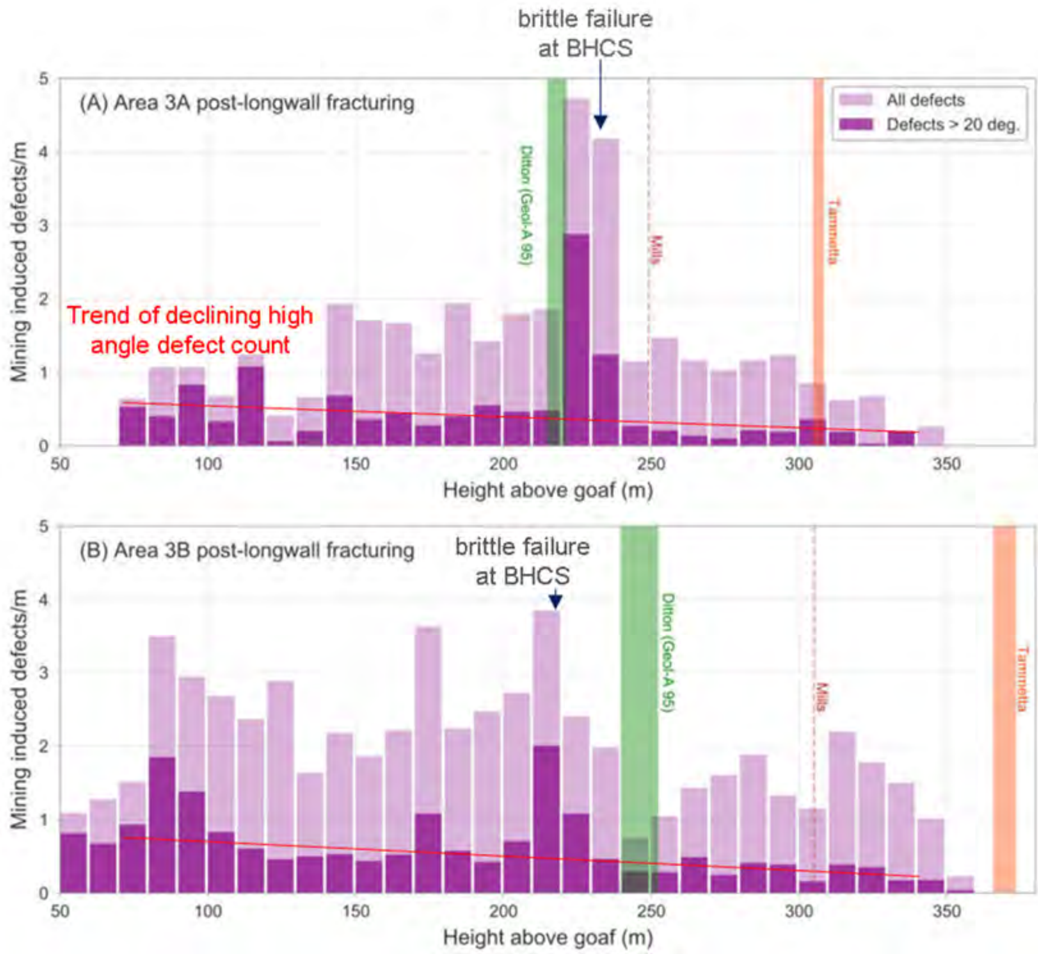
Figure 4-1 Geomechanical and groundwater conceptual model

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 (Kv) cannot be measured *in situ*, but based on the defect logging and presence of intense high angle fracturing, is assumed to be significantly higher than host strata.

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 (the exception to this is discussed below), while low angle fracturing occurs more consistently to the surface (**Figure 4-2**).



(modified after HGEO, 2020c)

Figure 4-2 Change in fracture mode with height above extracted panel

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 of Disconnected Fracturing	Zone of stress relaxation (#4); Zone of bedding plane dilation, some fracturing (#3)		B-zone	‣ 1.6 x panel width (W) (Mills, 2011); ‣ B/B95 – Ditton and Merrick (2014); or ‣ H (Tammetta, 2012)*.
②		lower zone of Connected Fracturing	Zone of large downward movement (#2)	Collapsed Zone	A-zone	‣ 1 x panel width (W) (Mills, 2012); ‣ H (Tammetta, 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 (as described for Longwall 12 investigations in HGEO, 2020c), 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. fracturing is 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 21
brittle, and less able to resist subsidence and sagging than the neighbouring strata.

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). This 22
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.

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, 2017a). 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 (2021) state that the probability of subsidence fracturing within the bed of Wongawilli Creek, due to Longwalls 22 and 23, “is considered to be low”.

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, 2020a and 2021a).

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, 2020a) 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, 2020a and 2021a).

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, Longwalls 22 and 23 are likely to have effects on Wongawilli Creek that are similar to those of previous longwalls in Area 3A and 3B longwalls, noting the earlier comment and assessment by MSEC (2021) 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 most of the previous Area 3A panels, but Longwalls 22 and 23 are typically slightly further from the creek.

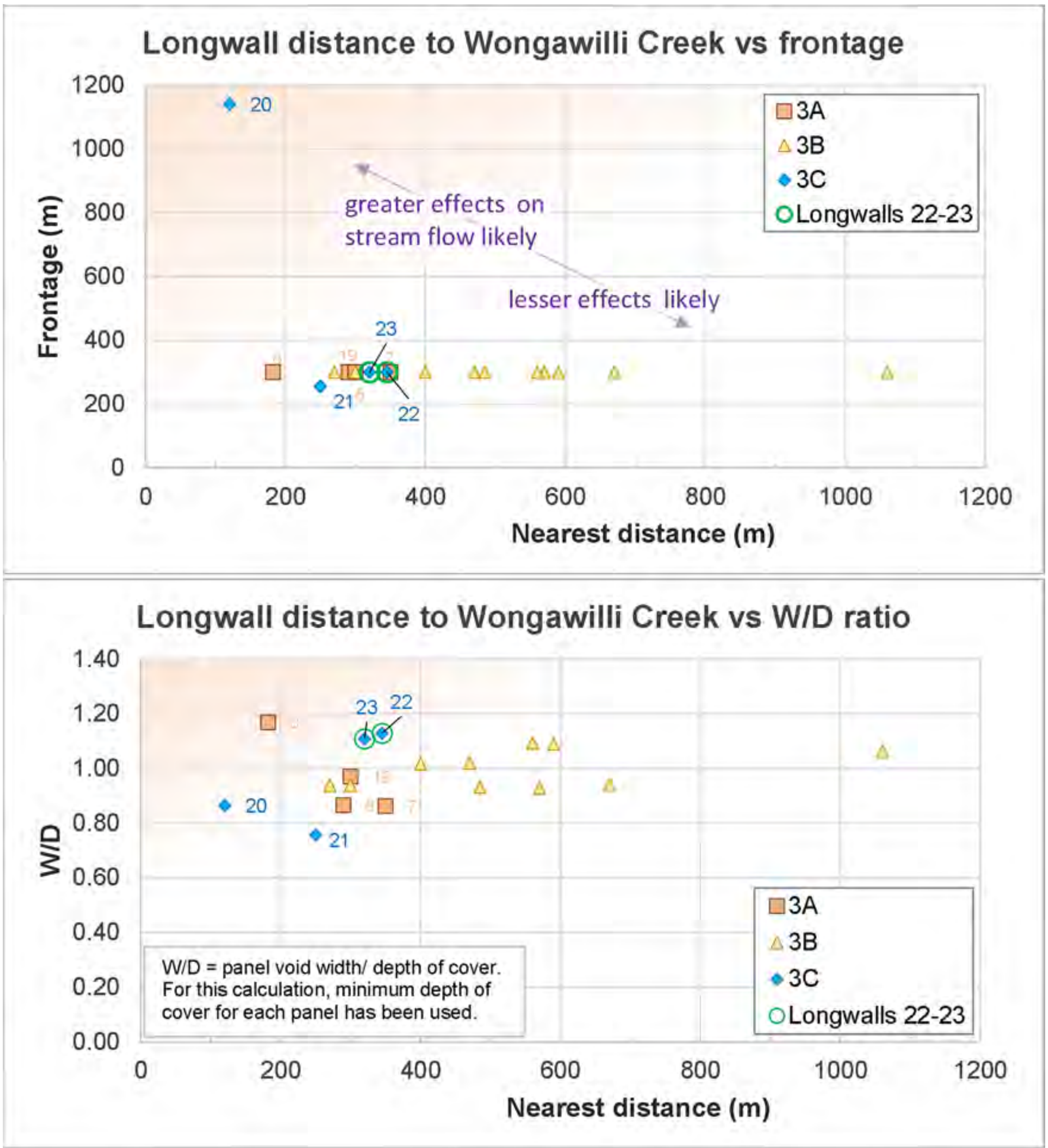


Figure 4-3 Distance and risk of flow reduction in Wongawilli Creek

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).

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 the remainder of Area 3B. There are a number of models for estimating the height of the zone of connected fracturing (discussed briefly in Section 2.6, PSM (2017)). There are also methods and schemes for estimating change in K (e.g. Tammetta, 2014; Guo *et al*., 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 18 is slightly less than that of recent Area 3B panels, at about 330 m, but has a higher 'minimum' depth of cover 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 (i.e. where fracturing is poorly connected or disconnected ③), the degree of drawdown becomes less towards the surface. Drawdown in the mid-Hawkesbury Sandstone is typically about 10-20 m, 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).

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 (based on observations in HydroSimulations (2014b) or review of bore S2009). 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 seals 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 (Redbank Creek) and other areas. The effectiveness of this is unclear. If such measures are ineffective, persistent flow losses in undermined creeks, such as those estimated in recent End of Panel assessments (HGEO, 2020a), 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 these effects 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 (2019), 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 Longwalls 22 and 23, 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 fault offsets (**Figure 4-4**), as well as the presence and properties of any fault gouge within the core of the fault.

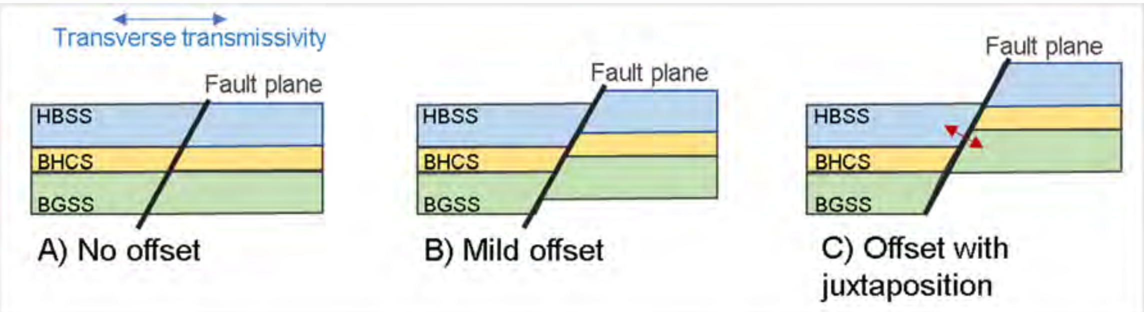


Figure 4-4 Conceptual models of transverse transmissivity and offset strata

These are addressed in the following sub-sections.

The displacement across the currently mapped faults near Area 3C is small (Section 2.5.1). This means there is minimal potential for juxtaposition of 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 minimal displacement and disturbance, there is little evidence for movement that would result in fracturing and deformation that would enhance permeability. Furthermore, the currently mapped faults near Longwalls 20 to 23 are relatively short in longitudinal extent, and are not considered to connect mine workings 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 nature of the mapped faults in this area, this is not considered to be a risk around Longwalls 22 and 23 (or 20 and 21).

4.2.3 Dykes

The east-west trending dykes near Longwalls 20, 21 and 22 (Section 2.5.1) are mapped within the coal measures, and cross the Wongawilli Seam. There are contrasting gas conditions in the seam in Area 3C: high gas contents around Longwalls 22 and 23 and low gas contents to the south of Longwall 22. This contrast was originally hypothesised to be due to the dykes acting as a barrier to fluid migration (i.e. flow of gas and groundwater). However, more recent investigation by IMC geologists suggests that the position of the dykes does not match the change in gas content, so a different mechanism must be responsible. In any case, strata above the coal measures are not thought to be intruded by the dykes, so are not affected by these features, and so drawdown from the Area 3C mining would be transmitted within the Scarborough, Bulgo and Hawkesbury Sandstones in a manner similar to that observed elsewhere at Dendrobium (as per the hydrographs in Section 3.7.2).

4.3 Risk pathways

Based on the data analysis and conceptual model, the primary risk pathways whereby longwall mining at Longwalls 22 and 23, 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.

- Direct subsidence beneath Swamp 07, surface cracking leading to loss of baseflow, or more likely, increased leakage from these surficial deposits. See HGEO (2021c) for more detail. There are no faults (or lineaments) mapped at near Swamp 07.
- Direct subsidence beneath parts of LC5 (by Longwalls 22 and 23), LC6 (Longwall 22 and the southeastern corner of Longwall 23), WC26 (Longwall 23), and minor subsidence at WC24 (Longwall 22). Cracking is likely to occur, and groundwater drawdown would occur, leading to reduced surface water flow and increased cease-to-flow frequency above and adjacent to the longwalls. There is a small, low confidence fault ("DF33") near LC6 (co-located with the dykes to the south of Longwall 22), described in Section 2.5.1 as having no significant displacement. Surface cracking effects at LC6 will result in loss of flow in that creek (Sections 3.6.2 and 3.9.5) whether this fault is present and significant or not. Other than the dykes parallel to WC24 (southeast of Longwall 22), there are no structures, particularly no faults, associated with the other features listed here (i.e. LC5, WC26).

- 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 dry periods in 2018 and 2019. 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 dykes and lineaments mapped at the southeastern corner of Longwall 22 and crossing Wongawilli Creek. Roadways to the west of Longwall 21 and beneath Wongawilli Creek have been developed through these dykes at seam level. There are no faults mapped that indicate a pathway or increased connection between Longwalls 22 and 23 and Wongawilli Creek.

- Groundwater drawdown or pressure reduction to the east of these panels, even to the point of resulting in a groundwater head gradient away from the reservoir. This would reduce baseflow an/or result in leakage from the reservoir. This effect is most likely to occur if drawdown occurs in the upper Bulgo Sandstone between Longwalls 22 and 23 and the reservoir (subsequent numerical modelling suggests that this is likely – Section 7.3.3). The Bald Hill Claystone is also in contact with the reservoir, but is not a transmissive unit, while the base of the Hawkesbury Sandstone is located above the Cordeaux Reservoir FSL near these longwalls. This effect could be exacerbated by subsidence deformation of the strata along the reservoir shoreline (beyond the panel footprint), similar to that observed around Avon Reservoir shoreline at Area 3B. Based on a comparison the depth from mined seam to reservoir FSL and the lateral distance from the longwall edge to the FSL (**Figure 4-5**), Longwall 22 and 23 have a similar risk of effects on the adjacent reservoir as did Area 3B Longwalls 16 or 17. However it is considered that leakage effects would not occur to the same magnitude as near Area 3B due to the different stratigraphic units, wetted area of those units and distances involved (Section 7.4.3). Regarding geological structures and potential pathways related to these:

    - Longwall 22 is adjacent (80 m north of) a set of east-west trending dykes ("DD9") that are inferred to intersect Cordeaux Reservoir, at a distance of 900 m from the southeastern corner of the proposed longwall. These dykes are not considered a pathway for groundwater transmission, and the distance (900 m) is significant.
    - There are no faults mapped near Longwalls 22 and 23 that intersect or are oriented toward the reservoir.

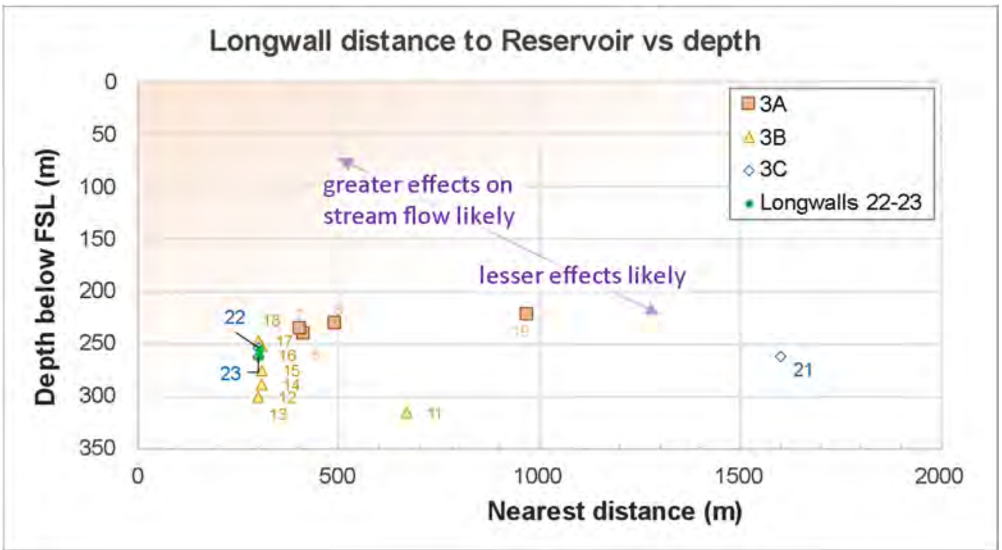


Figure 4-5 Distance and risk of effects on adjacent reservoirs

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 EIS for proposed Areas 5 and 6 (HS, 2019c). The following sections are brief, for the purpose of an SMP application. They focus on the key aspects of the modelling, and modifications to the EIS model are highlighted along with any items relevant to agency conditions or recommendations.

5.1 Model objectives

The groundwater modelling is required to inform IMC and regulators as to the potential effects of Longwalls 22 and 23, 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 and drawdown responses;
- Changes to surface water flow in nearby watercourses; and
- Induced leakage from water supply reservoirs.

5.2 Model implementation

5.2.1 Software selection

Over time (see **Appendix B**), 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, 2019).

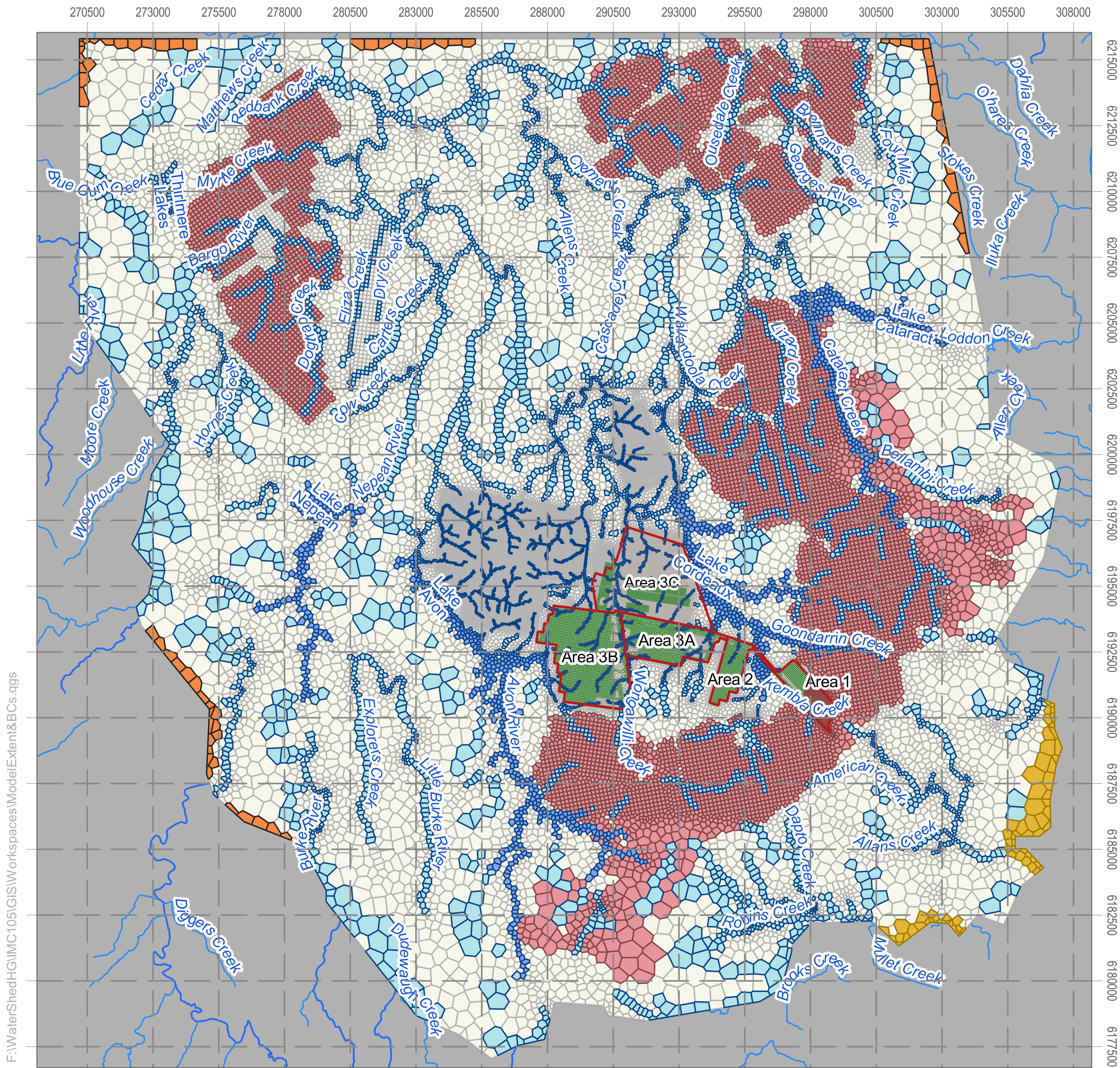
The model uses the ‘upstream weighting’ method for simulating unsaturated conditions (similar to the ‘pseudo-soil’ function in MODFLOW-SURFACT), as per recent modelling. Some earlier versions of the Dendrobium groundwater model have used Richards’ equation (e.g. HS, 2014; 2016a).

The head closure criterion specified in the MODFLOW-USG SMS solver was set at 0.05 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.



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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 proposed domains (Areas 3C, 5 and 6) are assigned uniform width and length of 50 m. i.e. Longwalls 20, 21, 22 and 23 are simulated with a 50 m square grid, as shown on **Figure 5-2**. A late revision to the mine plan has meant that the last line of cells at the eastern end of Longwall 22 are irregular (not square), and about half of these (i.e. 4 model cells) are slightly larger than 50 x 50 m; the largest of these cells is approximately 65 x 57 m.

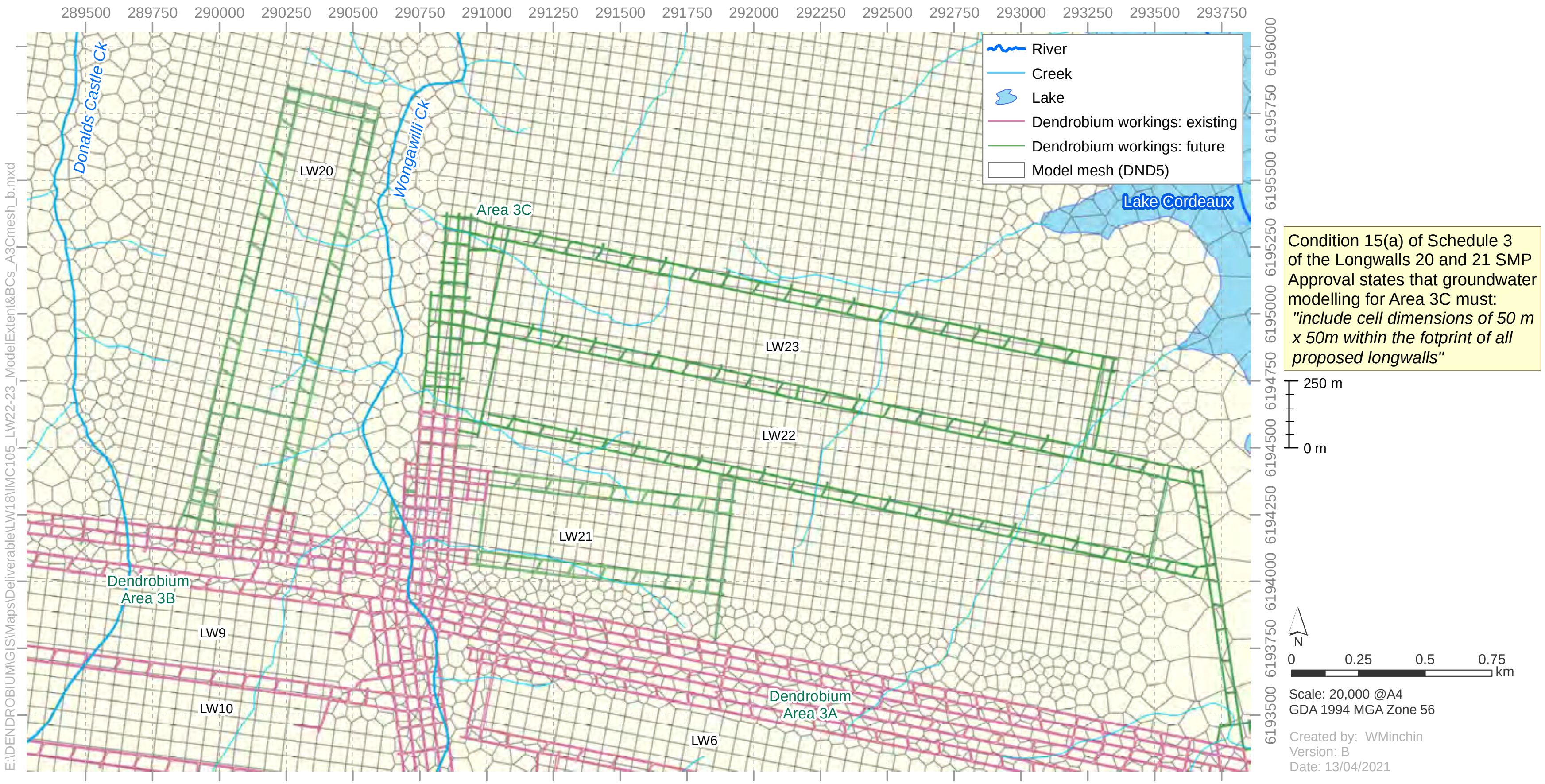


Figure 5-2 Detail of model mesh and cell size in Area 3C

The model consists of 17 layers (as per the EIS model, HS, 2019c), but with further modification from the EIS model around Area 3C, so each layer now 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 HydroSimulations (2019c). 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 within Longwall 22 are described in **Table 5-1**.

Table 5-1 Model layer assignment

Layer	Stratigraphy	Secondary Lithology	Thickness [m], mean	Thickness, Longwall 22
1	Regolith	Swamp deposits	Regolith: 5, swamp: 2	Regolith: 5
2	Hawkesbury Sandstone (upper)		24	2
3	Hawkesbury Sandstone (middle)		40	34
4	Hawkesbury Sandstone (lower)	Crinanite (Area 2)	33	40
5	Bald Hill Claystone	plus Garie and Newport Fms / Crinanite (Area 2)	27	26
6	Bulgo Sandstone (upper)	Colo Vale Sandstone (Area 3B) / Crinanite (A2)	53	52
7	Bulgo Sandstone (lower)	Colo Vale Sandstone (A3B) / Crinanite (A2)	40	52
8	Stanwell Park Claystone	Colo Vale Sandstone (A3B) / Crinanite (A2)	17	19
9	Scarborough Sandstone	Colo Vale Sandstone (A3B) / Crinanite (A2)	35	37
10	Wombarra Claystone	Crinanite (A2)	25	25
11	Coalcliff Sandstone	Wombarra Formation (A3B)	11	16
12	Bulli Coal Seam		2.3	2.1
13	Lawrence & Loddon Sandstones		28	25
14	Wongawilli Coal Seam	(working section)	4.2	4
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 compared to the modelling in HS, 2019a or 2019c.

The modelled time period, covering 1940 to 2200, is discretised into a total 203 stress periods. 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 HydroSimulations (2019c). 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. HS, 2019a, 2019c).

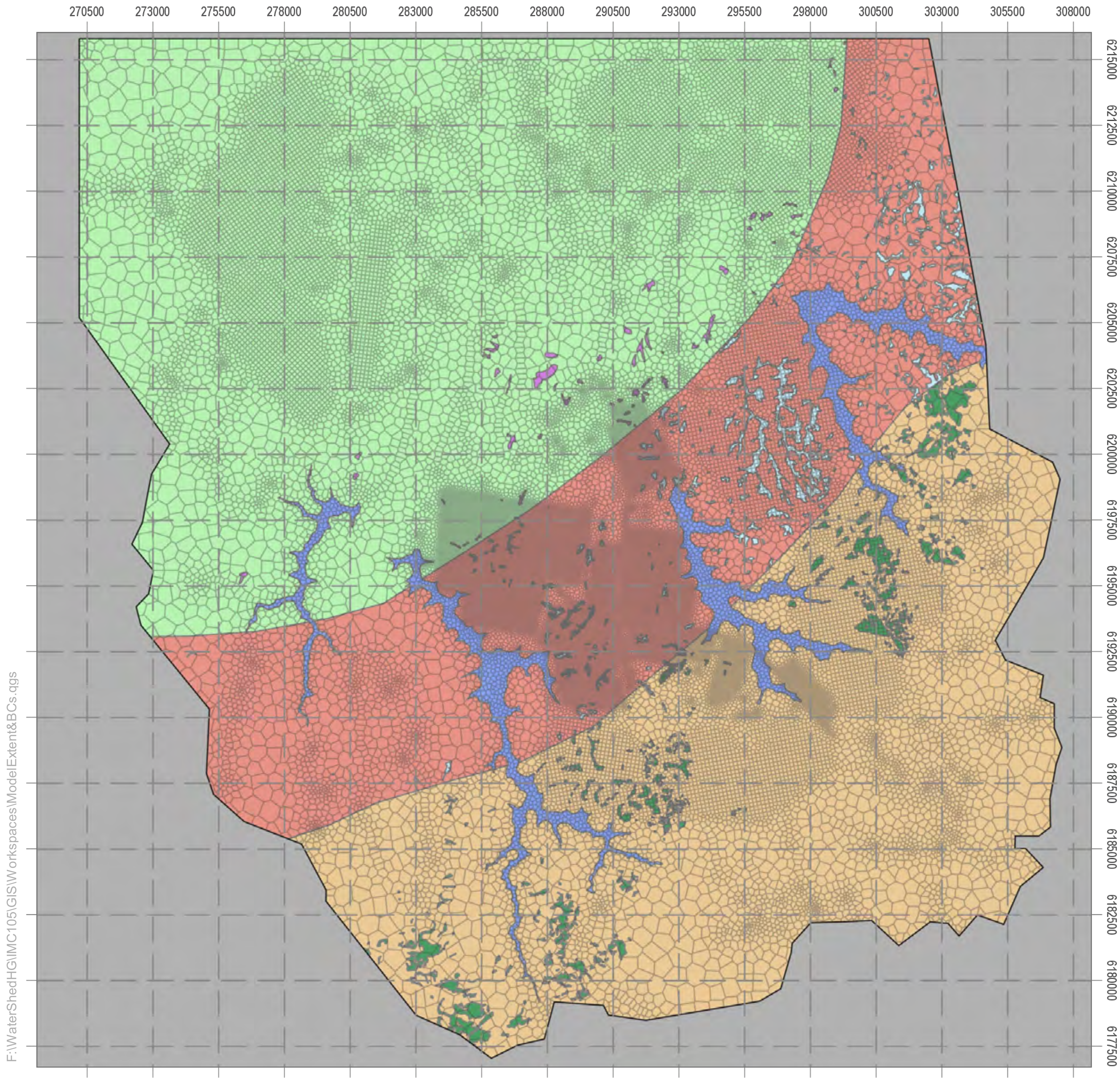
The model domain is divided into three zones representing broad 'average rainfall' zones, aligned with BoM long-term average rainfall contours, with higher rainfall and recharge at the top of the escarpment, declining to the west (away from the coast), consistent with estimates by AWRA and Crosbie (2015). 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.

The groundwater model simulates variable recharge rates until model stress period 124 (equivalent of March 2021), and then a constant recharge rate representing approximately average conditions (calculated from the period 2000-2020) has been utilised to simulate recharge and evapotranspiration from stress period 125 until the end of the simulation. Although this does not allow short-term variability to be represented in predictions of future conditions, using a constant rate allows stresses and associated impacts in the predictive period to be identified more clearly.



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Modelled Recharge Zones

Figure 5-3

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 HydroSimulations (2016a, 2019a, 2019c), 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.

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 'River' package as per the 2019a and 2019c models. The model simulates variable stream stages based on historical weather conditions until model stress period 124 (equivalent of March 2021 – **Appendix C**).

A constant stage representing average conditions has been used to simulate watercourses during the predictive period (stress period 125 until the end of the simulation). This allows the watercourses to 'leak' water to the underlying groundwater system to obtain suitable estimates of surface water losses as a result of mining activities.

Rivers 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).

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

5.4 Modelled subsidence and strata deformation

Background to this section is provided in Sections 0 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 (e.g. 2019a, 2019c) and in SLR, 2020a 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. The 'Stacked Drains' method has been employed in recent modelling at Dendrobium (e.g. HS, 2019a, 2019c; SLR, 2020a).

Given that IMC has initiated a (separate) study investigating post-closure hydrology and there is newly-available data from Dendrobium's centreline bore investigations (HGEO, 2020c and Section 3.6), 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 HS, 2013 and HS, 2014 model variants and is also used at other sites in the Southern Coalfield (e.g. Tahmoor Mine, Metropolitan Mine).

Surface flow reductions predicted by the groundwater model presented in the EIS (HS, 2019c) or for recent SMP approvals have been overly conservative compared to flow losses that have been estimated in the last End Of Panel report (HGEO, 2020b) via the revised TARP calculation methods (described in WatershedHG, 2019 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 recent End of Panel assessment (HGEO, 2020a). 'Stacked Drains' have been implemented in conjunction with TVM (Section 5.4.5). This will be the 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.

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 Height of Fracturing investigation (HGEO, 2020a), as described briefly in Section 3.6.

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

Feature	Longwall 22-23 model representation		Comment
within footprint	Kh (post-mining)	Kv (post-mining)	
Surface cracking zone	x 5	X 20	
Low angle fracture zone	x 20	x 15	
High angle (connected fracture) zone	Max of: x 150 and 0.01	Max of: x 50 and 0.002	Applied to centre-line model cells, based on comparison of Longwall 12 bore investigations
Caved zone	0.3	0.01	
Longwall (seam)	10	10	
Roadway / partial extraction	100	0.1	
Underlying floor	x 5	x 2	
Outside footprint			
Off-goaf <100m	x 4		Absolute values of 6E-2 up to about 2.5E-1 m/d also appropriate.
Off-goaf <300m	x 3		
Off-goaf <600m	x 2		

TVM parameters from:
\Model\GWmodel\Construction\FracZone\DND5\FracZone_DND5TR46sy_Dend_OtherMines_Offgoaf_TVM_EFault.xlsm

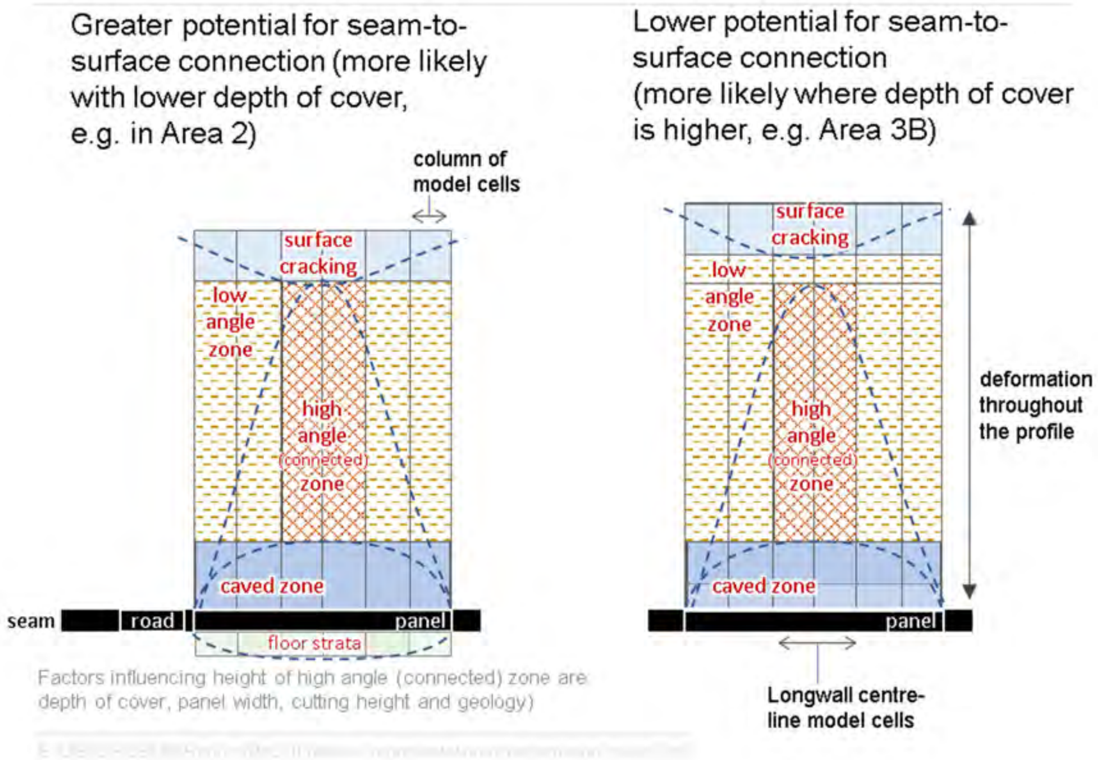


Figure 5-4 Model representation of conceptual property zones above the goaf

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

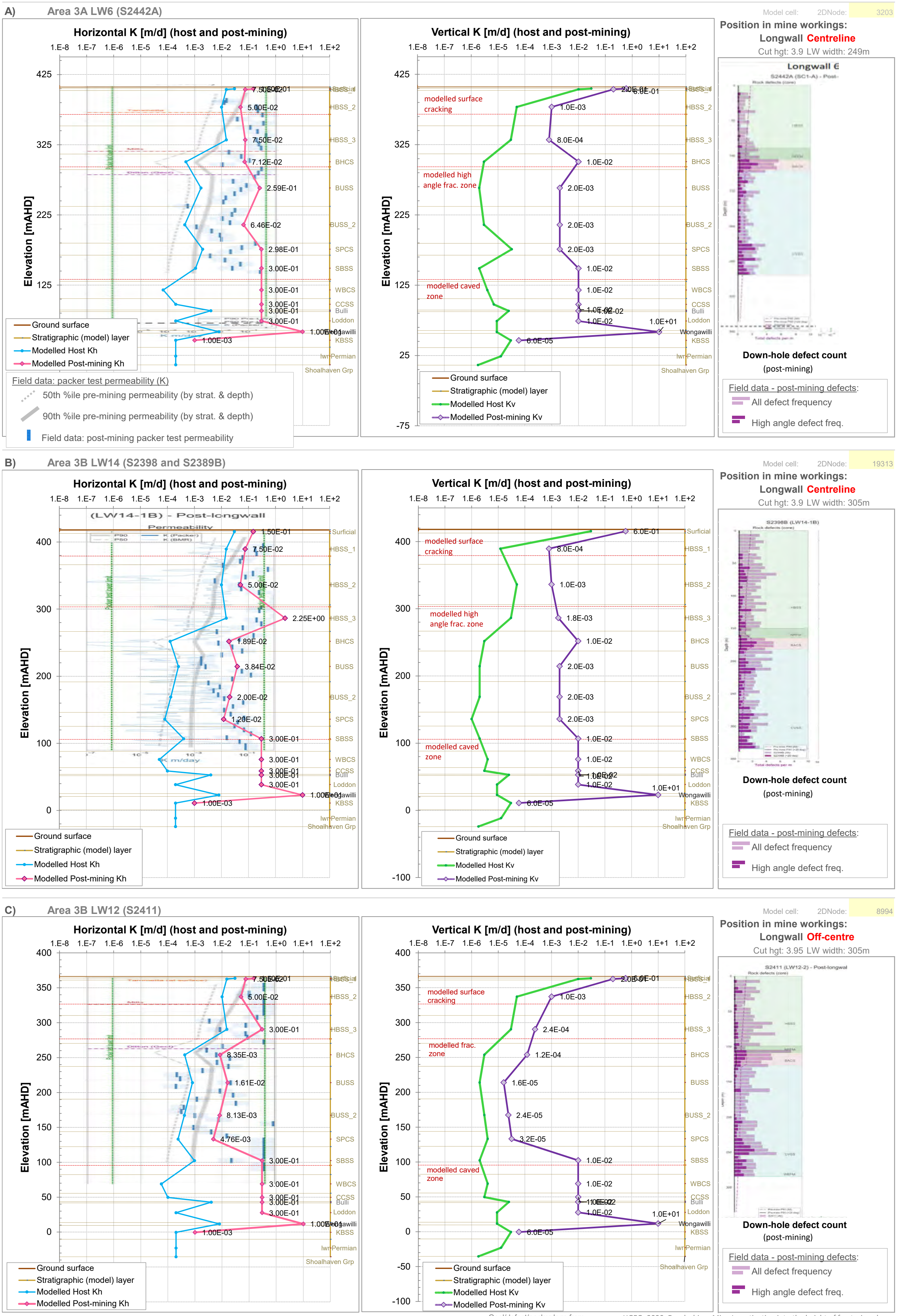
The results of model calibration to mine inflow, suggested that along with modification of the hydraulic conductivity, differentiation of model cells that are along the centre-line of panels and those that are off-centre should be adopted (**Figure 5-4**). **Figure 5-5a,b** show modelled profiles along centre-line locations in Areas 3A and 3B, while **Figure 5-5c** shows the profile at locations closer to the edge of a longwall panel (Area 3B Longwall 12).

5.4.3 Surface cracking zone

Surface cracking effects, extending down from the surface, were not the focus of HGEO (2020b), 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 (PB, 2015; PSM, 2017), as well as from SCT (2016) and SCT (2019). 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 (a complication also noted by Advisian, 2016).

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 experience at Dendrobium, Tahmoor and Metropolitan Mine.

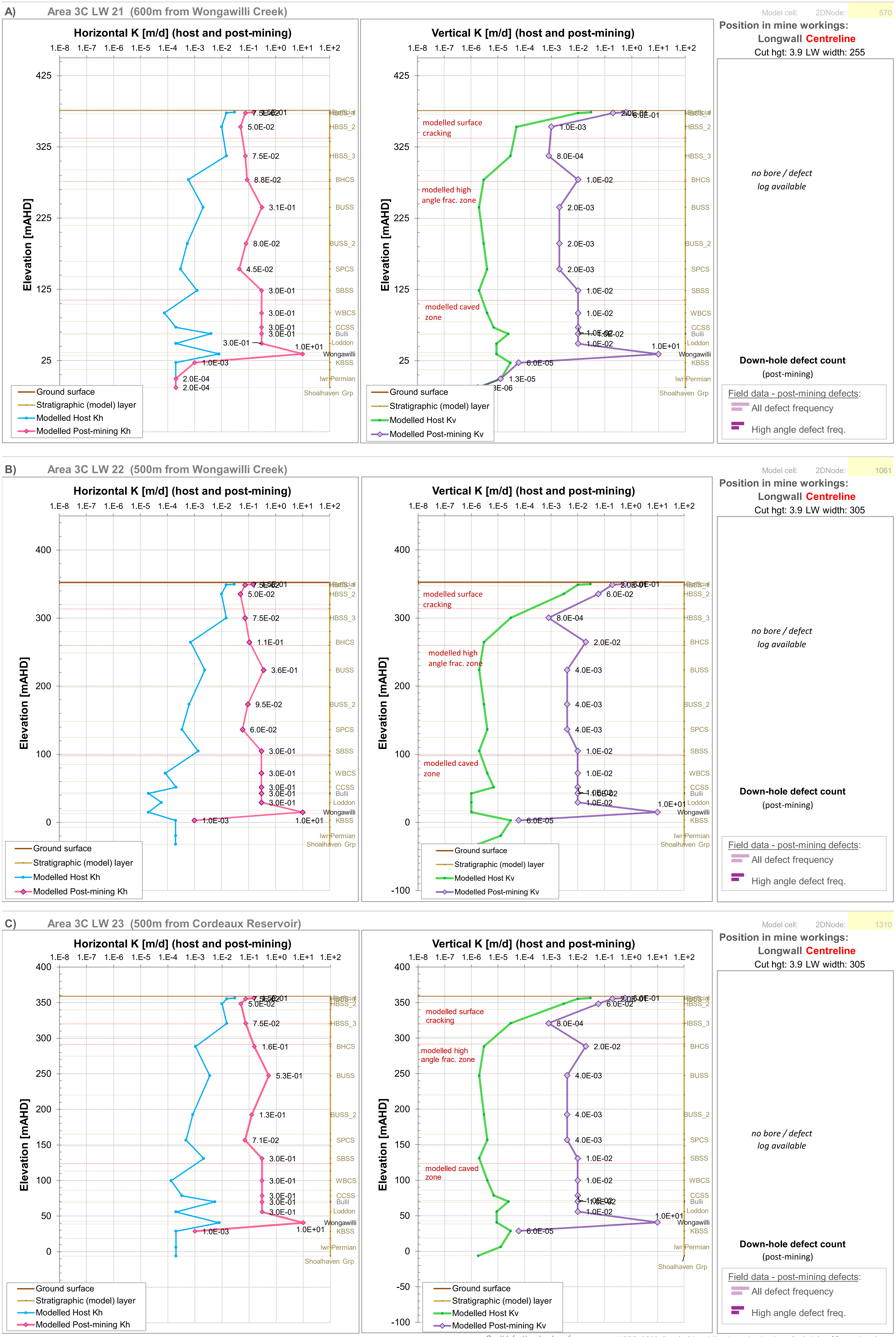
The representation of this surficial and near-surface process has been the primary focus of recent calibration effort. The profiles on **Figure 5-5** show the currently modelled Kh and Kv in the near-surface zone in comparison to field data from HGEO (2020b). **Figure 5-6** shows the modelled Kh and Kv at representative locations within the centreline of proposed Longwalls 20, 22 and 23.



Geol/defect/packer logs from: HGEO, 2020, Dendrobium Mine Investigation into the height of fracturing above extracted longwalls in Area 3, Dendrobium, report no. D19341.

E:\DENDROBIUM\Model\GWmodel\Construction\FracZone\DND5\[FracZone_DND5TR55_Dend_OtherMines_Offgoaf_TVM_EFault.xlsm]Report_ProfileModvObs2

Profiles illustrating modelled and observed Kh and Kv within the longwall footprint **Figure 5-5**



Geol/defect/packer logs from: HGEO, 2020, Dendrobium Mine Investigation into the height of fracturing above extracted longwalls in Area 3, Dendrobium, report no. D19341.

E:\DENDROBIUM\Model\GWmodel\Construction\FracZone\DND5\[FracZone_DND5TR55v2_Dend_OtherMines_Offgoaf_TVM_EFault.xlsm]Report_ProfileModvObs2

Profiles illustrating modelled Kh and Kv at Longwalls 21, 22 and 23 **Figure 5-6**

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. HGEO (2018b and 2019b) 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. 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 SMP 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. More work, modifying hydraulic conductivities and/or the modelled height of the high angle fracture zone, will be carried out to improve this.

However, in the short-term, '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, and with a conductance adopted from the Stacked Drains in the corresponding layer as estimated in HydroSimulations (2019c), which was estimated from host hydraulic conductivity (Kh and Kv) and from SCT's FLAC modelling.

In the earlier modelling for Area 3 SMP applications (HS, 2018; 2019a; 2019b) the 'Stacked Drains' have 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. As part of the modelling for the Dendrobium Extension EIS, HS (2019c) 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), with inputs to this method being obtained from review of SCT's FLAC2D modelling of 300 m wide longwall panels. This is consistent with the recommendations and discussion in IEPMC (2019a, 2019b).

Further details of the calculations are available in HydroSimulations (2019c). However, in terms of the representation of drawdown above and around longwall areas, which was a concern of the IEPMC, the results in Section 6.4.2 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 (2015) 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	0.8	m, above pillar#
	2.5	m, centre-line#
	1.65	m, averaged
Void space created	=3.9-1.65	
	=2.25	m (#1)
Depth of Cover [m]	340	average in panel
Average increase in porosity	= (3.9-1.65) / 340 = 0.66%"	

Modelled porosity enhancement					
Layer	Thickness* (m)	Host		Post-mining	
		Sy	Void (m)	Sy	Void (m)
					2.25 m (#1)
Wombarra Fm (L11)	30	0.004	0.06 m	0.033	0.495 m
Bulli Seam (L12)	2.5	0.016	0.04 m	0.06	0.15 m
LRSS (L13)	20	0.005	0.14 m	0.05	1.5 m
Wongawilli Seam (L14)^	4	0.015	0.06 m	0.10	0.4 m
Total			0.3 m		2.45 m
Porosity or void space difference			= 2.45 - 0.3 = 2.1 m		

from MSEC, 2020 (Longwall 22-23 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 (PB, 2015), 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**.

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).

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 (BSO), Tahmoor). There is now the further constraint of newly available post-mining permeability (Kh) data and defect logging from the extensive field investigation (HGEO, 2020c) that is 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 2, 3A and 3B has been a focus, with particular attention on water levels near Wongawilli Creek and Avon Reservoir (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 available core testing and packer testing datasets. As noted by the IAPUM (**Table 1-6**), 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 **Figure 3-4**. The model parameters do not represent a marked departure from previous modelling (see HS, 2019c or SLR, 2020a).

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 (2020). 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, and the relative change in the count and intensity of high angle defects through the sequence, as well as guided 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 1940-2021. This includes Dendrobium (up to Longwall 13), historical mining around Dendrobium (e.g. Nebo, Elouera, Wongawilli, Kemira etc.), and the parts of BSO, Tahmoor and Cordeaux Mines within the active model domain (**Figure 5-1**).

Table 6-1 Modelled Water Balance for Calibration Period (1940-2021)

MODFLOW component	Conceptual process	In [ML/d]	Out [ML/d]
RECHARGE	rainfall recharge	239.7	0.0
RIVER LEAKAGE	watercourses, reservoirs	50.3	35.1
EVT	evapotranspiration	0.0	252.0
DRAINS	mine inflow	0.0	17.2
HEAD DEP BOUNDS	regional GW flow	10.3	1.3
CONSTANT HEAD	flow to ocean, estuaries	0.0	0.03
STORAGE	groundwater storage	49.9 (decline in GWLs)	44.5 (rise in GWLs)
Total		350.1	350.1

Units are in ML/d. Results are from model run 5TR55 to SP124.

Rainfall recharge is the dominant input, while evapotranspiration and baseflow to watercourses/springs/reservoirs are the dominant outputs. The model simulates historical mine inflow for all mines in the model domain equal to approximately 8% of the rainfall recharge and 5% of all simulated inputs to the groundwater system. The model simulates a net reduction in groundwater storage (decline in groundwater levels) during the reported period, which is due to both an increase in longwall mining within the model domain, and a general reduction in rainfall late in this historical period (although wet conditions in 2020-21 have reduced that effect somewhat).

Groundwater mass balance error was computed by MODFLOW to be less than 0.01%.

6.4 Groundwater Levels

6.4.1 Summary

In accordance with the Area 3B SMP Condition 16(b), a large dataset of groundwater levels has been collated across a total of over 800 target instruments (bores, piezometers) at which over 50,000 targets have been used to assess model calibration to groundwater levels. The locations of boreholes and piezometers used for groundwater level calibration are mapped on **Figure 3-2**.

Of those sites/piezometers, 615 are piezometers in ‘deep’ bores. From the sub-daily or daily data recorded at those sites, the data have been converted into over 39,000 targets by taking the median value over each model stress period.

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

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

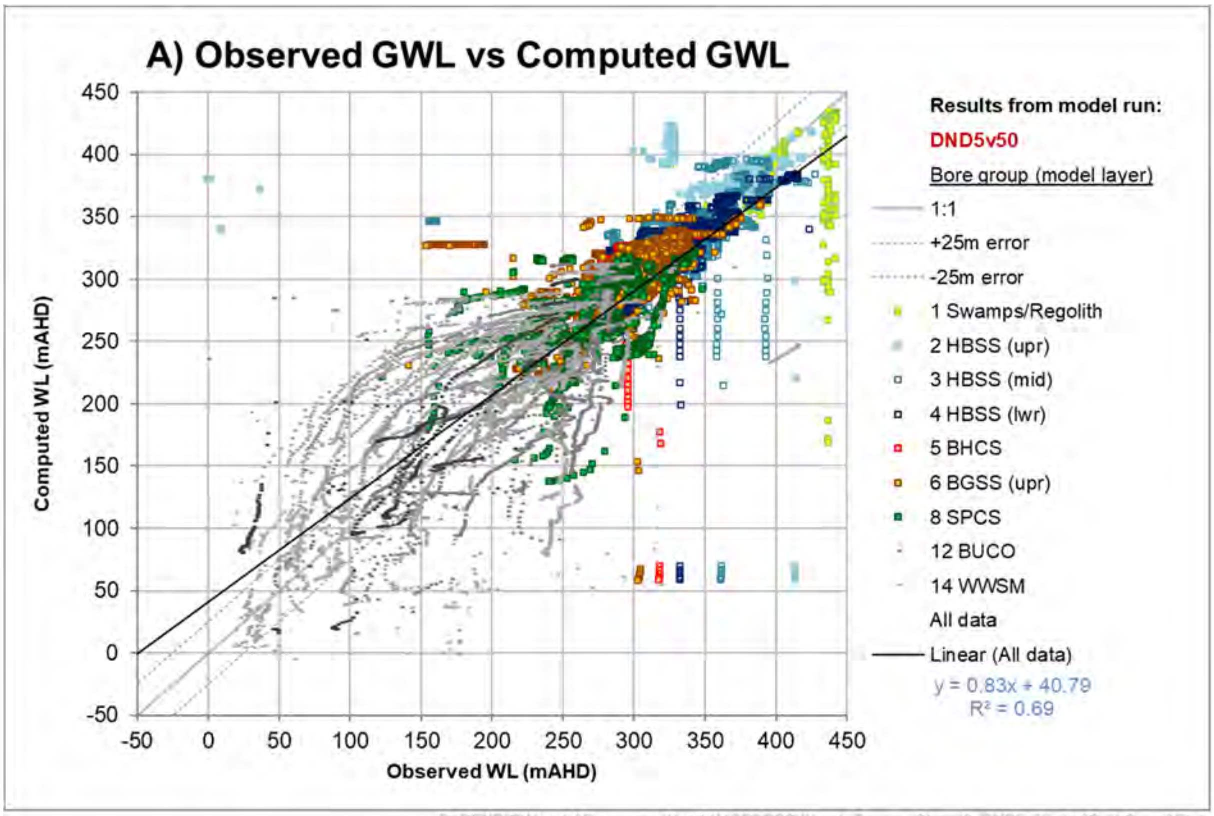


Figure 6-1 Summary X:Y plot of modelled vs observed groundwater levels

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 6-4 and **Figure 6-5**);
- 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 may be assigned to the lower Bulgo Sandstone but could be validly assigned to the upper Bulgo Sandstone;
- 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” targets on the right of **Figure 6-1**. This shows that the model overestimates drawdown at many these shallow piezometers.

The size of the dataset has meant that data ‘cleaning’ or the application of ‘weights’ cannot be carried out rigorously. Steps have been made to correct or remove clearly erroneous data (e.g. provided instructions to the data managers to fix some calculated heads obtained from some of the VWPs, such as occasional miscalculation between groundwater level, mAHD and pressure head, m; such as for

S1892, as noted in Section 3.7.2). However, it is often difficult to identify clearly incorrect data. As a result more than 99% of the dataset is weighted as a '1' for inclusion in the calculation of calibration statistics. Approximately 0,5% is weighted '0.1', representing suspect data that we cannot categorically classify as incorrect or correct. Approximately 0.4% is weighted as '0', i.e. considered to be bad data.

The SRMS error for the correlation between observed data and the transient model groundwater levels is 5.7%. This value is within the often-quoted example of 10 % (MDBC, 2001; Barnett *et al*., 2012), 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 -5.8 m. Both of these statistics represent a significant improvement on the groundwater model used in the Longwall 20 and 21 Groundwater Assessment (HS, 2019b).

6.4.2 Temporal trends (hydrographs)

A subset of calibration hydrographs is presented in **Figure 6-2** to **Figure 6-6**, 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 DPIE-Water.

These include groundwater levels at S1892 in Area 3A near Wongawilli Creek (Figure 6-2), at S1930 between Area 3B and Wongawilli Creek (**Figure 6-3**), a long record at S1932 above Area 3B Longwall 16 (Figure 6-4), water levels between Area 3C and Cordeaux Reservoir (S1969 - **Figure 6-5** and S2212 - **Figure 6-6**. Of these locations, S1892, S1969 and S2212 are most relevant to Longwalls 20-23.

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.

For example, at S1892, the model responds well to drawdown in the deepest piezometers (KBSS and LDSS, both close to the mined seam). Despite some errors in the recent observed data in the Bulgo and Scarborough Sandstone piezometers (Section 3.7.2), the model replicates the trends in drawdown in the shallow units, including the relationship of those layers to the stage in nearby Wongawilli Creek.

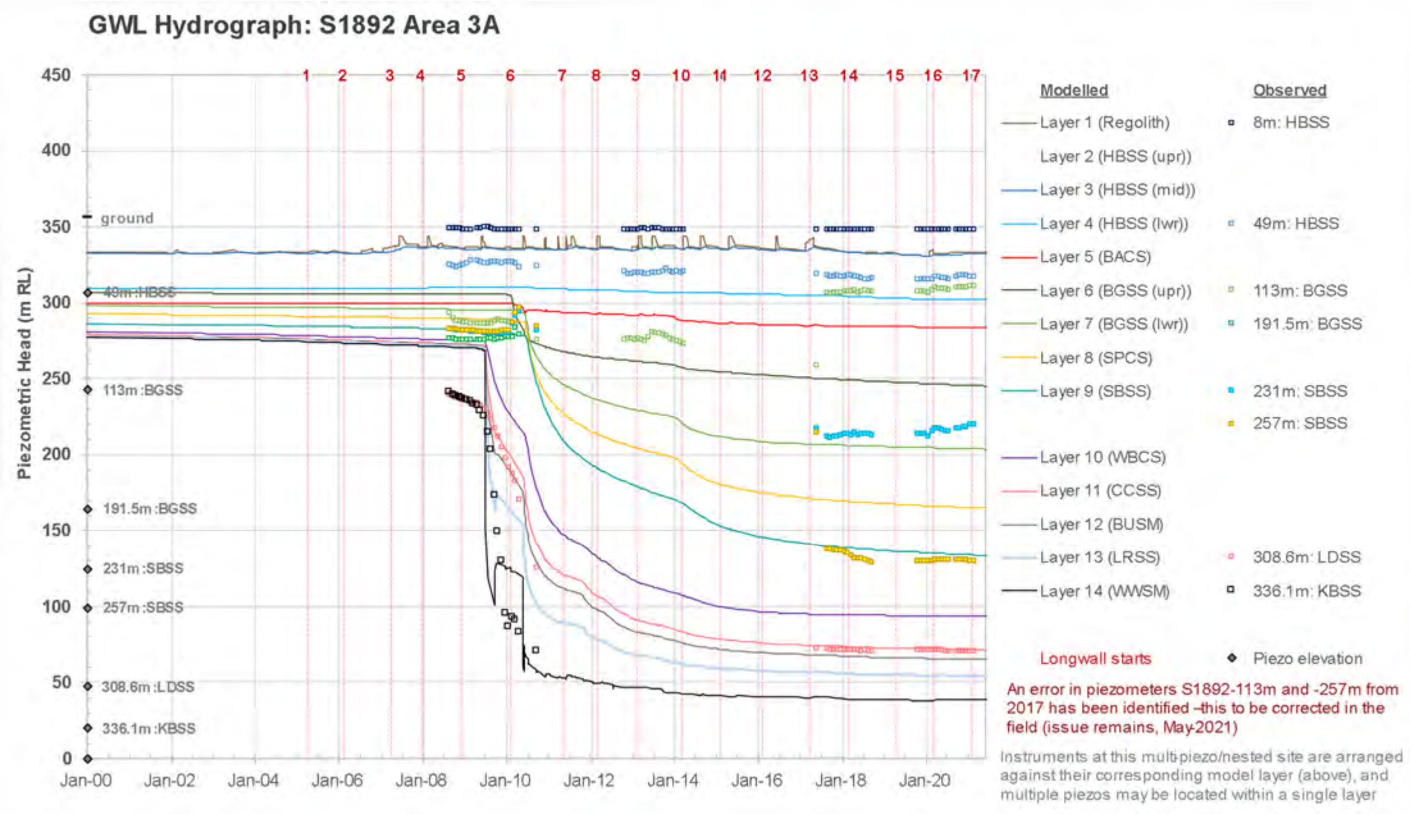


Figure 6-2 Modelled vs observed groundwater levels: S1892

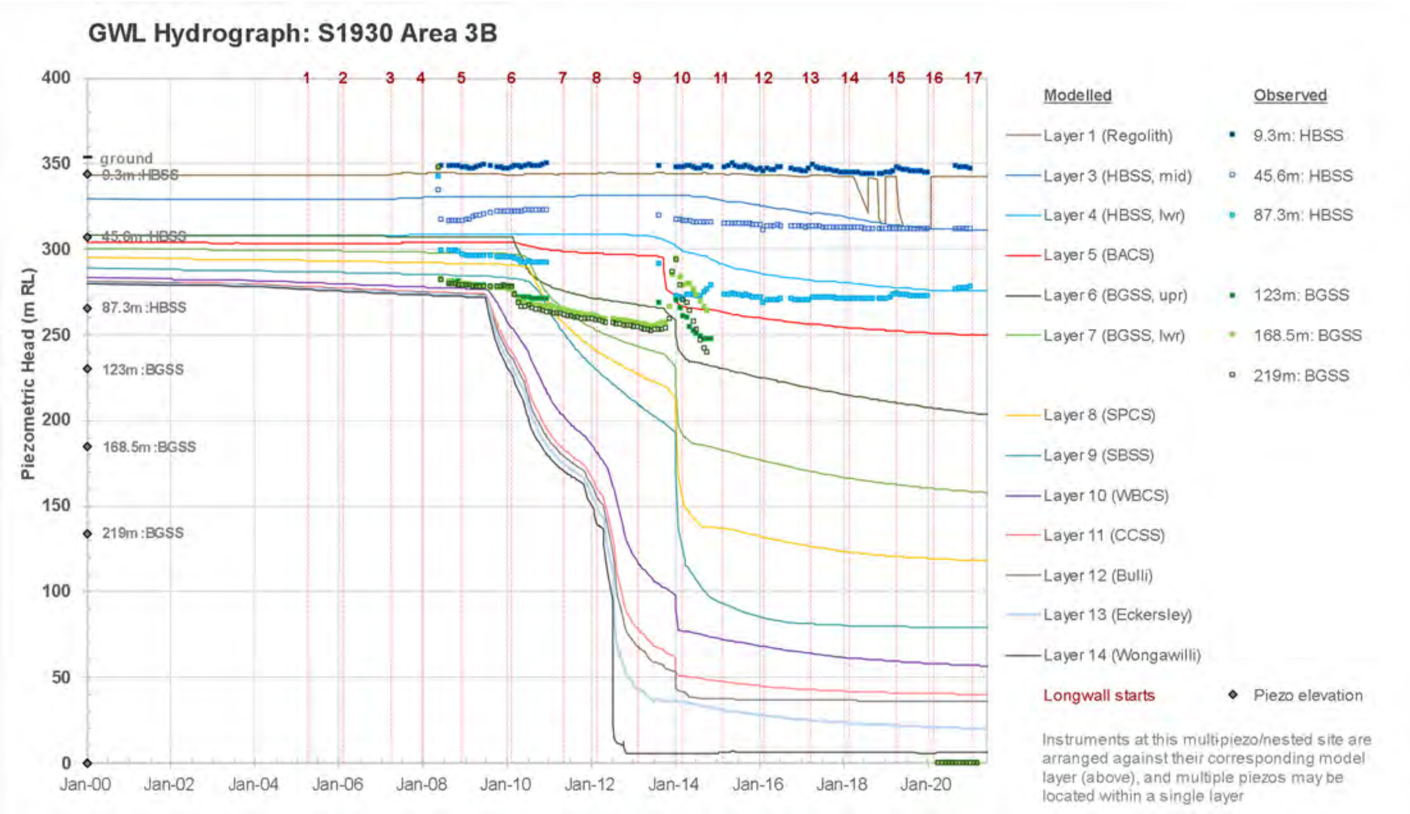


Figure 6-3 Modelled vs observed groundwater levels: S1930

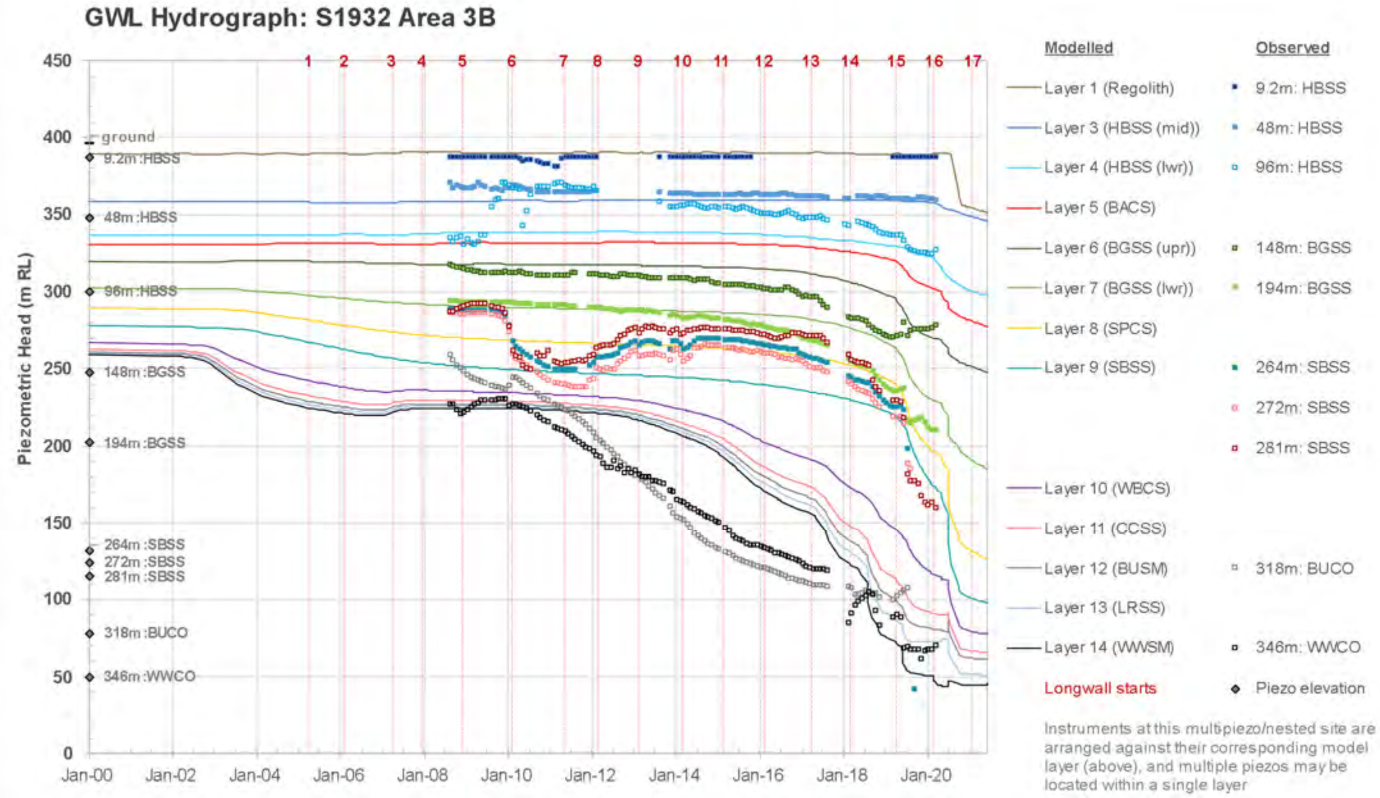


Figure 6-4 Modelled vs observed groundwater levels: S1932

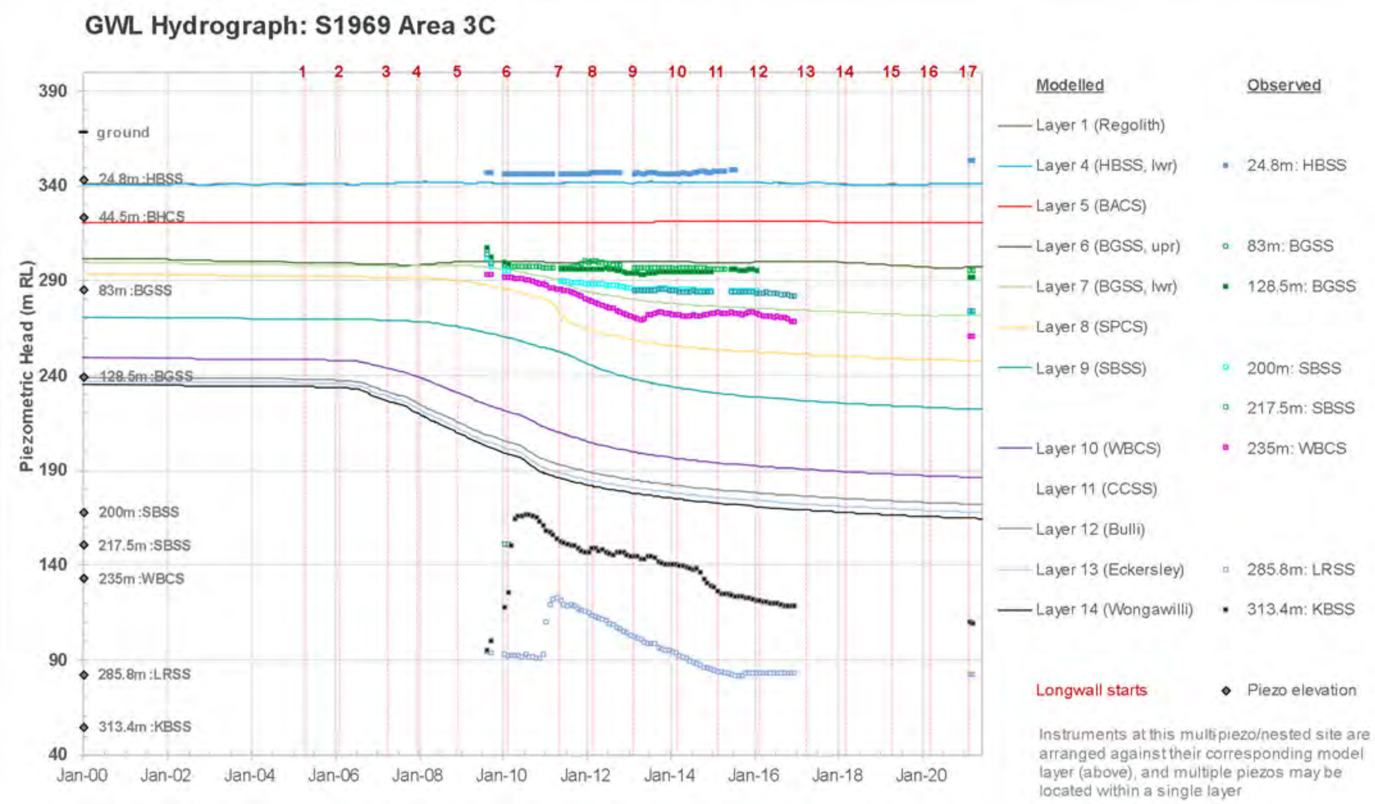


Figure 6-5 Modelled vs observed groundwater levels: S1969

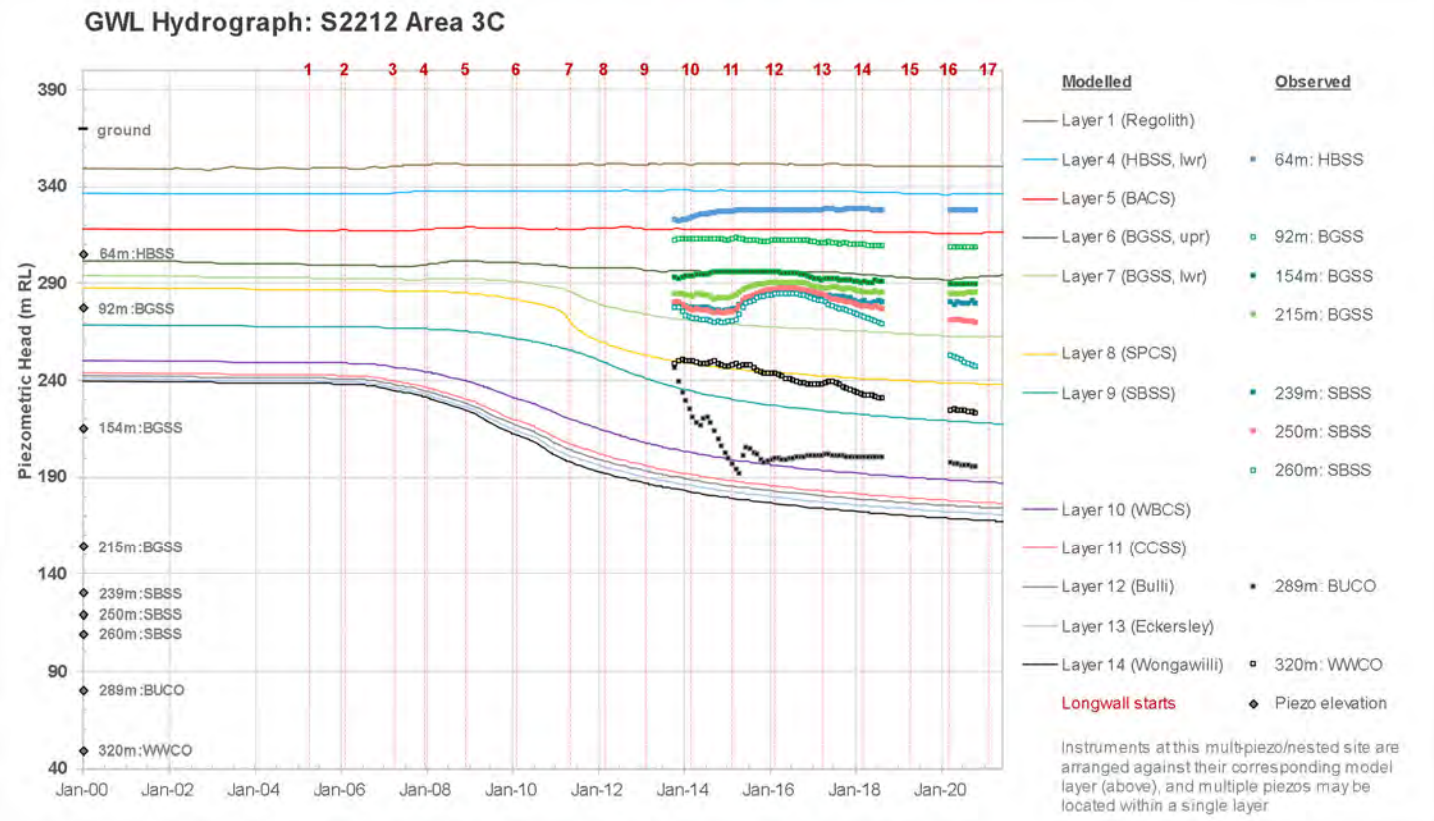


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Figure 6-6 Modelled vs observed groundwater levels: S2212

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 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, or geotechnical behaviour that cannot be captured in a regional model (e.g. multiple caving/subsidence events related to (multiple) longwall extraction).

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-mining case’ (model stress period 1);
- late-2020 (stress period 121), representing ‘recent or current conditions’;

- August 2026 (stress period 152); and
- 2200 (stress period 203).

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

Figure G5 to **Figure G9** (in **Appendix G**) present modelled groundwater level contour plots for model stress period 121 (June-2020).

The modelled water table (**Figure G5**) 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" (mid-2020), including drawdown concentrated above longwall panels.

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 and 16 at this time. Comparison against **Figure G2** shows how the model has simulated the change from the natural or pre-mining condition to mid-2020.

Contour patterns indicating mining related drawdown are more discernible in the lower Bulgo Sandstone (**Figure G7**). 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 and 16 in 2019-2020. Comparison against **Figure G3** shows how the model has simulated the change from the natural or pre-mining condition to mid-2020.

The Wongawilli Coal Seam (**Figure G8**) 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 Area 3B by mining activity at the Wongawilli (Elouera) Colliery. Comparison against **Figure G4** shows how the model has simulated the change from the natural or pre-mining conditions to mid-2020 in the coal measures.

6.4.4 Vertical Profiles

The following figures present a comparison of modelled and observed pressure head profiles at two sites:

- **Figure 6-7** shows heads at S2192-S2220, which is the longwall centreline bore above Longwall 9.
- **Figure 6-8** shows heads at S1885, which is at the southwest edge of Area 3A Longwall 89, near to Wongawilli Creek.

These figures show that the model representation of pre-mining pressures is generally good, and the change in pressures as a result of longwall mining is well represented.

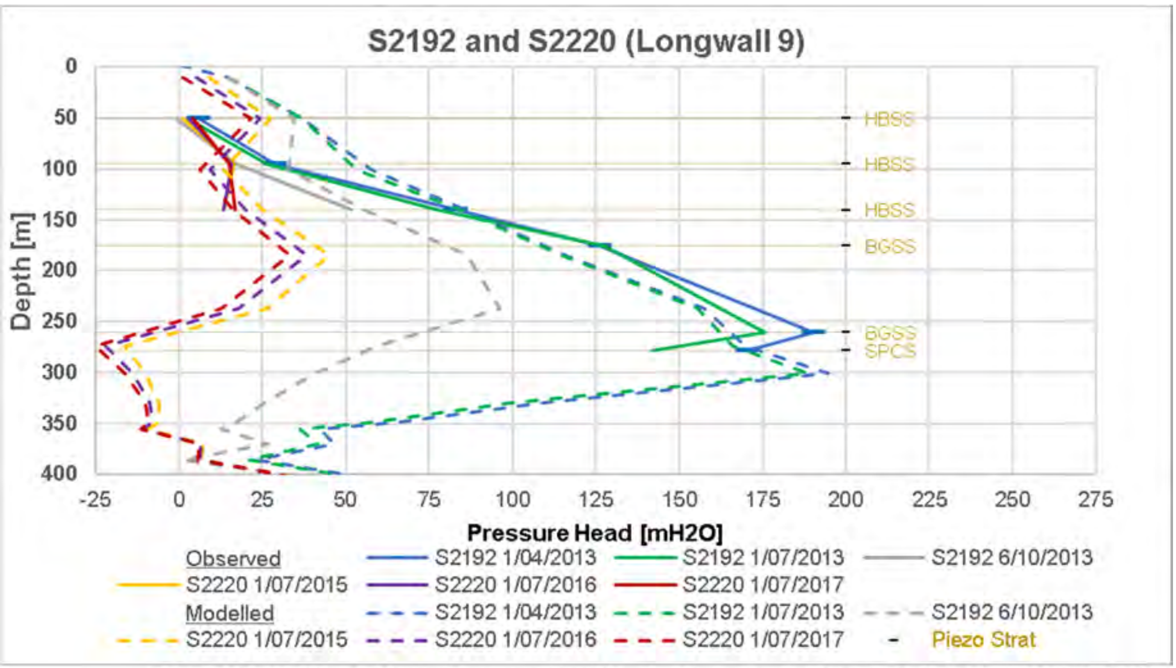

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Figure 6-7 Modelled vs observed groundwater pressure profile: S2192-2220

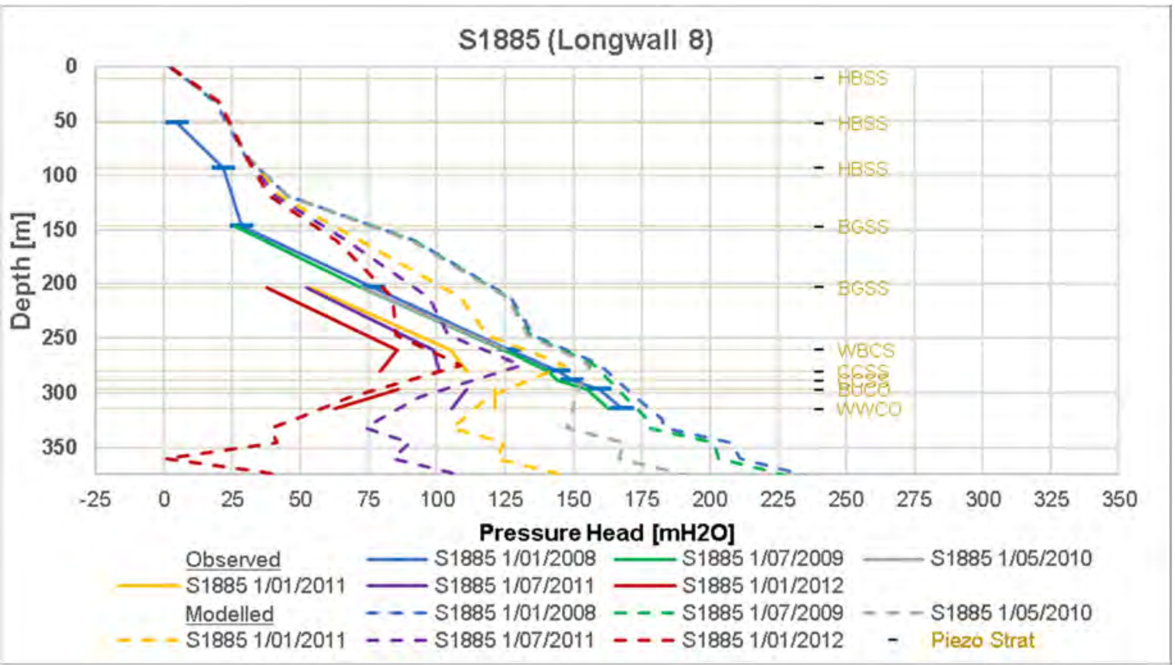

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Figure 6-8 Modelled vs observed groundwater pressure profile: S1885

6.4.5 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 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 6-9** and **Figure 6-10** compare the 'observed' and modelled inflows to each mine area and Dendrobium as a whole, respectively.

Model calibration to observed groundwater inflow is good, and with the exception of Area 2, the modelled volume of inflow is close to or slightly higher than what has been calculated. This allows a reasonable and conservative estimate of the regional groundwater response and representation of mining by the groundwater model. Key points from the inflow hydrographs on **Figure 6-9** are:

- Area 1 inflows are over-estimated for the calibration period, with the greatest difference between the modelled and observed datasets in the order of 1.2 ML/d. Despite this, the model provides an upper end estimate of total inflow to the mine area, making for a conservative estimate.
- Observed inflows to Area 2 show a baseline inflow of approximately 0.5-1 ML/d interspersed with short-lived peaks in response to heavy rainfall events. The model overestimates inflow during the period of longwall extraction in Area 2 (2007-2010). Following that, the modelled estimate is not able to capture the magnitude of the observed peaks, however, it does represent the timing well.
- Modelled inflow to Area 3A at the start of the longwall development is overestimated compared to the observed values, yet represents similarly timed peaks during this period. These peaks become muted over time after the completion of Longwall 8 in this area and the commencement of mining in Area 3B (Longwall 9). The modelled inflows follow the trendline of the calculated inflows well during this period, however, are unable to capture large inflow events in the first 2-3 years after the period of longwall extraction.
- Modelled inflows to Area 3B are quite good with the trend being consistent with calculated data. Modelled inflows during Longwalls 12 to 14 of Area 3B represent the upper end of observed inflows, and the model is a good match for these. The model overestimates inflow during 2018-2021 by about 2 ML/d.

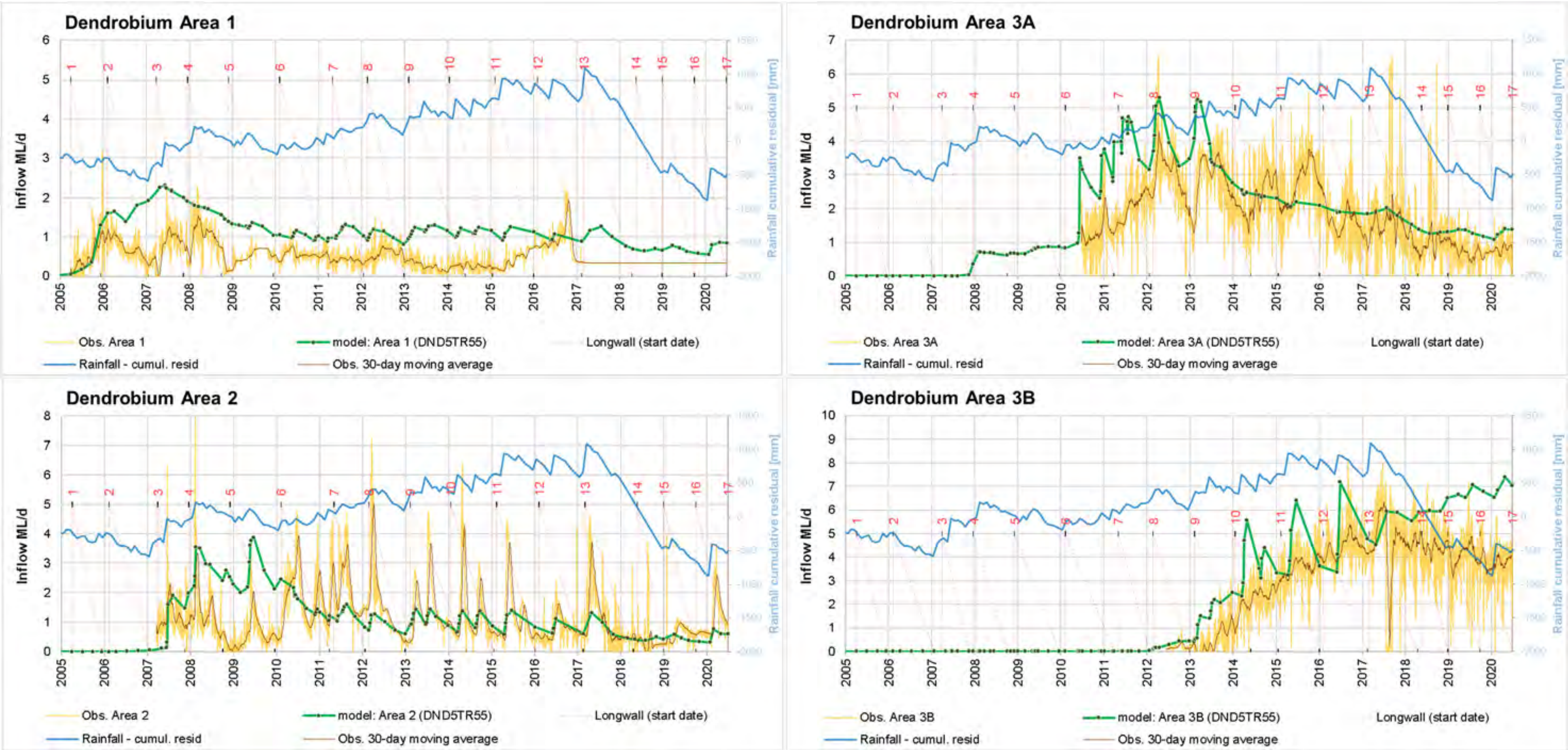

Figure 6-9 Modelled vs observed mine inflow: by area

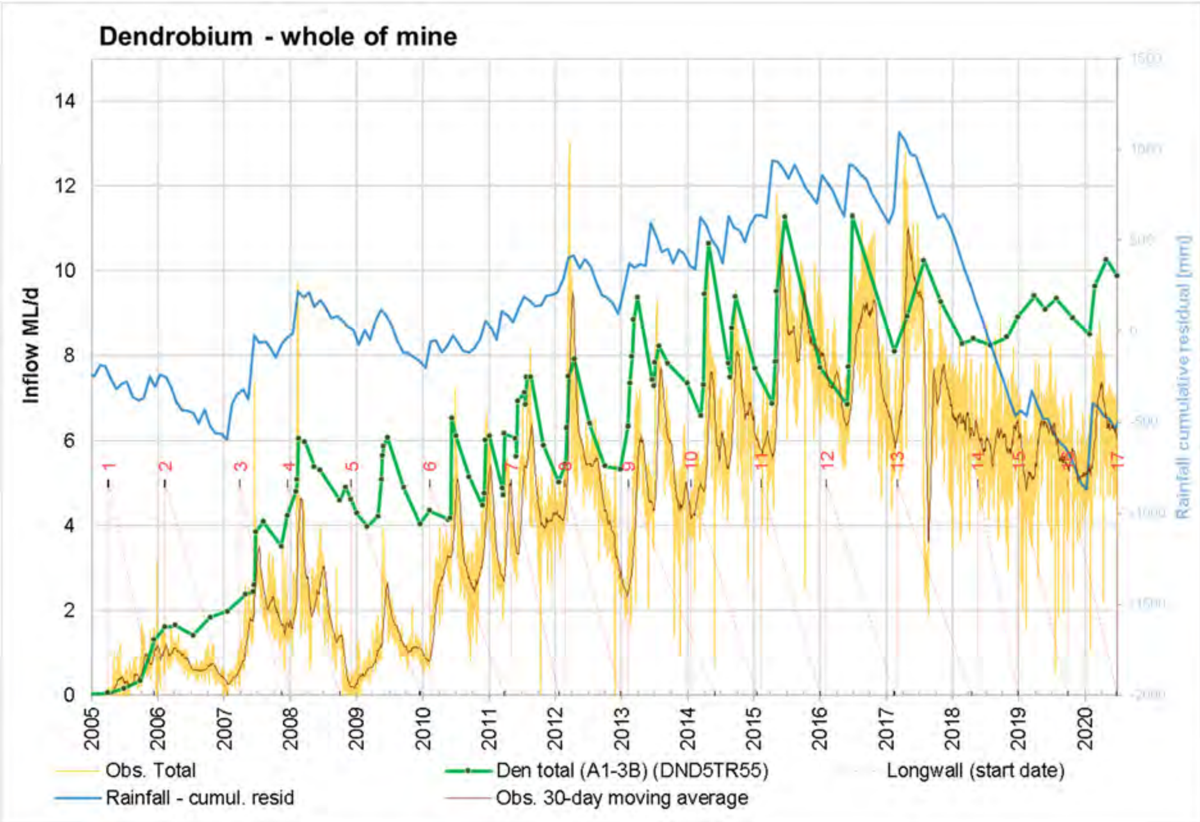

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Figure 6-10 Modelled vs observed mine inflow: Dendrobium total

A comparison of modelled and calculated inflows to the whole of mine (**Figure 6-10**) shows it is an appropriate match for the purpose of understanding the effect on the water balance of this groundwater system. The modelled inflows provide a more conservative, upper range estimate of the calculated inflows during mine progression.

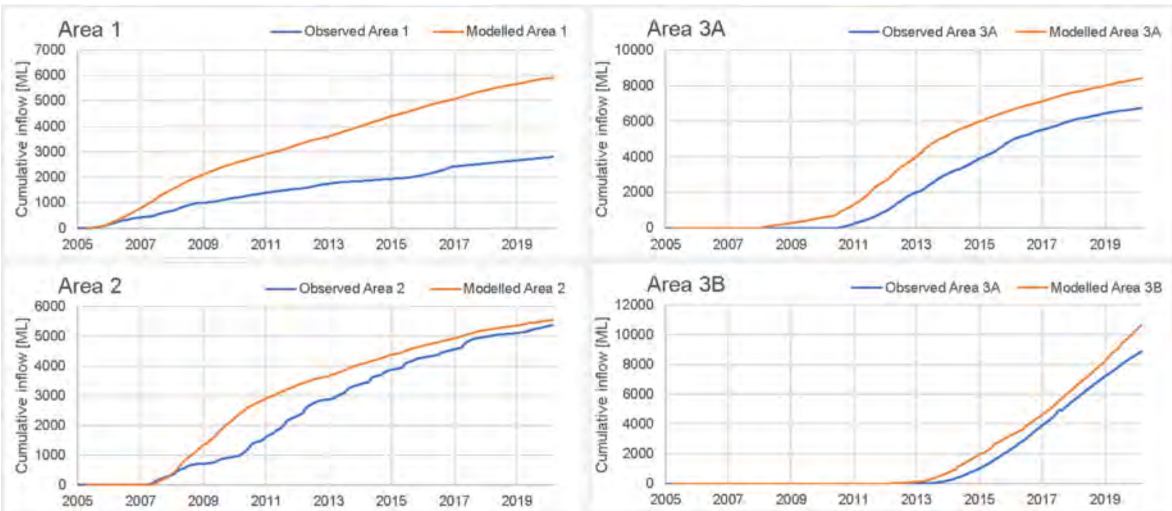


Figure 6-11 Cumulative modelled vs observed mine inflow by area

This is supported by a review of cumulative mine inflow to each mine area in **Figure 6-11**. The calibration to inflow indicates that the model reasonably represents recharge and permeability characteristics of the mining-affected system. 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.

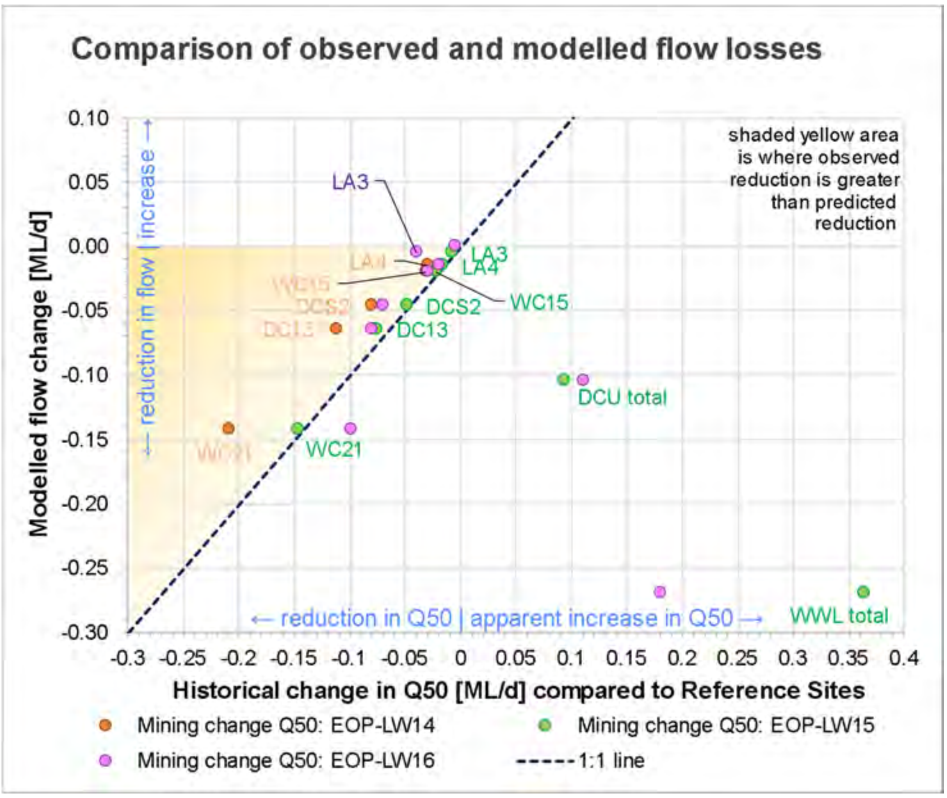
Versions of the model tested during calibration had lower and higher rates of inflow (to Area 3B, most importantly), however did not appropriately simulate losses from surface water systems, so the current model has been favoured, despite the higher than observed inflow in Area 3B.

6.6 Surface water flow loss

Recent analysis of flow data (WatershedHG, 2019 and HGEO, 2020a and 2021a) showed that flow reductions due to mining were evident in headwater streams and generally not discernible at downstream gauging stations.

Modelled surface water losses have been compared to these estimated historical losses as a means of model calibration and to understand the potential error in groundwater model predictions (**Figure 6-12**).

With respect to the downstream gauging sites DCU and WWL, the modelling is clearly conservative compared to the results derived from field data. With respect to LA3, results from the End of Panel for Longwall 15 cannot be relied on because it is based on very short records for both pre-mining and post-mining periods, while the model under-estimates flow losses at that site at the end of Longwall 16 (as for DCS2 after Longwall 16). Given those exceptions, the main findings from **Figure 6-12** are that the model provides an appropriate match to the losses estimated in the End of Panel report for Longwall 15 and for Longwall 16, while underestimating those from the End of Panel report for Longwall 14.



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Riv&Lake_BaseflowCapture_CalcSWImpactsV3_Dend_DND5TR46-54_44.xlsx

Figure 6-12 Comparison of historical and modelled surface water losses

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, this revised groundwater model does provide reasonable estimates of historical losses, but as described in HGEO (2020e) and Section 3.9.5 estimated historical losses may be influenced by 'wetness' or the availability of flow. That is, in dry periods there is less surface water flow available and so losses are smaller than in periods where there is more flow available. As a result, predictions need to account for uncertainty in modelled hydrogeological parameters, mining effects and also variability in rainfall and flow. Therefore, the groundwater model predictions of surface water losses provided in Section 7.4.5 are scaled and presented as a range to account for this.

6.7 Model performance

The regional model takes approximately 8 hours to run for the calibration or historical model (stress periods 1-124), with a further 5 hours for the predictive period (stress periods 125-203).

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 Longwalls 20, 22 and 23) being similar to the historical observed and simulated stresses.

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 Condition 13a (**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 7.4.6), 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 each the proposed Longwalls 20, 22, 23 as well as for the approved Longwall 21.

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 18 and of Dendrobium as a whole.

7.2.1 Uncertainty Analysis

A series of deterministic scenarios, as per the IESC Uncertainty Guidelines (Middlemis and Peeters, 2019) 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 groundwater assessment (specifically that for Longwall 18; WatershedHG, 2020), structural features are not considered a significant risk pathway for Longwalls 22 and 23 (Section 4.3), and therefore not considered explicitly in deterministic scenarios.

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

Scenario	Run	Name	Dendrobium	Connected fracture zone method	Other Mines	Comment
A	DND5TR45	Null	No Dendrobium	None	None	Hypothetical natural conditions
B	DND5TR60	Baseline	No Dendrobium	TVM	All	Baseline condition Comparison against D isolates effects of Dendrobium.
C1	DND5TR56	Dendrobium, no LW 21	All Areas 1, 2, 3A, 3C (LW 20-23) and all 3B except LW 21	TVM + Stacked Drains	All	Comparison against D isolates effects of LW 21.
C2	DND5TR57	Dendrobium, no LW 22	All Areas 1, 2, 3A, 3C (LW 20-23) and all 3B except LW 22	TVM + Stacked Drains	All	Comparison against D isolates effects of LW 22.
C3	DND5TR58	Dendrobium, no LW 23	All Areas 1, 2, 3A, 3C (LW 20-23) and all 3B except LW 23	TVM + Stacked Drains	All	Comparison against D isolates effects of LW 23.
C4	DND5TR59	Dendrobium, no LW 20	All Areas 1, 2, 3A, 3C (LW 20-23) and all 3B except LW 20	TVM + Stacked Drains	All	Comparison against D isolates effects of LW 20.
D	DND5TR55	Full Impact	All Areas	TVM + Stacked Drains	All	Enhanced K x 0.5 order of magnitude along 'Elouera Fault zone' following stress relief due to LW 18.
Deterministic uncertainty scenarios						
D2	DND5TR61	Full Impact: Offgoaf 1	as for D	as for D	as for D	Greater off-goaf permeability (Kh 2.5E-1 m/d) based on bores S2314/2435 (HGEO, 2019b).

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 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 including modelled historical groundwater levels (**Figures G1-G8**) to enable review of changing water levels through time. **Figures G9-G12** present the results Aug-2026 (stress period 152), after Longwall 23 (and at end of Longwall 20), while **Figures G13-G16** present results for 2200 or approximately 175 years after mining (stress period 203).

Figures G9-G12 indicate that significant drawdown would occur within the Wongawilli Seam (up to 250-300 m from pre-mining conditions within the footprint of the Area 3C longwalls), upper Bulgo Sandstone (approximately 80 m) and lower Hawkesbury Sandstone (10-20 m). The water table is also predicted to be disturbed by about 20-40 m in some locations above Longwall 22 and 23, 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 north of the Area 3C longwalls, simulated pre-mining heads in the lower HBSS (Layer 4) are about 300 mAHD (**Figure G2**) and are simulated to have declined 20 m to 280 mAHD by 2026 (**Figures G2 and G10**). At the same location, the depressurisation in the Bulgo Sandstone (Layer 6) is also simulated to show a 45 m decline in groundwater levels, falling from 305 mAHD (**Figure G3**) to 260 mAHD (**Figure G11**). The drawdown in the Wongawilli Seam is about 160 m at the same point (declining from 300 mAHD to approximately 140 mAHD). The water table is not predicted to be affected at this distance.

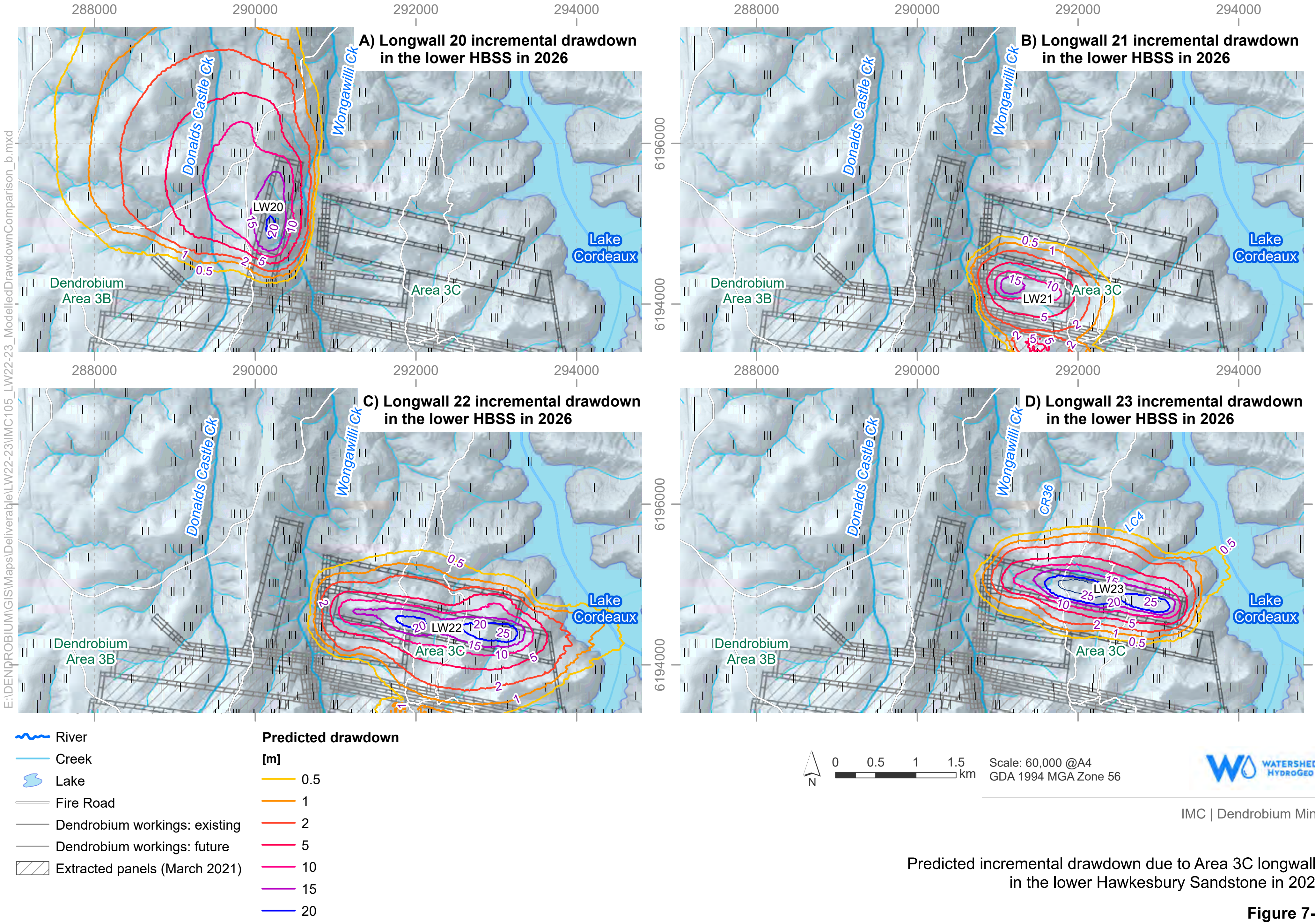
At a distance of approximately 2 km north of Area 3B, modelled drawdown in the lower HBSS is approximately 1 m (comparing **Figures G2 and G10**), while in the Bulgo Sandstone the drawdown is approximately 25 m at this distance (**Figures G3 and G11**), and is 85 m in the Wongawilli Seam (**Figures G4 and G12**).

Comparison of groundwater levels well into the future (**Figures G13-G16**) with pre-mining conditions (**Figures G1-G4**) suggest that water levels in the lower Hawkesbury Sandstone, as well as the water table, would recover to 10-20 m below pre-mining levels around much of Longwalls 22 and 23, primarily due to changes in permeability in the shallow strata. Water levels in the Bulgo Sandstone are predicted to remain depressed by 10-20 m (in the area of Longwall 22 and 23 and 21) compared to pre-mining conditions, but to recover to closer to pre-mining levels around Longwall 20. Water levels in the Wongawilli Seam would recover to near or above pre-mining levels around Longwalls 22 and 23.

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 comparison of the effects of the different longwalls in Area 3C, the incremental drawdown in the lower Hawkesbury Sandstone at the end of mining in Area 3C (in 2026) has been mapped on **Figure 7-1**. This has been calculated as the difference between the full impact scenario and each scenario without one of Longwalls 20, 21, 22 or 23 (**Table 7-1**).



WATERSHED HYDROGEO

IMC | Dendrobium Mine

Predicted incremental drawdown due to Area 3C longwalls in the lower Hawkesbury Sandstone in 2026

Figure 7-1

Figure 7-1A shows that the predicted drawdown due to Longwall 20 is quite extensive to the north and west, extending under Donalds Castle Creek. The drawdown cone is restricted to the east by Wongawilli Creek, and the predicted 2 and 5 m drawdown contours intersect the creek suggesting that the drawdown would be mitigated by captured flow from the creek.

Figure 7-1B shows that the predicted drawdown due to Longwall 21, which is restricted to between Longwalls 6 and 22, and the 0.5 and 1 m contours intersect Wongawilli Creek to the west of the panel.

Figure 7-1C shows that the predicted drawdown due to Longwall 22, which is restricted to between Longwalls 23 (north) and Longwalls 6 and 21 (to the south). The 0.5 m contour of the drawdown cone intersects Wongawilli Creek to the west of the panel and the drawdown cone intersects and extends into Cordeaux Reservoir to the east.

Figure 7-1D shows that the predicted drawdown due to Longwall 23, which is restricted to the south by Longwall 22, and extends approximately 600 m to the north and into the catchment of CR36. Like the incremental drawdown cone for Longwall 22, the 0.5 m drawdown contour from Longwall 23 intersects Wongawilli Creek to the west of the panel, and the drawdown cone intersects Cordeaux Reservoir to the east.

7.3.3 Hydrographs – groundwater levels

A series of hydrographs are presented to illustrate predicted groundwater trends at a number of representative locations around Area 3C. 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 3C longwalls.

Groundwater levels at monitoring bore S1892, to the north of Longwall 6 and south of Longwall 21, are presented on **Figure 7-2.** The effects of mine dewatering on pressures in the Wongawilli Seam (WWSM) are clear: the simulated effects of Area 3A are evident as >200 m drawdown in 2009-10. The simulated effects of Longwalls 21 and then 22 and 23 are shown in 2023-25, with additional drawdown of approximately 10 m. Recovery in the WWSM is indicated to be to levels about 50 m above the 'No Dendrobium' baseline, due to simulated connection with overlying strata. In the Bulgo Sandstone, maximum drawdown is predicted to be up to about 75 m, to below the stage of Wongawilli Creek, and the incremental drawdown due to Longwall 21 is approximately 5-10 m.

Maximum drawdown in the lower Hawkesbury Sandstone is predicted to be almost 15 m, but remaining above Wongawilli Creek. Drawdown in the water table at this location is predicted to be approximately 3-6 m.

Groundwater levels at monitoring bore S2212, to the east of Longwall 22 and near to Cordeaux Reservoir, are presented on **Figure 7-3**. Drawdown from historical workings at Dendrobium is smaller at this site than at S1892. The model simulates historical drawdown of about 80 m in the WWSM, 10 m in the Bulgo Sandstone, and in the order of a metre in the Hawkesbury Sandstone.

The model suggests that the Area 3C longwalls will cause a further 100 m drawdown in the WWSM, of which the incremental drawdown due to Longwall 22 is discernible on **Figure 7-3** (being approximately 20 m but declining over time). Modelled Bulgo Sandstone water levels show drawdown of about 10 m due to Area 3C and again the incremental effect of Longwall 22 is the greatest at this location.

Water levels in the lower Hawkesbury Sandstone are predicted to decline by 5 m in response to Area 3C. Incremental drawdowns in the lower Hawkesbury Sandstone are shown in more detail in Section 7.3.2. The water table shows a very small (<1 m) but persistent decline, depending on the scenario.

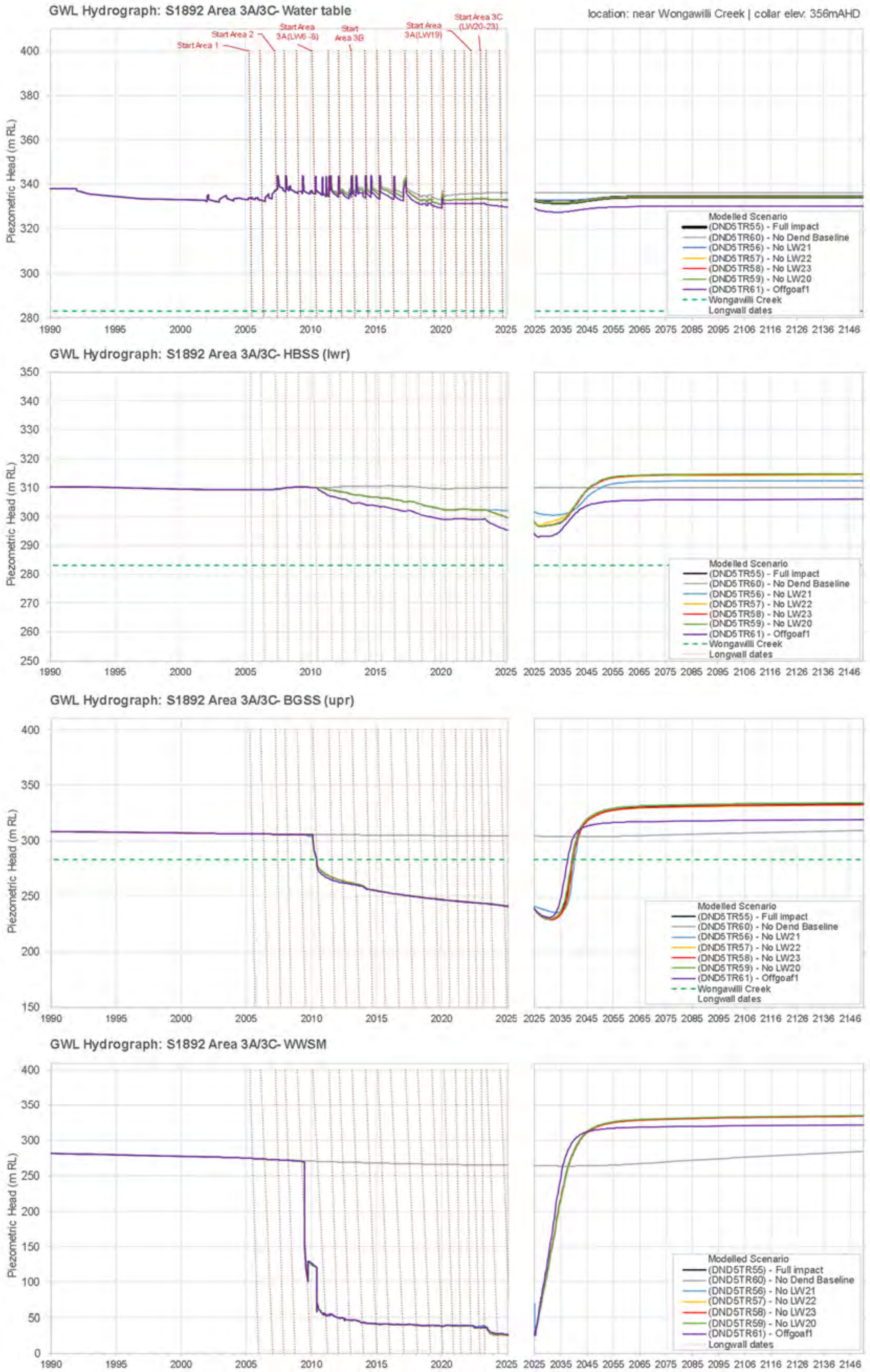


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Figure 7-2 Modelled groundwater levels at S1892)

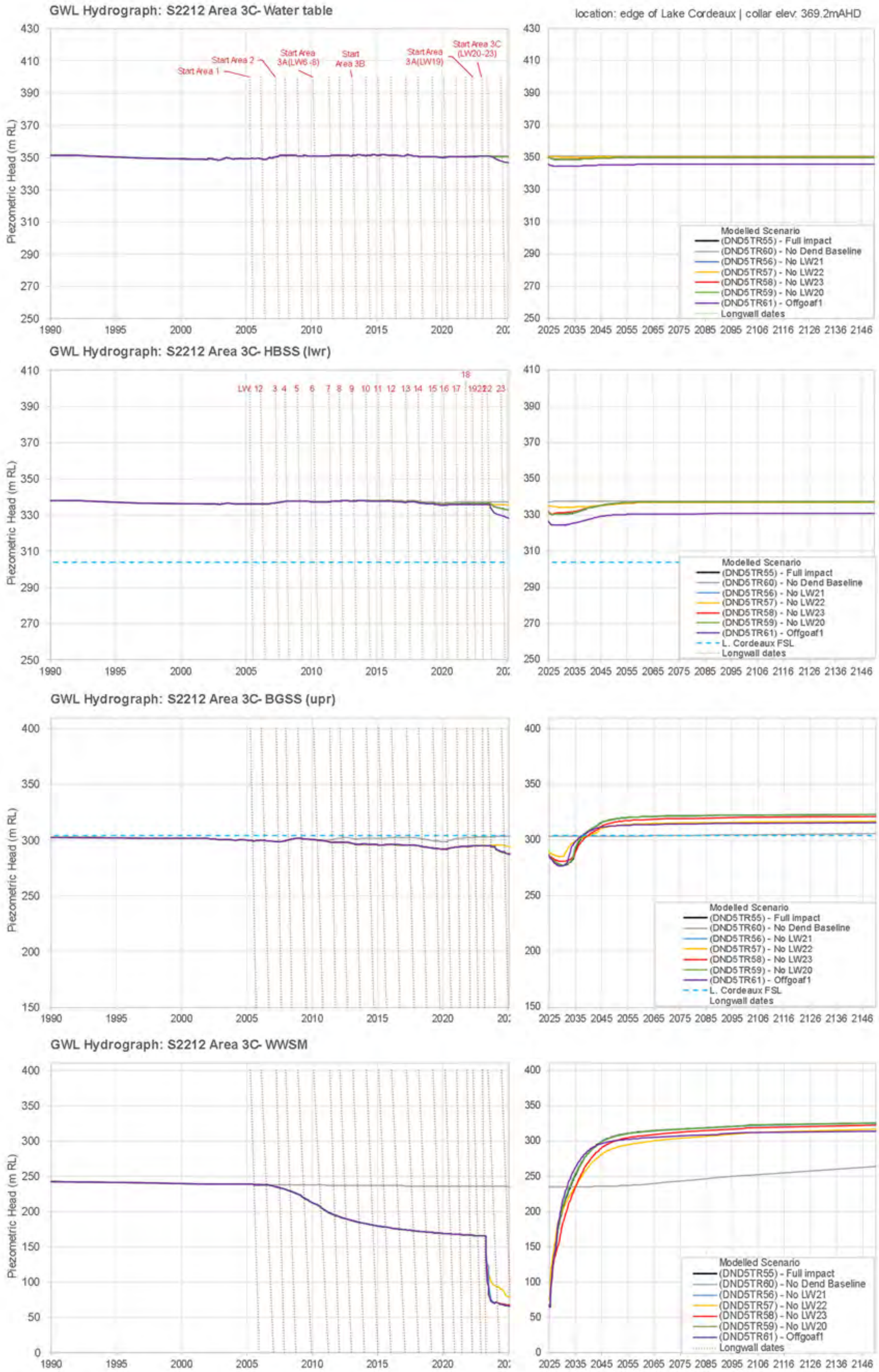

Figure 7-3 Modelled groundwater levels at S2212

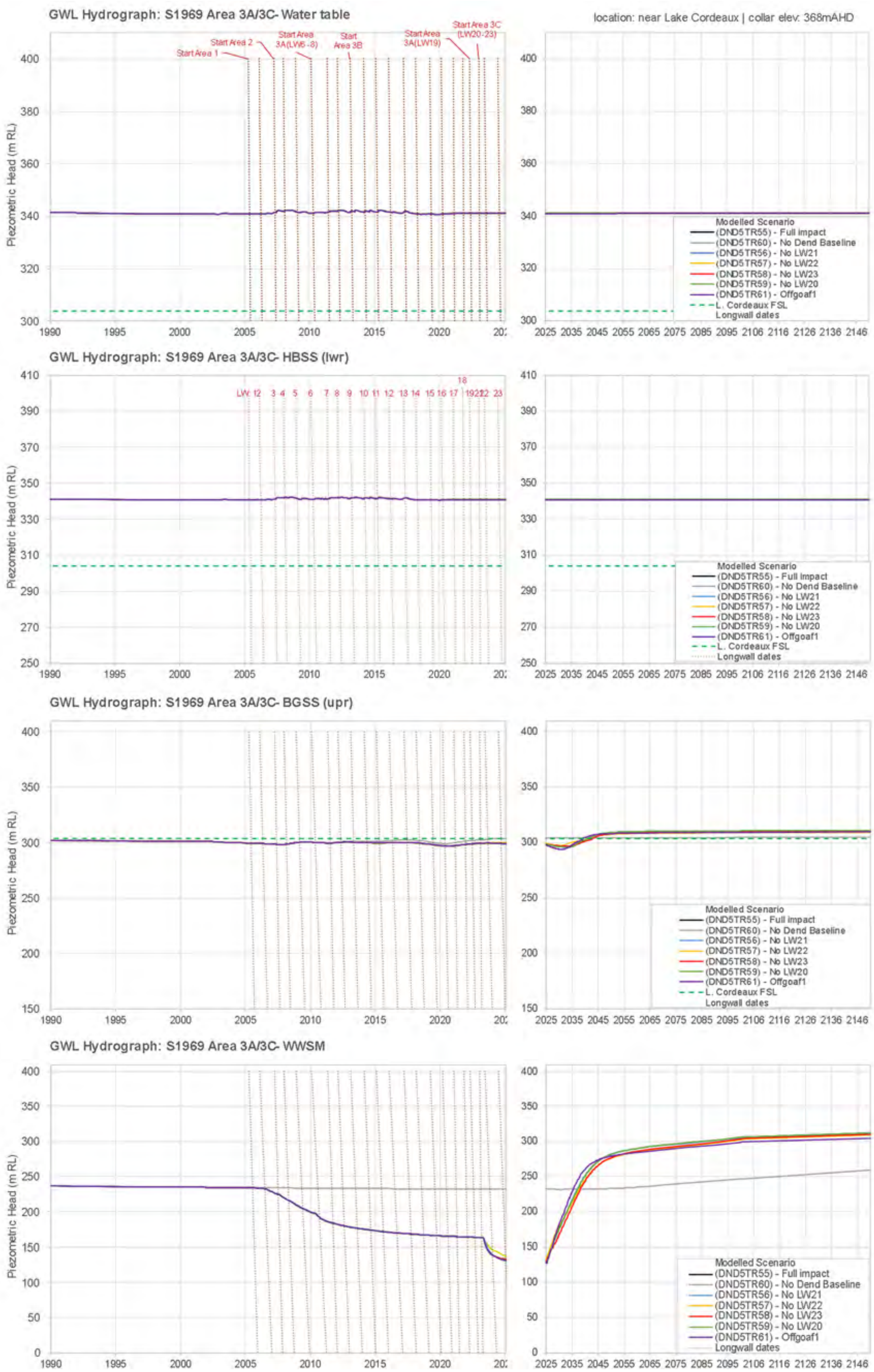

Figure 7-4 Modelled groundwater levels at S1969

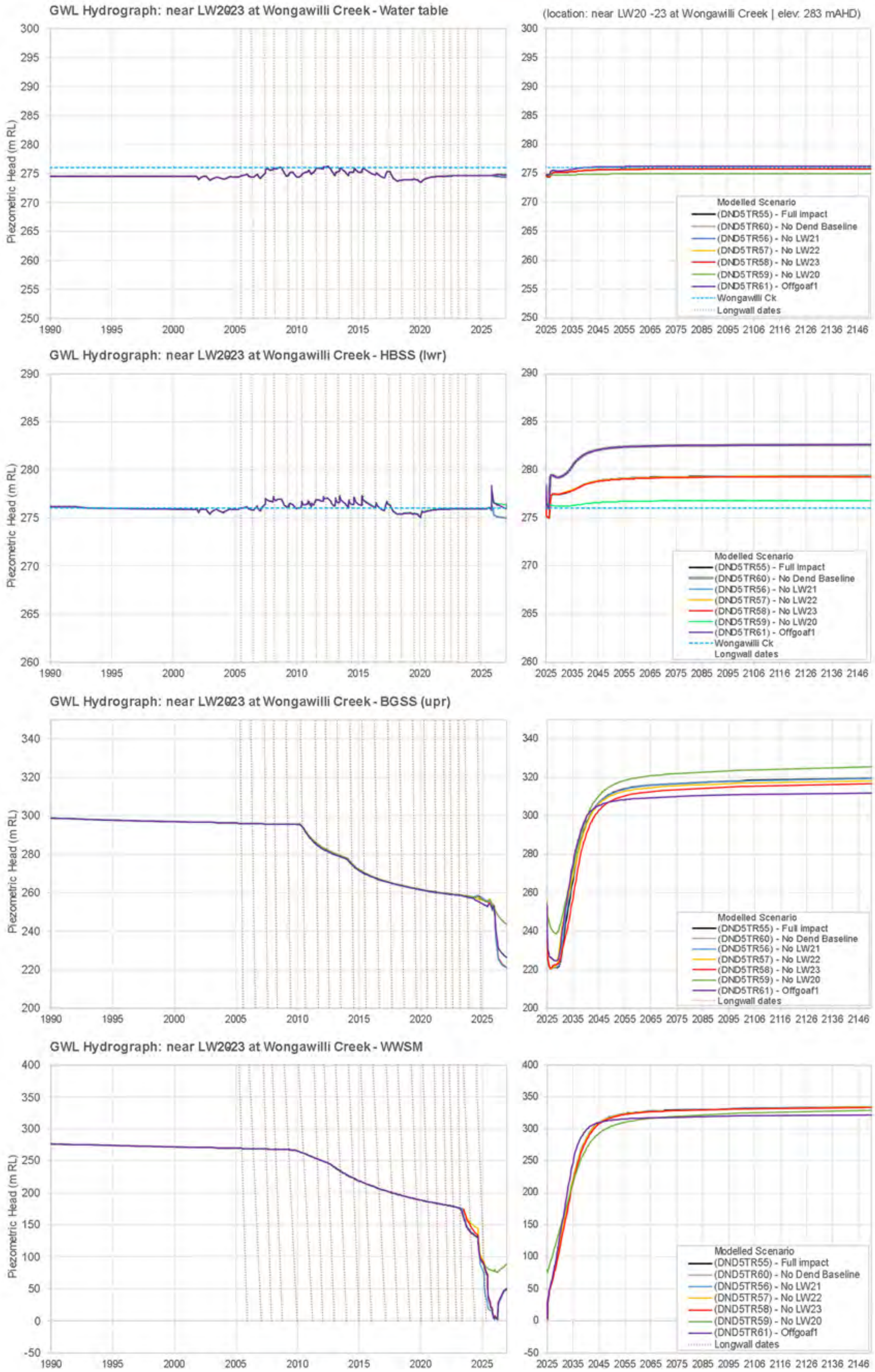

Figure 7-5 Modelled groundwater levels at Wongawilli Ck near Longwalls 20-23

Groundwater levels at S1969 between Area 3A and 3C (approximately 250 m west of Cordeaux Reservoir) are presented on **Figure 7-4**. Like water levels in the WWSM at S2212, drawdown of up to 80 m is simulated in response to Area 3A longwall extraction. The modelling suggests that drawdown due to Area 3C extraction would be 30-40 m at this location, with subsequent recovery beyond natural WWSM pressures.

Bulgo Sandstone water levels show very little drawdown due to Area 3A operations, with Area 3C predicted to cause up to 5 m drawdown. There is no drawdown predicted in the lower Hawkesbury Sandstone or the water table at this location (also see Section 7.3.2).

Figure 7-5 shows modelled groundwater levels at a location between Longwalls 23 and 20 (nearer to the latter), adjacent to Wongawilli Creek. There is no monitoring bore at this site.

The model simulates consistent drawdown from 2010 in the WWSM due to Area 3A and 3B extraction, to a total of 70-80 m drawdown. Area 3C is then predicted to cause a further 175 m drawdown. There are mild differences between the model scenarios without Longwalls 21, 22 and 23, but the total drawdown is similar in all cases. The run without Longwall 20 shows a difference in total drawdown of approximately 80 m. Predicted recovery in the WWSM is related to greater than natural pressures.

Groundwater pressures in the Bulgo Sandstone are simulated as having been drawn down by 40 m due to Areas 3A and 3B, and then predicted to decline a further 100 m due to Area 3C, mainly due to Longwall 20, but with some incremental effects from the other panels. Like the WWSM, recovery is predicted to be to levels above pre-mining pressures.

There are only mild differences in the simulated groundwater levels in the lower Hawkesbury Sandstone at this location. The main differences are in the simulated post-mining levels. In all the scenarios where Longwall 20 is simulated, the proximity to that longwall means that the shallow strata are simulated with enhanced hydraulic conductivity due to valley closure processes. This means that the model simulates more flux and higher post-mining water levels in this area (an effect that is even greater in the more conservative Offgoaf 1 scenario (Section 7.1). The effect is possibly unrealistic, however there has been attention paid to this mechanism by PSM (2017) and others, and it may be that the degree of K enhancement and/or the area over which it is applied in the modelling needs further revision.

There are only subtle differences in the simulated water table, noting that effects on the water table may be mitigated by the capture of surface water at this location, and also the simulation of enhanced K in the off-goaf areas means that post-mining levels are predicted to be slightly higher than pre-mining.

7.3.4 Groundwater pressure head profiles

This section presents modelled pressure head profiles around Longwall 18. Each figure shows pressure head profiles through time and for the full vertical sequence of layers. Pressure head is calculated as the groundwater level (mAHD) minus the elevation of the centroid of the relevant model cell. MODFLOW calculates heads that are averaged across a model cell. As a result of this, some structural error will occur, especially across thick units (e.g. Hawkesbury Sandstone and Bulgo Sandstone layers).

Figure 7-6 shows the modelled pressure head profile at S1892 (location shown on **Figure 3-2**). The profile shows monitoring data for 2008 and 2018, so the modelled profile can be compared to observed data. This shows a reasonable match to the observed data, including from pre-mining conditions (2008), following the extraction of Area 3A longwalls to 2018. The model indicates that pressure heads are already 0-50 m lower than pre-mining pressures through the upper half of the profile, and are predicted to decline only slightly more following Longwall 20 extraction (2026), pressures. The model predicts that by 2070 there would be almost full recovery in the upper layers, and recovery beyond natural in lower layers as a result of greater connection (via fracturing) to the upper layers in longwall footprints to the north and south of this site.

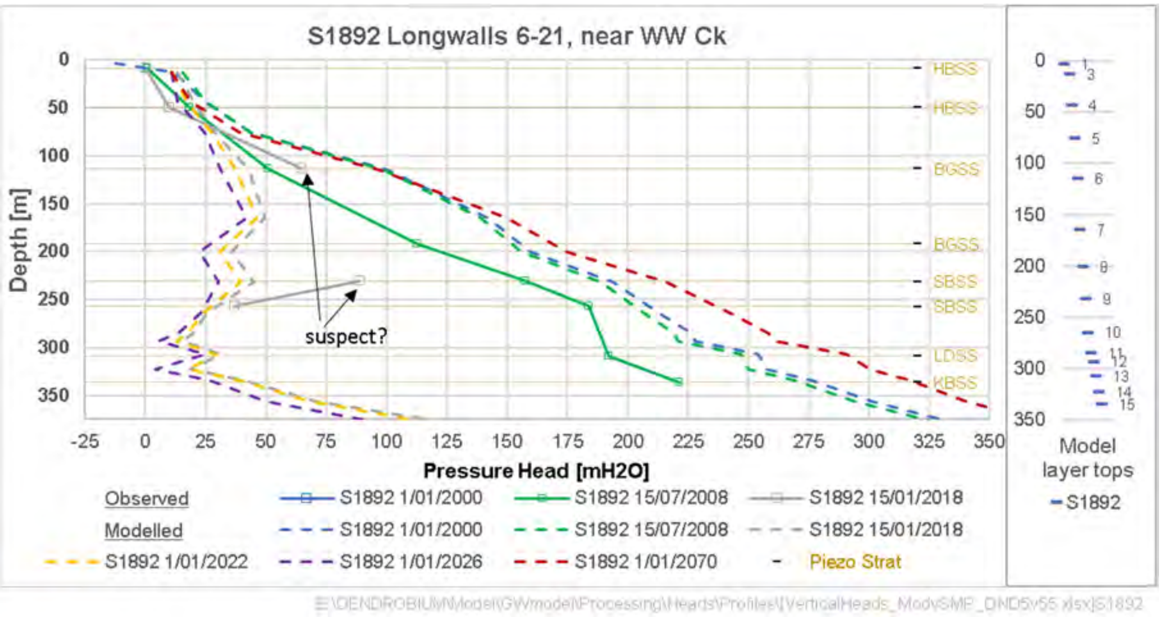

Figure 7-6 Modelled groundwater pressure profile at S1892

Figure 7-7 shows the modelled pressure head profile at monitoring bore S2212 to the east of Longwall 22 and near to Cordeaux Reservoir (**Figure 3-2**). There is monitoring data for 2014 and 2017, so the modelled profile can be compared to observed data. This shows a reasonable match to the observed trends, with the greatest differences in the Scarborough Sandstone piezometers.

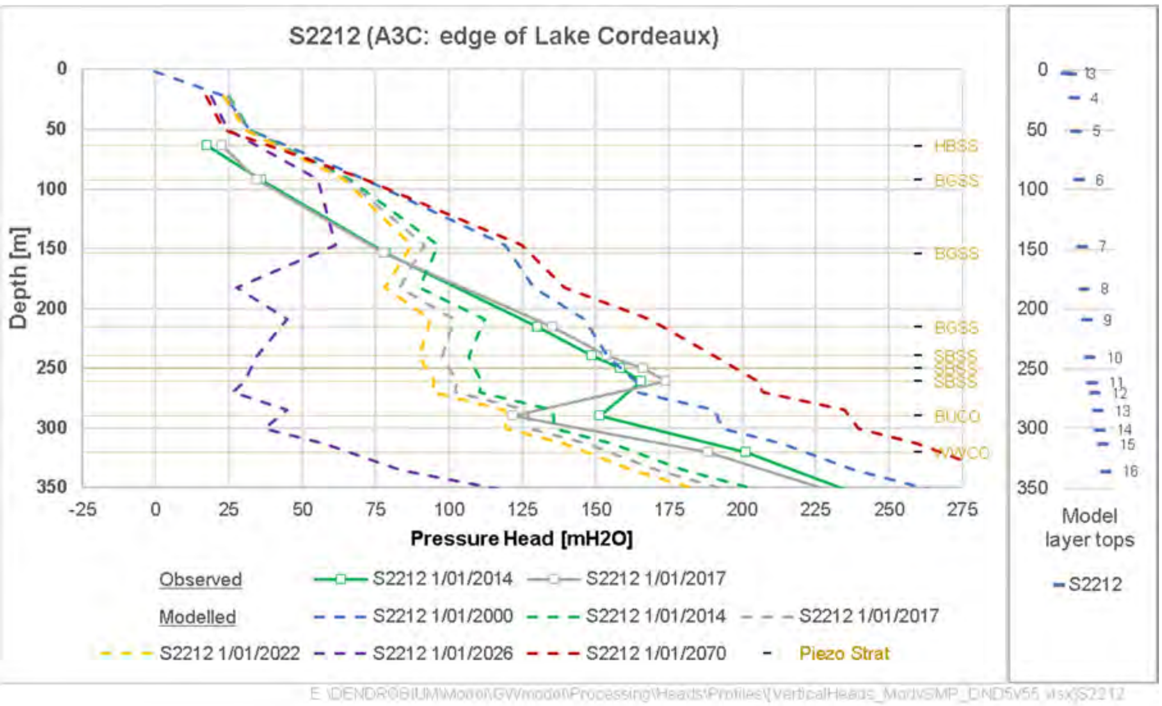

Figure 7-7 Modelled groundwater pressure profile at S2212

As with **Figure 7-6** (above), the modelled profiles for S2212 show the pre-mining conditions in 2000, then the effect of nearby mining at Area 3A is evident as drawdown in 2014 and 2018. Following Longwall 22 extraction, pressures drop significantly (to 2026), with pressures of 10-40 m simulated through much of the profile, and being significantly lower than pre-mining pressures. The model predicts that by 2070 there would be almost complete recovery in the upper layers, and recovery beyond natural in lower layers as a result of greater connection (via fracturing) to the upper layers.

Figure 7-8 shows the modelled pressure head profile 500 m northwest of Longwall 23, 200 m east of Longwall 20 and adjacent to Wongawilli Creek. There is no monitoring bore here, so the modelled profiles are not compared to observed data. The modelled profiles show the pre-mining conditions in 2000, then the effect of nearby Area 3A and 3B mining (located 1.5-2 km to the south) is evident as drawdown in 2015 and mid-2020. Following Longwall 22 and 23 extraction (2025), pressures will have declined further. The effects of Longwall 20 (shown in the 2027 profile) would be to reduce pressures further, with low but positive pressures simulated through much of the profile. Recovery would commence in the late 2020s and the model simulates full recovery in this area by 2050-2070.

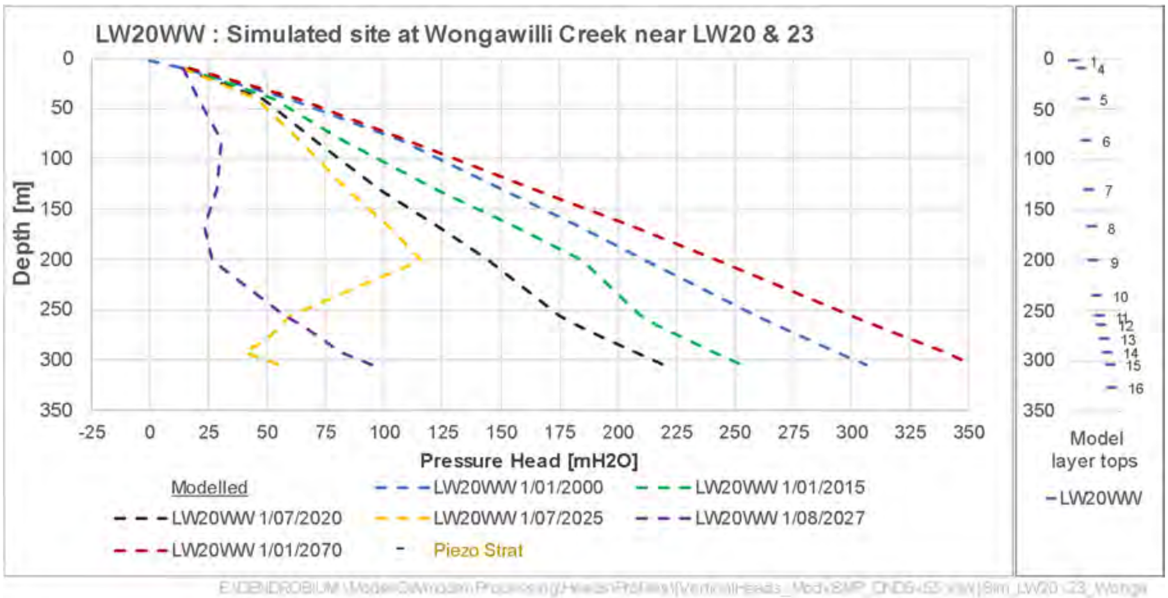

Figure 7-8 Modelled groundwater pressure profile at Wongawilli Creek in Area 3C

For most of the pressure head profiles on **Figure 7-8**, drawdown in the lower Hawkesbury Sandstone (model layer 4) is approximately 1 m, and about 15 m in the Bald Hill Claystone (layer 5). These units are present at or just below the base of Wongawilli Creek, and drawdown here would cause effects on low flows in the creek similar to those observed in recent years further upstream in Wongawilli Creek (WatershedHG, 2018). The pressure head profile for 2027 on **Figure 7-8** suggests that the extraction of Longwall 20 would further reduce groundwater pressures in the Bald Hill Claystone by about 25 m, and in the lower Hawkesbury Sandstone by <1 m at this location.

7.3.5 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 22 or 23, 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 22 increment	Longwall 23 increment
GW040945	110-170 m	HBSS	4	0.0	0.0	0.0
GW068119	9-19 m	Shoalhaven Group	17	0.0	0.0	0.0
GW102528	17-169 m	HBSS	3, 4	0.0	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 20 to 23), historical mining around Dendrobium, and the parts of the approved Tahmoor Mine and the Appin/BSO Mine that lie within the active model domain.

Table 7-3 Modelled Water Balance for Predictive Period (2021-2060)

MODFLOW component	Conceptual process	In [ML/d]	Out [ML/d]
RECHARGE	rainfall recharge	189.0	0.0
RIVER LEAKAGE	watercourses, reservoirs	46.3	25.4
EVT	evapotranspiration	0.0	197.4
DRAINS	mine inflow	0.0	9.0
HEAD DEP BOUNDS	regional GW flow	6.0	1.6
CONSTANT HEAD	flow to ocean, estuaries	0.00	0.03
STORAGE	groundwater storage	7.5 (decline in GWLs)	15.4 (rise in GWLs)
Total		248.8	248.8

Units are in ML/d. Results are from model run 5TR55: SP125-197.

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).

7.4.2 Forecast groundwater inflow

Inflow to Area 3C

Modelled inflow to Area 3C (with and without each of Longwalls 20, 21, 22 and 23) is presented on **Figure 7-9B**, while the incremental contribution of each of those longwalls to the total Area 3C inflow is plotted on **Figure 7-9A**. These figures show the results from the base case model without each of the Area 3C longwalls and the results from the scenario considering higher off-goaf permeability – Section 7.2).

The model suggests that inflow to Area 3C, would peak at the end of Longwall 23, at approximately 5 ML/d (**Figure 7-9B**). The scenario simulating higher off-goaf permeability has little difference on predicted inflow to Area 3C.

Within Area 3C, the incremental effect of Longwall 22 is expected to be an increase in inflow of approximately 2-3 ML/d, and the effect of Longwall 23 is expected to be an increase of approximately 2-3.5 ML/d. The inflow due to Longwall 21 is simulated as up to 1.5 ML/d, while the incremental increase due to Longwall 20 is 1.3 ML/d.

The larger incremental effects of Longwalls 22 and 23, compared to those of Longwalls 20 and 21, is due to the geometry of these panels, the slightly larger panel width and the significantly larger panel length (**Table 1-1**).

Inflow to Dendrobium

The current or recent inflow to Area 3B is above 4 ML/d (Section 3.9.3), indicating the model is overestimating recent inflow to this domain by about 2 ML/d (Section 6.5). Taking this into consideration, the expected inflow to Area 3B, at the end of all approved and proposed Area 3B longwalls, is expected to be in the range of 5-9 ML/d, most likely in the lower end of this range.

The model forecasts that inflow could rise to about 14 ML/d (**Figure 7-10**), although it is noted that the model tends to overestimate inflow by about 2 ML/d. The scenario simulating higher off-goaf permeability increases total inflow by 5-10%. Inflow is forecast to remain below the current annual groundwater entitlement held for Dendrobium Mine (9,185 ML/yr or >25 ML/d).

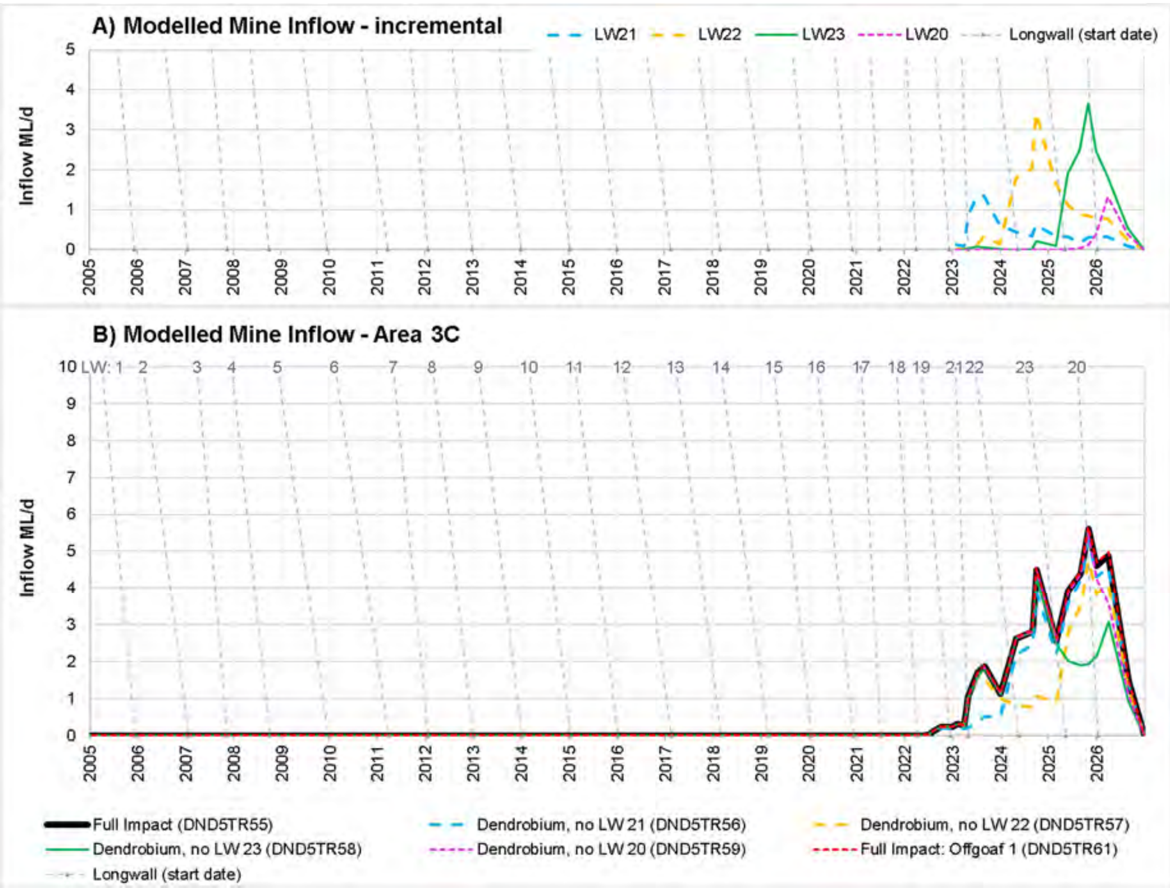

Figure 7-9 Modelled groundwater inflow to each longwall and Area 3C

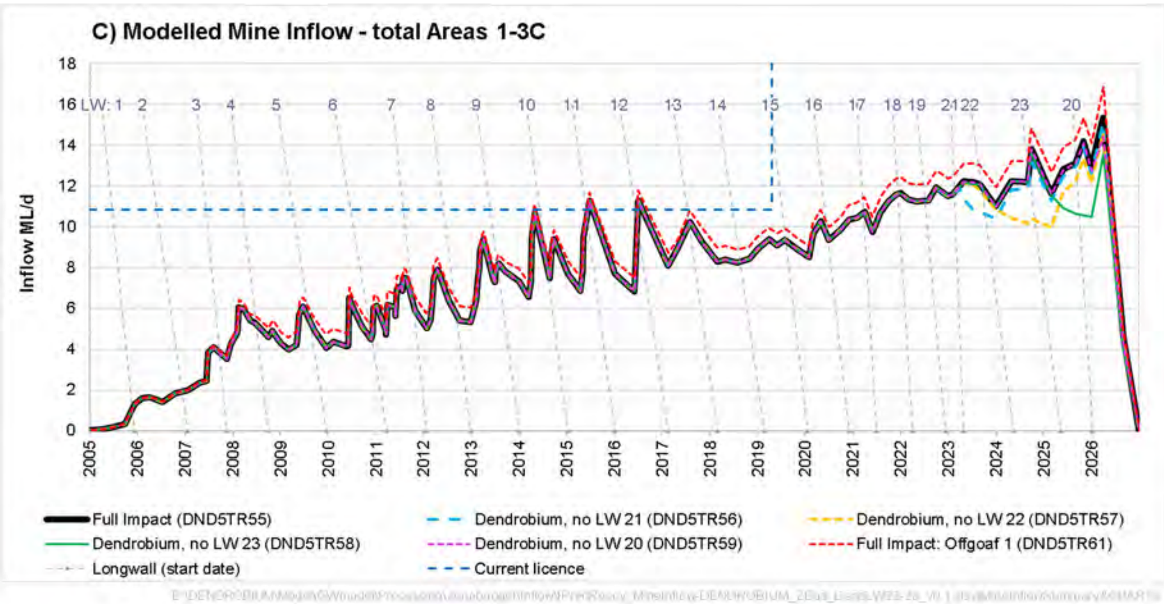

Figure 7-10 Modelled groundwater inflow to Areas 1-3C

7.4.3 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 is 0.11-0.36 ML/d, averaging 0.23 ML/d. 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 Dams Safety NSW's 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 each of the relevant Area 3C longwalls is related to the predicted drawdown in Section 7.3.2. The predicted incremental leakage is summarised in **Table 7-4**.

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

	Longwall 21	Longwall 22	Longwall 23	Longwall 20	Dendrobium Areas 1-3C
Maximum leakage	<0.01	0.08	0.05	<0.01	0.11-0.36
Nearest distance from reservoir	1.6 km	300 m	300 m	2.5 km	220 m (Area 1)

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7.4.4 Simulated Leakage from Avon Reservoir

The maximum leakage from Avon Reservoir as a result of 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 0.18 ML/d. More discussion of these results is presented in WatershedHG (2020), which focusses on the potential effects of longwalls in Area 3B.

These leakage estimates are less than the Dams Safety NSW's prescribed tolerable limit for Avon Reservoir (1 ML/d).

The model estimates that the incremental leakage from Avon Reservoir due to Longwalls 22 and 23 is zero. The same applies to Longwalls 20 and 21.

7.4.5 Simulated 'Incidental Take' from Watercourses

Area 3B SMP 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. The same approach has been here.

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 zones. **Appendix H** presents charts showing whole-of-mine effects on watercourses around Dendrobium. These charts show a range of surface water losses for the 5-year periods. Where historical losses (reductions in median flow) are available from recent End of Panel Assessments, these are plotted to illustrate the performance of the model.

Results for the watercourses near to and most affected by Longwalls 22 and 23 are shown in **Table 7-5** and **Table 7-6** respectively. Results for other watercourses can be provided but are not tabulated in this report.

The range in the following tables represents the minimum to maximum loss, which is also shown in the whole-of-mine effects on the charts in **Appendix H**. The maximum losses in **Appendix H** and the following tables accounts for potential permanency of effects.

The tables below show that the effects of Longwalls 22 and 23 are greatest on LC5, LC6 and WC24 and WC26, and on Wongawilli Creek (when considering the accumulated losses in tributaries and the main channel of the creek).

Table 7-5 Predicted Reduction in Surface Water Quantity (ML/yr): Longwall 22 increment

5 Year Interval	LC5	LC6	WC24	WC26	lower Wongawilli Creek	Wongawilli Creek (to WWL) (accumulated)	CR36
2011-15	0	0	0	0	0	0	0
2016-20	0	0	0	0	0	0	0
2021-25	-0.006 - -0.020	-0.004 - -0.012	0.000 - -0.002	-0.002 - -0.010	-0.001 - -0.002	-0.002 - -0.006	0.000 - 0.000
2026-30	-0.022 - -0.072	-0.021 - -0.070	-0.012 - -0.041	-0.009 - -0.038	-0.005 - -0.018	-0.011 - -0.040	-0.002 - -0.008
2031-35	-0.022 - -0.074	-0.021 - -0.070	-0.014 - -0.050	-0.010 - -0.042	-0.006 - -0.022	-0.025 - -0.089	-0.002 - -0.008
2036-40	-0.022 - -0.074	-0.016 - -0.070	-0.013 - -0.050	-0.004 - -0.042	-0.005 - -0.022	-0.024 - -0.089	-0.002 - -0.008
2041-45	-0.020 - -0.073	-0.011 - -0.070	-0.010 - -0.050	-0.004 - -0.042	-0.004 - -0.022	-0.015 - -0.089	0.000 - -0.008
2046-50	-0.017 - -0.072	-0.006 - -0.070	-0.008 - -0.050	-0.004 - -0.042	-0.003 - -0.022	-0.010 - -0.089	0.000 - -0.008
2051-55	-0.015 - -0.072	-0.005 - -0.070	-0.005 - -0.050	-0.001 - -0.042	-0.003 - -0.022	-0.007 - -0.089	-0.001 - -0.008

Negative value = reduction in surface water flow.
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Table 7-6 Predicted Reduction in Surface Water Quantity (ML/yr): Longwall 23 increment

5 Year Interval	LC5	LC6	WC24	WC26	lower Wongawilli Creek	Wongawilli Creek (to WWL) (accumulated)	CR36
2011-15	0	0	0		0	0	0
2016-20	0	0	0	0	0	0	0
2021-25	-0.004 - -0.009	-0.001 - -0.005	0.000 - -0.001	-0.039 - -0.138	0.000 - -0.002	-0.002 - -0.007	0.000 - -0.001
2026-30	-0.017 - -0.060	-0.008 - -0.025	-0.001 - -0.004	-0.036 - -0.138	-0.006 - -0.021	-0.042 - -0.145	-0.002 - -0.006
2031-35	-0.017 - -0.061	-0.010 - -0.035	-0.003 - -0.012	-0.025 - -0.138	-0.007 - -0.026	-0.043 - -0.149	-0.003 - -0.010
2036-40	-0.017 - -0.061	-0.007 - -0.035	-0.004 - -0.014	-0.011 - -0.138	-0.006 - -0.026	-0.033 - -0.149	-0.002 - -0.010
2041-45	-0.016 - -0.061	-0.001 - -0.035	-0.003 - -0.014	0.000 - -0.138	-0.005 - -0.026	-0.021 - -0.149	-0.001 - -0.010
2046-50	-0.015 - -0.061	0.002 - -0.035	-0.002 - -0.014	0.007 - -0.138	-0.004 - -0.026	-0.015 - -0.149	-0.001 - -0.010
2051-55	-0.014 - -0.061	0.005 - -0.035	0.000 - -0.014	-0.039 - -0.138	-0.004 - -0.026	-0.012 - -0.149	-0.001 - -0.010

Negative value = reduction in surface water flow.
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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 7-7**.

The total take from Wongawilli Creek and Donalds Castle Creeks is predicted to be up to 430 ML/yr (moderate impact estimate, but ranging 280 to almost 1000 ML/yr).

We consider that the likely impact or take is toward the lower end of these estimates (based on comparison against End of Panel surface flow assessment results – Section 6.6 and **Appendix H**). The 'most likely' impact, based on comparison of the modelled and historical losses has been provided in relevant Surface Water Assessments (HGEO, 2020e,g), noting that future rainfall and flow conditions as well as uncertainties in the groundwater model representation of mining effects, will influence future losses.

We consider that the likely impact or take is toward the lower end of these estimates (based on comparison against End of Panel surface flow assessment results – Section 6.6 and **Appendix H**). The 'most likely' impact, based on comparison of the modelled and historical losses has been provided in relevant Surface Water Assessments (HGEO, 2020e,g), noting that future rainfall and flow conditions as well as uncertainties in the groundwater model representation of mining effects, will influence future losses.

Short-term effects may be higher than is 'expected' based on the 5-year intervals (**Table 1-3**).

Table 7-7 Predicted change in surface water flow (ML/d): Dendrobium total

5 Year Interval	Donalds Castle Creek (to DCU)	LC5	LC6	WC26	Wongawilli Creek (total)	CR36
2016-20	-0.06 - -0.22	0.000 - -0.001	-0.017 - -0.050	-0.081 - -0.057	-0.27 - -0.94	0
2021-25	-0.18 - -0.42	-0.010 - -0.030	-0.048 - -0.144	-0.012 - -0.085	-0.54 - -1.90	-0.000 - -0.001
2026-30	-0.13 - -0.42	-0.056 - -0.168	-0.069 - -0.207	-0.031 - -0.218	-0.62 - -2.18	-0.005 - -0.018
2031-35	-0.15 - -0.42	-0.059 - -0.177	-0.066 - -0.207	-0.033 - -0.228	-0.63 - -2.22	-0.006 - -0.023
2036-40	-0.15 - -0.42	-0.078 - -0.235	-0.069 - -0.208	-0.028 - -0.228	-0.56 - -2.23	-0.005 - -0.023
2041-45	-0.12 - -0.42	-0.059 - -0.235	-0.007 - -0.208	-0.016 - -0.228	-0.41 - -2.23	-0.001 - -0.023
2046-50	-0.10 - -0.42	-0.042 - -0.235	0.028 - -0.208	-0.002 - -0.228	-0.29 - -2.23	-0.001 - -0.023
2051-55	-0.01 - -0.42	-0.030 - -0.235	0.049 - -0.208	0.009 - -0.228	-0.23 - -2.23	-0.003 - -0.023
Maximum annual take, ML/yr	50 to 170	30 to 90	25 to 80	23 to 80	230 to 810	2 to 10

Negative value = reduction in surface water flow.
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7.4.6 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 7-8 Predicted reduction in surface water flow to reservoirs (ML/yr)

5 Year Interval	Avon Reservoir catchment		Cordeaux Reservoir catchment	
	Moderate	Range	Moderate	Range
2016-20	-5	-3 to -11	-136	-91 to -318
2021-25	-59	-39 to -137	-154	-104 to -358
2026-30	-180	-120 to -419	-221	-147 to -515
2031-35	-232	-155 to -542	-261	-174 to -609
2036-40	-233	-155 to -544	-265	-177 to -618
2041-45	-191	-128 to -446	-227	-151 to -529
2046-50	-113	-75 to -264	-133	-89 to -311
2051-55	-53	-35 to -123	-54	-36 to -127

Negative value = reduction in surface water flow.
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Taken alongside the results in Section 7.4.5, the revised model suggests that Dendrobium Mine could take up to 930 ML/yr (range 615 to 2,100 ML/yr) of surface water during the period 2021-2040 and declining thereafter:

- 500 ML/yr (range: 330-1,100 ML/yr) from the water supply catchments; and
- 430 ML/yr (range 285-1,000 ML/yr) from Wongawilli and Donalds Castle Creeks.

Note 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 some correlated lineaments are the main structural features of note near Longwall 22. There are few mapped faults, and those in this area have been drilled through and shown to have no significant displacement. Therefore, based on current data, geological structures are not considered a significant risk pathway for Longwalls 22 and 23.

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 be up to 12 ML/d, although this is still slightly (approximately 2 ML/d) greater than is considered realistic given the calibration to Areas 3A and 3B. The extraction of:
  - Longwall 22 would cause an increase in inflow of up to 2-3 ML/d.
  - Longwall 23 would cause an increase in inflow of up to 2-3.5 ML/d.
- Simulated leakage from Cordeaux Reservoir is predicted to be less than the prescribed tolerable limit, being up to 0.36 ML/d. The incremental rate of loss due to Longwall 22 is 0.08 ML/d and 0.05 ML/d for Longwall 23.
- The incremental leakage from the Avon Reservoir due to extraction of Area 3C Longwalls 22 and 23, or due to Longwalls 20 and 21, would be effectively zero.
- Incidental surface water capture has been estimated using the groundwater model and tabulated as required in **Table 7-7**. The predicted take is up to 430 ML/yr from all surface water sources and catchments, while the incremental take due to Longwalls 22 and 23 across all nearby watercourses is up to approximately 90 ML/yr for each longwall (**Table 7-5** and **Table 7-6**).
- Two tributaries of Cordeaux Reservoir (LC5 and LC6) and Wongawilli Creek tributary WC26 would be the watercourses most affected by extraction of Longwalls 22 and 23. Smaller watercourses will also be affected, such as WC24 (which is also adjacent to Longwall 21).
- Longwall 20 would most likely affect tributaries WC23 and WC25.
- As well as effects to small tributaries, Longwalls 22 and 23 would cause a reduction in flow in Wongawilli Creek, 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, Longwalls 22 and 23 are likely to have similar effects to those observed on Wongawilli Creek due to 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 18 km from Dendrobium Area 3C (**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, 2020e), however it is likely that groundwater drawdown and cracking due to extraction of Longwalls 22 and 23 will affect Swamp 07.
- The nearest registered "water supply work" (i.e. private bore) is >4 km south or south-east of Dendrobium Area 1, and over 8 km from Longwalls 22 and 23. 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:	**Level 1**
	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. 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).	
Water pressure A cumulative pressure head decline of not more than a 2m decline, at any water supply work.	Minimal impact consideration classification:	**Level 1**
	There is a very minor risk of depressurisation in excess of the water supply work drawdown criterion within the Permo-Triassic strata (at GW112386).	
Water quality	Minimal impact consideration classification:	**Level 1**
	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.	

8.2 Recommendations

Recommendations for future data analysis and modelling are as follows:

8.2.1 Monitoring and analysis

As noted in Section 2.4.1, new surface water monitoring sites are being planned for watercourses around Area 3C.

As per the Area 3C SMP requirements (Schedule 3, Condition 8), IMC should assess if inflow to Area 3C longwalls can be isolated from inflow to Areas 3A and 3B, and where to monitor the inflow, both in terms of volume/rate and water chemistry. The difference with Area 3C compared to Areas 2,3A and 3B is that Area 3C will be developed from south to north, i.e. moving down dip. Based on the data received in early 2021 (Section 3.9.3), inflow to Area 3C first workings has been recorded separately from other areas (Area 3A and 3B).

Over-goaf investigation bores are planned for Longwalls 22 and 23 (bores S2514 and S2518 on **Figure 3-2**), and another is planned for above Longwall 21. This will be packer tested, logged for defects and have piezometers installed to assess pre-mining conditions, similar to the recent over-goaf bores described in HGEO (2020c). This will be rehabilitated prior to mining, and then a similar post-mining bore will be installed. Similar pre- and post-mining bores will be required in Area 3C.

Where access allows, monitoring of pre- and post-mining conditions should be carried out:

- between Longwalls 22 and 23 and Cordeaux Reservoir. This monitoring should replicate the monitoring conducted between Area 3B and Avon Reservoir, i.e. including testing of pre- and post-mining strata permeability and groundwater levels. This monitoring needs to consider that some piezometers in this area have already ceased (e.g. at S2208) and others (e.g. S2059, S2212) are likely to be directly affected by mining of Longwalls 22 and 23, and this has implications for long-term monitoring plans (see below). A "shoreline" monitoring site with two bores is recommended, located approximately 200 m north-northeast of S2212 and Longwall 22 and 200 m from the FSL, and site access is being investigated. This site is recommended to comprise:
    - a bore into the mid-Bulgo Sandstone (BGSS), packer tested and then equipped with at least 3 VWPs, including one approximately 20 m below Cordeaux FSL.
    - an adjacent standpipe (OSP) bore, screened at the same level (20 m below FSL) to allow verification of groundwater pressures recorded at the VWP and to allow sampling for water quality analysis.
    - and following extraction of Longwall 22, this site should be re-drilled and packer tested again to quantify any change in strata permeability.
- between Area 3C longwalls and Wongawilli Creek, with piezometers in the Hawkesbury Sandstone (in particular) and Bulgo Sandstone. IMC has drilled an inclined monitoring bore (bore S2508, shown on **Figure 3-2**) between Wongawilli Creek and the western ends of Longwalls 22 and 23.

The evolution of longwall mine plans means that some of the sites identified in the previous version of the long-term monitoring plan (SLR, 2020b) will no longer be suitable for long-term monitoring (e.g. bore S2059) and it is recommended they be replaced in monitoring plans by sites identified above (S1969 and/or new Area 3C sites).

Future analysis of mine inflow should consider the reconsolidation of caved strata, as outlined in Section 2.6. This may be most evident in the inflow hydrograph in Area 3A, which was quite variable, and moderately responsive to rainfall trends up until 2016, and has become much more muted since then.

The main pathways for longwall mining, specifically at Longwalls 22 and 23, to pose a risk to water features are outlined in Section 4.3. Groundwater TARPs are suggested in **Table 8-2** in order to monitor the effects, and compare against modelled behaviour. This is a framework at this time, and following input from agencies and confirmation of monitoring locations and data, would be finalised in the relevant WIMMCP for Area 3C.

Table 8-2 Suggested structure of groundwater TARPs for Area 3C

Parameter	Monitoring	Basis for Triggers	Actions / Response
Groundwater levels near Cordeaux Reservoir	Groundwater level and pressure monitoring at bores between Longwalls 22 and 23 and the reservoir, e.g. ▪ S1969, and ▪ a new site recommended near Longwalls 22 and 23, focussing on the Bulgo Sandstone and Hawkesbury Sandstone.	Use pre-mining water levels as baseline for S1969, but earliest available for any new sites. Comparison of actual groundwater levels and calculated drawdown against modelled levels and forecasted drawdown (e.g. 6 m after Longwalls 22 and 23 in upper Bulgo Sst at S1969), as follows: ▪ L1: >75% of base case model drawdown (i.e. 'approaching prediction'); ▪ L2: >100% of base case model drawdown ▪ L3: >125% of base case model drawdown.	Compare observed against modelled drawdown in base case and scenarios. Reporting and notification. Revision of associated predictions (e.g. fluxes) if necessary.
Groundwater levels near Wongawilli Creek	Groundwater level and pressure monitoring at bores between Longwalls 22 and 23 and Wongawilli Creek, e.g. ▪ S2508 ▪ S1892	As above. Use pre-mining water levels as baseline for S1892, but earliest available for S2508.	As above.
Groundwater quality	A new OSP site recommended near Longwalls 22 and 23.	Monitoring for water quality changes (deterioration as well as 'freshening') beyond baseline to investigate possible movement of freshwater from the reservoir toward Area 3C.	Assess for deviation from baseline (and against Reference site if suitable site exists). Reporting and notification.

8.2.2 Modelling

First workings in Area 3C have proceeded faster than anticipated by WatershedHG, and the model representation of these requires updating in the near future, although longwall extraction in that domain will not occur until late 2022.

The over-estimation of inflow, especially for recent years in Area 3B and the underestimation of peak inflows in Area 2 requires further investigation. This requires finding a balance between maintaining current calibration to groundwater levels, while reducing Area 3B inflow and possibly increasing Area 2 inflow, and improving surface water loss estimates. The mis-match between modelled and observed inflow, especially for the post-longwall inflows in Areas 3A and recent inflows to Area 3B, may be related to the reconsolidation of caved strata, as outlined in Section 2.6.

Further investigation and calibration of Kv (and perhaps Kh) 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 aim to completely remove the 'Stacked Drains' and rely solely on the TVM method of simulating enhanced hydraulic properties as a result of fracturing. This may also improve the representation of swamp water tables – currently the model over-estimates drawdown and/or needs improvement in how 'dry' swamp sediments are represented in reporting and statistics (e.g. such as on **Figure 6-1**).

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 post-mining recovery.

The development of an uncalibrated local-scale groundwater model of the Cordeaux Reservoir shoreline, similar to that developed by HGEO for Avon Reservoir, should be considered for the purpose of a second method of estimating leakage from the reservoir to groundwater as a result of mining. A difficulty with the simulation of the Cordeaux Reservoir shoreline, compared to the Area 3B-Avon situation, is the longer frontage of all Dendrobium areas near to the Cordeaux Reservoir shoreline and multiple stratigraphic units (**Figure 2-3**), however the model could be focussed on the lake shoreline between Sandy Creek and the dam wall, where the reservoir is primarily hosted in the Hawkesbury Sandstone, Bald Hill Claystone and Bulgo Sandstone to reduce the length of shoreline and minimise stratigraphic complexity.

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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: 15/05/2021
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	Dendrobium Water Balance Readings - April 2021.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)	S1892_Dend 99.xlsx S1930_Dend 112.xlsx S1932_Dend 114.xlsx S1969_Dend 118.xlsx Dend S2212.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	
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)	Latest Surface Flow and Rainfall to March 2021.xlsx	
Summary of flow data from all Dendrobium sites	Consultant (WatershedHG)	SWFlowData_Compiled_Wshed_v4_20210219.xlsx	