WaterNSW submission to the Independent Expert Panel on Mining in Sydney Catchment – Task 1 Matters

May 2018

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1. INTRODUCTION

1.2. Role and Responsibilities of WaterNSW

1.2.1. Statutory Role

The *Water NSW Act 2014* sets out the objectives, functions, powers and regulatory responsibilities of WaterNSW. A key responsibility under the Act is for WaterNSW to ensure that 'declared catchment areas and water management works in such areas, are managed and protected so as to promote water quality, the protection of public health and public safety, and the protection of the environment'. WaterNSW has regulatory powers to control access to Special Areas and to manage mining activities and impacts in the declared Sydney catchment area.

1.2.2. WaterNSW Mining Principles

WaterNSW has defined Mining Principles to manage mining and coal seam activities in Declared Catchments. A link to the WaterNSW Mining Principles is given below:

http://www.waternsw.com.au/water-quality/catchment/mining

The Principles establish the outcomes WaterNSW considers essential to protect the drinking water supplies to the four and half million people of Sydney, Illawarra, Blue Mountains, Southern Highlands, Goulburn and the Shoalhaven. A key policy position of WaterNSW is that:

- WaterNSW opposes any longwall mining located within the Dams Safety Committee notification areas surrounding WaterNSW's dams in the Declared Catchment, or elsewhere, where it is predicted to damage Sydney drinking water supply infrastructure.

The Principles address the following:

- Protection of water quality;
- Protection of water quantity;
- Protection of human health;
- Protection of water supply infrastructure;
- Protection of the ecological integrity of Special Areas; and
- Provision of sound and robust evidence regarding environmental impacts.

1.3. Special Areas and declared Sydney catchment area

The declared Catchment collects and stores up to 2.6 million megaliters of water to supply Sydney, the Blue Mountains, the Illawarra, the Southern Highlands, parts of the Shoalhaven and Southern Tableland areas. The Catchment is extensive, covering parts of the hydrologic catchments of the Hawkesbury–Nepean, Shoalhaven and Woronora Rivers and extending over 16,000 km^2.

The Catchment extends from north of Lithgow on the Coxs River, from the head of the Shoalhaven River in the south near Cooma, and from the Woronora River in the east to the source of the Wollondilly River west of Goulburn. The Catchment includes the entire catchment area upstream of Warragamba Dam, including the Coxs, Kowmung, Nattai, Wollondilly and Wingecarribee River sub-catchments and their tributaries. It also covers the upper Nepean catchment upstream of the Nepean, Avon, Cordeaux & Cataract Dams and upstream of the Pheasants Nest and Broughtons Pass Weirs, and the small catchments of the Greaves Creek, Cascade, and Woodford Dams in the Blue Mountains. Outside of the Hawkesbury-Nepean Basin, it includes the catchment of the Woronora River upstream of Woronora Dam, and the catchments of the Shoalhaven and Kangaroo Rivers, upstream of Tallowa Dam.

The major water supply catchments (Upper Nepean, Shoalhaven, Warragamba, Blue Mountains and Woronora) are divided into 27 sub-catchments from an operational viewpoint. The sub-catchments drain into reservoirs that store 'raw water', i.e. water has not been treated. WaterNSW delivers the water via a network of rivers, pipes and canals to water treatment plants, where it is treated and delivered to customers in the Greater Sydney region. The water supply system has some flexibility to balance storage needs, and can be reconfigured during times of drought, high rainfall or maintenance. There are however some constraints in this flexibility however, for example the Avon Dam is particularly important for the Illawarra Region's drinking water supply.

The declared Sydney catchment area is entirely underlain by coal measures, but for various reasons active coal mining in the region is limited to the Southern and Western Coalfields. Whilst some western coal mines have encroached into the declared Sydney catchment and Springvale Mine is discharging mine waters into the Lake Burragorang/Coxs River headwaters, no active mining in the Western Coalfields is currently occurring within the declared catchment. In the Southern Coalfields, WaterNSW considers the greatest current and historic risks to the Sydney water supply are posed by mining operations beneath the Metropolitan and Woronora Special Areas. Current mining leases and active, proposed and historical mining footprints in these Special Areas are shown in Figure 1-1.

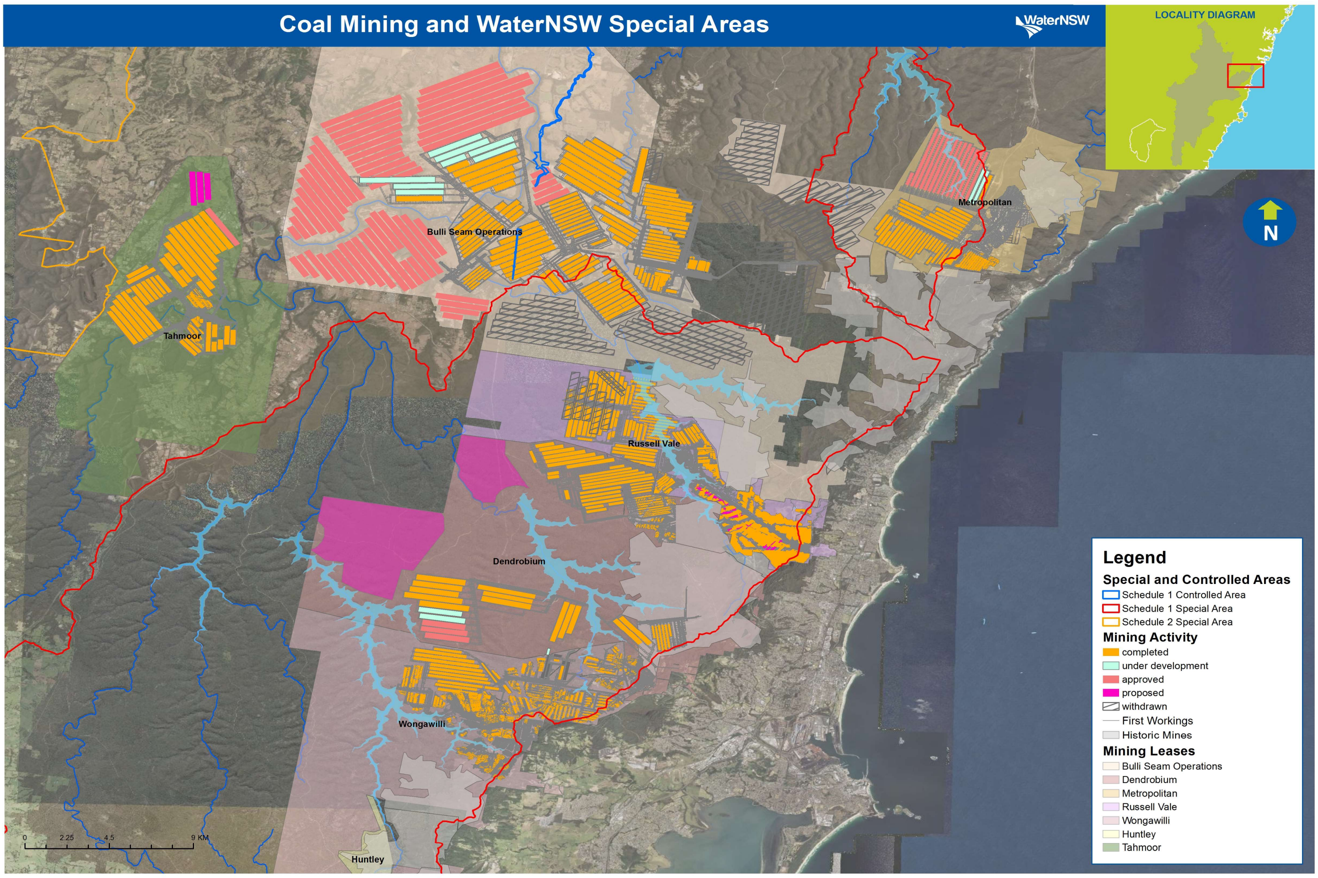

Figure 1-1. Current mining leases and active, proposed and historical mining footprints in Metropolitan and Woronora Special Areas

1.4. Surface Water Resources

The volumes and key features of WaterNSW's water storages on the Woronora Plateau, comprising the Nepean, Avon, Cordeaux & Cataract Dams and the Pheasants Nest and Broughtons Pass diversion weirs, are set out in Table 1-1.

Table 1-1: Water resources of dams and diversion weirs on Illawarra Plateau

Storage	Total Operating Capacity (ML)	Water Surface Area at Full Supply (ha)	Catchment Area (ha)	Security Yield (Ml/a)
Woronora	71,790	400	7,225	9,500
Cataract	97,190	850	12,618	20,000
Cordeaux	93,640	780	8,684	14,000
Avon	146,700	1,050	14,256	20,800
Nepean	67,730	330	31,824	19,000
Broughtons Pass Weir	50	1.31	8,169	6,000
Pheasants Nest Weir	25	0.25	13,596	5,000

1.5. Role of the Independent Expert Panel on Mining in the Special Areas

The Terms of Reference state that the Independent Expert Panel (IEP) will:

1. **Undertake an initial review and report on specific coal mining activities at the Metropolitan and Dendrobium coal mines in the Greater Sydney Water Catchment Special Areas,** including:
    a. A review of the findings and recommendations of previous studies and reports, including but not confined to the reports:
        i. *Height of Cracking – Area 3B*, prepared by PSM, dated 16 March 2017
        ii. *2016 Audit of the Sydney Drinking Water Catchment*, prepared by Alluvium, dated June 2017.
    b. A review of the types and reliability of *prediction, monitoring and remediation methodologies currently used for assessing and managing the effects, impacts and consequences of mining activities* at the Metropolitan and *Dendrobium coal mines as they relate to water quantity, including having regard to historical data and performance.*
    c. *Provide advice and recommendations on measures required to improve approaches to prediction, monitoring, rehabilitation and reporting* at the Metropolitan and Dendrobium coal mines, including having regard to cumulative risks posed to the quantity of drinking water available in the Greater Sydney Water Catchment Special Areas.
    d. Based on the outcomes TOR 1(a) to 1(c), provide advice to Government on how to respond to the findings and recommendations of reports reviewed as part of TOR 1a.
    e. In developing its advice, the Panel will meet, undertake site visits, seek information and data, and consult as needed.
    f. In delivering its report, the Panel will provide comment on and make observations or recommendations about any information or factors the Panel believes relevant; or further work that should be undertaken.
    g. A progress update on the report is to be delivered no later than 30 April 2018 and the report is to be delivered no later than 31 July 2018.

2. **Undertake a review of current coal mining in the Greater Sydney Water Catchment Special Areas with a particular focus on risks to the quantity of water available, the environmental consequences for swamps and the issue of cumulative impacts,** including:
    a. A review and update of the findings of the *2008 Southern Coalfield Inquiry (Impacts of Underground Coal Mining on Natural Features in the Southern Coalfield – Strategic Review)* for mining operations at the Dendrobium, Metropolitan, Russell Vale and Wongawilli mines, including recommending measures to improve the way mining effects, impacts and consequences in relation to water quantity are assessed and managed.
    b. In developing its advice, the Panel will meet, undertake site visits, seek information and data, and consult as needed.
    c. Establish a process for and invite public submissions, including from public authorities and special interest groups.
    d. In delivering its report, the Panel will provide comment on and make observations or recommendations about any information or factors the Panel believes relevant, including requirements to strengthen monitoring networks or undertaking further scientific research.
    e. The report is to be delivered no later than 31 December 2018.

3. **Provide advice as required to the Department of Planning and Environment on mining activities in the Greater Sydney Water Catchment Special Areas,** which may include but is not confined to:
    a. A Subsidence Management Plan application for Longwall 16 at the Dendrobium mine.
    b. An Extraction Plan application for Longwall 303 at the Metropolitan mine.
    c. An Environmental Impact Statement for the Dendrobium Extension Project.
    d. A Preferred Project Report for the Russell Vale Underground Expansion Project.
    e. A modification application for the Wongawilli mine.

To assist the Panel, WaterNSW proposes to provide advice within this submission only on the items contained in Task 1 above, and we will offer a separate submission to address Task 2 in the near future.

2. HEIGHT OF CRACKING STUDY AND ASSOCIATED REPORTS

2.1. Height of Cracking Report (PSM, 2017)

This landmark study was commissioned by DPE, who engaged PSM to examine the available monitoring information from the Dendrobium Mine in order to understand the distribution of fracturing and groundwater responses to the longwalls which have been mined to date. The key outcomes of the report from WaterNSW's perspective are summarised in the following sections.

2.1.1. Key findings

As suggested in WaterNSW's submission on the SMP application for LW14-15 and confirmed by subsequent investigations (PSM, 2017; Hgeo 2017b), the vertical extent of fracturing (alternatively termed cracking by PSM) from the surface is greater than was predicted by IC and most[1] of the documents used to support the company's 2008 planning application and subsequent SMP applications (2013, 2015).

Given the functions described in Section 1.2 and our understanding of consequent risks on WaterNSW values identified in Advisian (2016), the implications of the surface-to-seam fracturing at Dendrobium Mine in terms of increased surface water losses and reduced long-term groundwater levels on the Special Area catchments are a major concern to WaterNSW. The Height of Cracking Report (denoted hereon as HoCR) findings have confirmed that subsidence form Dendrobium Mine is causing impacts greater than were predicted and approved.

The key outcomes of the HoCR from WaterNSW's perspective are summarised in Table 2-1.

Table 2-1: Summary of key findings of Height of Cracking Report (PSM, 2017) with NSW comments

Study Findings	WaterNSW Comments/Observations
Groundwater monitoring and fracture investigations data show no evidence that a "constrained zone" exists over Dendrobium longwalls, and that post-mining depressurisation extends right through to the surface. Depressurisation through the vertical profile is not limited to areas above longwall panels but extends well beyond the footprint of these panels. There is no direct evidence of full desaturation – rather the data suggests that most overburden rocks remain saturated but with very significant depressurisation at most locations.	These findings confirm WaterNSW's interpretations of the Parsons Brinckerhoff (2015) study and other evidence at Area 3B, e.g. drying of creeks and swamps over longwalls. It is important to note that much of the confidence provided to the various coalfield inquiries about how underground mining effects would be separated from catchment impacts is based on the premise of effective aquitards and intact constrained zones – this confidence has clearly been challenged at Dendrobium and the underlying premise needs to be urgently reconsidered.
Water inflow rates into the mine workings is responding to rainfall, confirming that direct hydraulic connections (connective cracking) exist between the mine workings and the surface, particularly in Area 2.	The evidence presented by PSM and the peer reviewers is consistent with WaterNSW suggestions in numerous submissions that subsidence over Dendrobium longwalls has caused relatively rapid and direct hydraulic connections between surface and

[1] The exception to this statement were two groundwater modelling reports prepared by Coffey Geotechnics (2012a; 2012b) in support of the SMP Application for Dendrobium Area 3 longwalls, which predicted that surface depressurisation caused by surface-to-seam connective cracking was likely to occur in some locations. IC subsequently replaced Coffeys with HydroSimulations as their hydrogeological modelling advisers. DPE approved the SMP with a condition requiring that an updated modelling report be provided, and the Coffeys reports were effectively superseded by a HydroSimulations modelling report which predicted that surface depressurisation would not occur.

Study Findings	WaterNSW Comments/Observations
There is evidence that Areas 1, 3A and 3B mine inflows are also responding to rainfall, suggesting connectivity also in these areas While measurable increased hydraulic connection between the Avon and Cordeaux Reservoirs and mine workings at Dendrobium Mine were not demonstrated to the Peer Reviewers' satisfaction, such connection is feasible.	mine workings. It is inevitable that slower, more tortuous connections to surface catchments also exist which would not result in rapid inflow responses, as indicated by increased recharge observed next to Lake Cordeaux and increased permeability next to Lake Avon. Some surface water resources will also be diverted into non-connective cracks, further draining the Special Area catchments and reservoirs without registering as mine inflows.
Neither of the two models used to estimate the height of free drainage above longwalls is robust – neither properly and adequately accounts for geology, the mechanics of rock behavior and time dependent hydrogeology processes.	The authors and the peer reviewers have collectively suggested that neither of the prevalent models used to predict the height of desaturation above longwalls is valid. This effectively means that predictions of subsidence impacts on water resources cannot be reliably made using current knowledge. WaterNSW does however note that the more conservative prediction method developed by Paul Tammetta appears to have been more successful in predicting the "height of depressurisation" over the Dendrobium longwalls.
There are still a number of gaps and uncertainties in the knowledge base and investigations of real and potential mining effects and their impacts could have been improved if the overall geological, geotechnical, hydrogeological and mining context had been better investigated, modelled and monitored.	One issue reported by PSM is that some data that should have been available was not, for example the extensometer data referred to by Parsons Brinckerhoff (2015). WaterNSW recommends that this data be sought by DPE or OCSE and provided to the IEP for review and/or explanation. PSM also make it plain that, despite a large array of piezometers and other monitoring at Dendrobium, the most important questions about fracturing and depressurisation cannot currently be answered because there is insufficient information and/or knowledge. These knowledge and information gaps remain a key concern to WaterNSW.
The primary controls for avoiding connective cracking to the surface and limiting the magnitude and extent of impacts on groundwater are restricting mining height and restricting panel width, and the primary control for avoiding adverse impacts of geological structures is to leave a buffer of adequate width against such features	WaterNSW strongly supports this conclusion, but notes that the reliable prediction of adequate buffer dimensions has proved elusive to date. We further support E/Professor Galvin's conclusion there is a likelihood of mine to surface connective cracking and rainfall ingress over some areas of proposed Dendrobium Longwalls 16 to 18 if the planned dimensions of these panels are not substantially reduced.

2.1.2. Recommendations

Principal recommendations of the HoCR (PSM, 2017) and associated peer reviews and summary interpretations are summarised with WaterNSW's comments in Table 2-2.

Table 2-2. Summary of Height of cracking study report (PSM, 2017)

Key Recommendations	WaterNSW Comments/Observations
The findings of the 2008 Southern Coalfields Inquiry should be updated and its scope expanded to include man-made water storages. Geomechanical modelling incorporating fluid flow in three dimensions with sub-meter discretisation of the physical domain, supported by field and	There is a great deal of important information about impacts from mining beneath water catchments which has come to light since the last Inquiry, and WaterNSW strongly supports this recommendation and the Panel's role in examining the new information.

Key Recommendations	WaterNSW Comments/Observations
laboratory measurements of rock properties and flow through fractures, is likely to provide a pathway to (stochastically) estimate the distribution of connective cracking with reasonable certainty. Numerical modelling of the mechanical and hydrogeological response of the rock mass to mining may also aid in design, notwithstanding that this approach also has limitations and the need for calibration against field performance.	These improvements in understanding are discussed at some length in WaterNSW's Literature Review report (Advisian, 2016), and will be discussed further in a subsequent submission to the IEP. Recommendations on improving predictive modelling approaches are discussed in Section 4 below.
Review the water balance for Cordeaux Reservoir and investigate the implications of the anomalous recharge patterns in piezometers adjacent to Areas 2 and 3A with Cordeaux Reservoir	This is one of several lines of evidence regarding potential surface water diversion to the adjacent and underlying aquifers which urgently needs to be examined and quantified. WaterNSW would be pleased to assist or work with the Panel in this regard.
Undertake additional monitoring between Area 3B and Avon Reservoir Review potential current and future impacts of continued mining on Avon Reservoir. Evaluate the effects of valley bulging when considering future mining near Avon Reservoir.	Some additional monitoring and investigations are being undertaken by Illawarra Coal between Avon Dam and the Dendrobium panels. WaterNSW agrees that this monitoring and investigation results should be closely examined by the IEP. Recommendations on improving monitoring approaches are discussed in Section 5 below.
Careful consideration needs to be given to verifying the location of all projected geological structures prior to the approval of future longwall panels in Area 3B and to leaving a substantial buffer against these structures if there is any possibility that they may directly or indirectly connect with a surface water storage.	WaterNSW strongly concurs with this recommendation. The risks of geological structures greatly increasing subsurface connectivity between the workings and Lake Avon are considered high for proposed Longwalls 16-18, and the geological integrity of this area needs to be exhaustively examined prior to assessing the risks from these proposed panels.
Undertake investigations pre- and post-mining to better define and confirm the cracking and dilation of the rock mass above longwall panels in Area 3B.	Some of these investigations are programmed by IC in accordance with requirements in the SMP Approval for Longwalls 14 and 15. WaterNSW recommends that the adequacy and outcomes of these investigations be closely examined by the IEP and that the review assess the results and advise on what further investigations are warranted.
Key areas for DPE and the major stakeholders to consider are – do any of the impacts need to be better quantified, and what are the appropriate acceptability criteria for these impacts?	WaterNSW suggests that the most important impact which needs to be quantified is the volume of surface water being diverted from drinking water catchments. We would be pleased to work with DPE and the IEP to progress this work and to develop appropriate acceptability criteria.

2.2. Peer Review and Associated Reports

DPE separately engaged two leading experts in mine subsidence (E/Prof Galvin) and hydrogeology (Dr Mackie) to peer-review the HoCR and to provide focused advice on subsidence and groundwater aspects of the SMP application being made at that time for Dendrobium Longwalls 14-18. Besides those conflated above with the HoCR comments, the key findings (from WaterNSW's perspective) of these reviews are summarised below.

Emeritus Professor Galvin (Galvin and Associates, 2016) advised that:

- The groundwater model used by Illawarra Coal should not be considered a robust physical and mechanistic depiction of ground behavior above longwall panels at Dendrobium mine.

- It is highly probable all swamps overlying Longwalls 14 to 18 will experience a significant reduction in groundwater level and that, in some cases, these levels may not recover in the long term.
- Experience over Longwalls 9 to 11 indicates that all watercourses overlying Longwalls 14 to 18 will be susceptible to moderate to severe impacts.

Dr Mackie (Mackie Environmental Research, 2016) commented on mine water inflows and groundwater modelling, and advised that:

- Variability in the measured mine water ingress supports a strong correlation to rainfall recharge in Areas 2 and 3A and moderate correlation in Area 3B. It is therefore reasonable to assume that seam to surface connected cracking has developed over Areas 2 and 3A and that potentially, Area 3B could exhibit the same response as result of a reducing depth of cover over future Longwalls 14 to 18. The evolution of a connected regime in Area 3B could in turn have implications for leakage from Avon Dam.
- The volume of diverted surface runoff into the mine that would otherwise have reported to either Cordeaux or Avon dams or to Wongawilli Creek was estimated by Dr Mackie to be in the order of 5 GL for the six year mining period from January 2010 to January 2016. WaterNSW estimates that over the period analysed by Dr Mackie, the surface contribution of 5 GL accounts for about 44% of total Dendrobium mine water ingress (11.4 GL). [WaterNSW comment: These estimations are much greater than those suggested by the mining company and their advisers, who most recently suggest that surface water contributions make up less than <10% of mine inflows (HydroSimulations, 2016).]
- Until such time as the concerns raised are addressed, a precautionary approach to mining should be adopted.

2.3. WaterNSW comments on Height of Cracking study outcomes

Although the HoCR focused specifically on evidence at the Dendrobium Mine, the report's findings have implications for the prediction and understanding of surface water, groundwater and ecological impacts throughout the Special Areas of the declared Sydney catchment area. It is important to understand how different the consequences of mining have been in response to subsidence effects at Metropolitan, Russell Vale and other mine in the Special Area, and thereby to deduce what the key influences on these consequences are.

The most important finding of the HoCR from WaterNSW's perspective is that the subsidence effects observed at Dendrobium Mine are resulting in impacts and consequences well in excess of the predictions made in support of the mine's planning and post-approval applications. An important observation in this regard is that the Performance Measures identified in the mine's planning approvals have largely failed to identify or prevent the significant consequences which have since occurred. Equally troubling is that none of the numerous studies and interpretative reports commissioned by IC on exactly the same issues identified the true magnitude of the subsidence effects – several of them presenting almost the complete opposite (e.g. HydroSimulations, 2015, 2016b, DGS 2016).

From WaterNSW's viewpoint, the single most important consequence which has been highlighted by the HoCR is that subsidence induced by the Dendrobium Mine longwalls is likely to be resulting in significant diversion of surface water which would otherwise contribute to Greater Sydney's water supply. The associated degradation of water quality and ecological integrity of Special Area catchments are also of concern.

These results suggest that mine dimensions should have been constrained to values where such widespread and significant consequences did not occur. It will be an important task for the Panel or government to consider how appropriate guidance can be developed on how to constrain mining dimensions to avoid this scale of subsidence effects in the future.

A further important finding arising from the HoCR and associated review reports is that independently engaged studies produce different results to those engaged by mining proponents. WaterNSW consequently recommends that the Panel consider this and make recommendations aimed at ensuring that such studies generate information in which all stakeholders can have confidence.

3. CATCHMENT AUDIT 2016

3.1. Key Audit findings

The independent three-yearly audit of Sydney's drinking water catchment identified 'Mining in the Special Areas' as one of five Priority Issues for the catchment.

The first-listed issue listed under "Key findings and recommended responses" from the audit report (Alluvium, 2017a) is:

Mining in Special Areas: *The Audit found an emerging issue of unquantified loss of surface flows associated with the cumulative impacts of underground coal mining activities. This issue requires attention and should be considered in implementation of the Metropolitan Water Plan and activation of licensing under Section 60I of the Water Management Act 2000 and in accordance with the NSW Aquifer Interference Policy. Greater understanding of the effect of multiple mine workings on Catchment water yield is required, and this understanding should be reflected in relevant mine planning, appropriate water licensing, and the regulation of those licences.*

3.2. Audit Recommendations

The Catchment Auditors made six recommendations specifically directed at reducing mining risks and impacts in the Special Areas as presented in Table 3-1.

Table 3-1. Catchment audit recommendations (Alluvium, 2017a)

ID	Recommendation	Responsibility
M1	Establish the scope and commence a state-owned regional surface water and groundwater geotechnical model.	DPE / Lands & Water (L&W, formerly DPI Water)
M2	Activate licensing under Section 60I of the Water Management Act 2000 and in accordance with the NSW Aquifer Interference Policy to regulate surface water loss to mine workings.	L&W
M3	Establish an independent panel to review the monitoring, analysis and reporting program relevant to mines operating in the Catchment.	DPE
M4	Investigate thresholds at which mining activities cause loss of surface water to mine workings, and impact the yield of individual Sydney catchment water supply systems. Results to be considered in the Metropolitan Water Plan.	Metropolitan Water Directorate / WaterNSW
M5	Identify surface water flow monitoring requirements in mining approval conditions.	DPE

ID	Recommendation	Responsibility
M6	Compile all empirical evidence of mining impacts in the Sydney Drinking Water Catchment in a regional cumulative impact assessment.	DPE

3.3. WaterNSW comments on Catchment Audit (2016) recommendations

WaterNSW is working to address the Audit Recommendations to which it has been allocated primary or secondary responsibility and is supporting other agencies tasked with the other Recommendations, and we look forward to discussing this with the Panel in due course. In the interim, we would like to offer the following suggestions on how the mining-related recommendations set out above might best be addressed by WaterNSW and other public authorities to which they have been assigned.

3.3.1. M1 – Scope and develop integrated surface water and groundwater geotechnical model for the Special Areas

The concept of developing a regional numerical model simulating geotechnical, hydrogeological and hydrological behavior for the Sydney Basin, the Southern Coalfields or at least the Special Areas has been an aspiration of State and Federal agencies for many years.

One reason that it hasn't been done as yet is that it is an extremely complex and difficult task, but more specifically a regional model can't be realistically progressed until the relationship between longwall mining and changes in surface water and groundwater responses can be better quantified. These difficulties are discussed in the following paragraphs but to be clear, WaterNSW believes that an improved understanding of hydrological and hydrogeological responses to longwall mining is required, and that this would ultimately lead to development of a government-sanctioned integrated hydrological, geotechnical and hydrogeological model capable of accurately predicting responses to mining.

The ability of authorities to adequately understand and model the Sydney Catchment and the major current and possible future activities in it was investigated by the NSW Chief Scientist & Engineer (OCSE, 2014). This Review examined current approaches to assessing cumulative impact and their limitations, and investigated whether a more quantitative approach was possible.

As part of the Review, the Chief Scientist held a workshop with acknowledged experts in a range of relevant disciplines to examine the core question of whether cumulative impacts of mining activities in the Catchment could currently be determined. The Executive Summary of the report (OCSE, 2014) presents the following key passages:

> *Consensus among the experts consulted was reached relatively quickly: answering these questions with quantitative precision is impossible at present given insufficient geological, geophysical and hydrogeological data available on current activities. If such data were available, they would drive data fusion models of the Catchment or allow the construction of more conventional deterministic, parametric models. If such models could be built, they would provide the framework for examining predictions of cumulative impacts and would provide a mechanism for explaining measured impacts and attributing them to the most likely causes.*
>
> *Accordingly, the Review makes a series of recommendations that a range of data be collected and/or sourced from past data collections so that the construction of data fusion and deterministic, parametric models of water quantity in the Catchment can*

commence as a matter of urgency. This would provide the information to the SCA to manage the Catchment; to the Department of Planning to manage approvals; and to industry for submission to the planning process and for monitoring of activities – to ensure that unforeseen impacts are not occurring or, at least, are detected at an early stage.

In summary, the Review has found that we cannot yet build a complete model to understand the cumulative impacts of multiple activities in the Catchment (or even, at precise levels, impacts from single activities). However, the technologies to do so are now available and, with more data collected, it will soon be possible. The Review found that water quality issues can largely be managed through treatment works although an upgrade to infrastructure would be needed in the future to maximise this capability. On water quantity, the Review has found measuring and predicting the impact of single activities is difficult – more data from diverse sources is needed to make significant progress on this. That said, current activities should proceed while this data is gathered; the current impacts are not seeming to affect water quantity in a major way.

The review report includes a set of five recommendations to achieve the mid-term goal of modelling water responses to mining-induced subsidence:

- That Government create a whole-of-Catchment data repository.
- That Government develop a whole-of-Catchment environmental monitoring system.
- That Government commission computational models which can be used to assess the impacts on quantity and quality of surface water and groundwater.
- That Government encourage the use of data visualisation tools for examining 3D representations of the Catchment.
- That Government establish an expert group to provide ongoing advice on cumulative impacts in the Catchment

The Federal Department of the Environment (DoE) recently examined the potential of developing a basin-wide numerical model to assist in “baselining” and analysing potential cumulative impacts from coal mining. The work was undertaken by the Commonwealth Office of Water Science (OWS, a division of DoE) in collaboration with CSIRO and Geoscience Australia as part of the BioRegional Assessment Program, and instigated at the request of the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC).

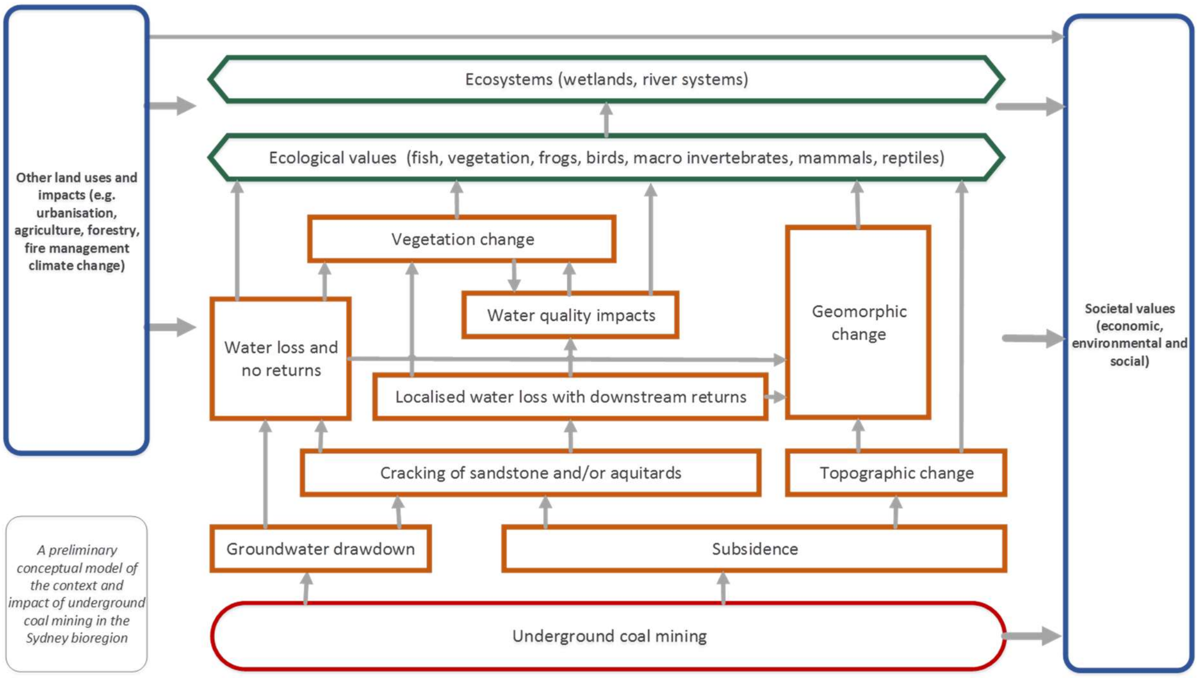

Figure 3-1 A conceptual diagram of underground coal mining context and impacts (Alluvium, 2017b)

Following an initial analysis and summation of available data, OWS held a workshop in April 2017 which brought together a range of agencies, academics and industry practitioners to discuss the current limitations that are currently limiting or preventing analysis of the cumulative impacts of longwall coal mining in the Sydney Basin. The outcomes from this workshop have been published (Alluvium, 2017b. A central graphic prepared by OWS to facilitate discussion is reproduced as Figure 3-1. Although the workshop was not successful in identifying a clear path forward for modelling key hydrological processes in the Sydney Basin, a broad consensus was reached that the current state of knowledge about how longwall mining affects surface water and groundwater resources is effectively preventing the development of a unified geotechnical, hydrogeological and surface water model for the Southern Coalfields.

WaterNSW has been examining this same question in order to inform our assessment of the project and cumulative impacts from longwall mining on our values, particularly on surface water volumes, water quality and ecological health of the Special Areas (Advisian, 2016). We have undertaken and intend to undertake further research to resolve these questions, but our current position accords with the OCSE and OWS workshop outcomes discussed above, i.e. that the current state of understanding of these issues is insufficient to enable an integrated numerical model to be developed. We are however keen to work with the IEP, the coal industry and the community to map out a path to addressing the critical data and understanding gaps.

3.3.2. M2 – Activate licensing under Section 60I of the Water Management Act 2000 and in accordance with the NSW Aquifer Interference Policy to regulate surface water loss to mine workings

WaterNSW endorses this recommendation, and is providing our support for its implementation by NSW Lands and Water (LaW).

3.3.3. M3 – Establish an independent panel to review the monitoring, analysis and reporting program relevant to mines operating in the Catchment

WaterNSW strongly supports this recommendation and commends the NSW Government and particularly the Department of Planning and Environment for implementing it by establishing the Independent Expert Panel.

We look forward to working with and supporting the IEP in its review, and this submission forms part of our contribution.

3.3.4. M4 - Investigate thresholds at which mining activities cause loss of surface water to mine workings, and impact the yield of individual Sydney catchment water supply systems

WaterNSW is considering how to assess future mining proposals utilising the best available science. An important foundation for this is the Literature Review of Underground Mining Beneath Catchments and Water Bodies, prepared by a team of specialist consultants (Advisian, 2016). The literature review report, available on WaterNSW website (http://www.waternsw.com.au/water-quality/catchment/mining), summarises the global and local state of knowledge (as of 2016) with respect to the following key subject areas related to mining beneath the Special Area catchments:

1. Subsidence engineering
2. Groundwater responses to subsidence
3. Mechanisms of surface water loss due to subsidence
4. Ecology of Special Areas and likely impacts
5. Risk assessment frameworks

A summary of the Literature Review report is provided as Appendix A.

WaterNSW would welcome the opportunity to discuss the issue of surface water loss and how thresholds may be set with the Panel at the earliest opportunity.

3.3.5. M5 - Identify surface water flow monitoring requirements in mining approval conditions

WaterNSW's recommendations in regard to improving flow monitoring are set out in Section 5.2.3

3.3.6. M6 - Compile all empirical evidence of mining impacts in the Sydney Catchment in a regional cumulative impact assessment

This recommendation is strongly endorsed by WaterNSW, and has been an aspiration of government for many years. A qualitative summary of recognised impacts in the Special Areas is being compiled by WaterNSW and will be included in a future submission to the Panel. We hope that this summary, along with the Literature Review (Advisian, 2016) will provide a useful basis for building an empirical database of mining impacts in the Sydney Drinking Water Catchment, on which a cumulative impact assessment may one day be attempted.

The first challenge in fulfilling this recommendation is to identify, access, and compile all relevant monitoring data from mining proponents. Most modern mine planning approvals require that certain information be posted on the company's website for a period of time. The requirement has led to companies posting annual or End of Panel reports plus a limited number of other interpretative reports, which is welcome but falls far short of a database of examinable data. Accessing all company-held environmental monitoring data for the Special Areas has been an aspiration and intention of WaterNSW for many years, and recommendations for data and reporting improvements are discussed in Section 6.

Another key reason that an empirical evidence database has not yet been compiled is that there remains significant uncertainty about how to quantify impacts caused by subsidence. As explained in our literature review (Advisian, 2016), significant data gaps remain in many key aspects, including:

- Measuring losses from the three principal recognised mechanisms by which subsidence may divert surface water into bedrock aquifers (see pre- and post-mining figures in Attachment B) is currently not feasible, and there is currently no consensus on how they can be reliably estimated, let alone predicted.

- The desiccation of swamps cannot reliably be predicted by current methods. Recent experience in the Special Areas is that while virtually every swamp that is undermined at the Dendrobium Mine has gone dry, only some of those undermined by the Metropolitan Mine longwalls appear to have been similarly impacted. For those upland swamps that have been hydrologically altered due to subsidence-induced fracturing, the time taken until ecosystems are radically altered appears to be variable and difficult to predict or measure. It has been demonstrated in numerous undermined swamps for example that desiccation makes them much more vulnerable to subsequent bushfire and erosion effects.

- Monitoring of surface water, groundwater and ecological impacts is inevitably time-limited. There has rarely been two years of comprehensive baseline monitoring prior to mining approval as notionally required by various guidelines, and even two years of monitoring will never capture the full seasonal and inter-seasonal (particularly phenomena such as the Millennium Drought) range of conditions. Equally, monitoring of post-mining conditions rarely lasts more than a few years, whereas it is likely that it would take decades for new equilibrium groundwater, surface water and ecological conditions to become established after longwall subsidence has occurred. As a result, WaterNSW is not aware of any set of longwalls in the Special Areas where post-mining equilibrium conditions have been established and confirmed through adequate surface water, groundwater and ecological monitoring.

4. PREDICTIVE MODELLING IMPROVEMENTS

As identified in Section 1.5, one of the main sub-tasks assigned to the IEP is to:

- Review the types and reliability of prediction, monitoring and remediation methodologies currently used for assessing and managing the effects, impacts and consequences of mining activities at the Metropolitan and Dendrobium coal mines as they relate to water quantity, including having regard to historical data and performance.

- Provide advice and recommendations on measures required to improve approaches to prediction, monitoring, rehabilitation and reporting at the Metropolitan and Dendrobium coal mines, including having regard to cumulative risks posed to the quantity of drinking water available in the Greater Sydney Water Catchment Special Areas.

WaterNSW allocates considerable resources to reviewing predictive modelling reports, which are typically presented to support impact predictions in mining company proposals. We also review the monitoring reports on the impacts which subsequently occur. On this basis we feel well placed to offer the Panel reflections of current monitoring, modelling and reporting practices and how they could potentially be amended to improve the quality and accuracy of their predictions. Predictive modelling issues are discussed in this section, and monitoring and reporting are discussed in Sections 5 and 6 respectively.

4.1. WaterNSW's Approach to Predictive Modelling and Uncertainty

After firstly summarising the elements which are common to all of our recommendations on predictive modelling, more specific discussion is provided on subsidence modelling, surface water and groundwater modelling in the following sub-sections. It is worth noting here that prediction of ecological impacts is normally limited in current practice to extrapolations of water modelling predictions.

4.1.1. Issues with current predictive modelling approaches

One of the most important resources and, at the same time, sources of uncertainty in the assessment of underground mining effects is the application of complex numerical and analytical models to predict impacts from mining-induced subsidence. A particularly prevalent example of this is the use of groundwater models to predict both groundwater and surface water impacts and consequences from subsidence, and these are discussed in more detail under the relevant groupings below.

WaterNSW suggests that there are numerous deficiencies in the manner that predictive modelling is currently being used to support mining applications in NSW coalfields, in particular we are concerned about the following aspects of current numerical modelling practice:

- There is insufficient discussion with stakeholders at the outset to clarify precisely what the modelling should be aiming to do, i.e. modelling objectives are poorly specified. An important consequence of this is that the models are not providing optimal information to assist regulatory decision-makers (in our case DPE, L&W, DSC, DRG) to understand the level of risk associated with mine design and to inform other management decisions.

- The assumptions which are made when developing the models, such as what processes are most important to be modelled, how they are conceptualised, selection of appropriate parameter values, boundary conditions and numerous other aspects are not adequately disclosed or discussed in current modelling reports. Even more importantly, the suitability and applicability of the chosen model as the best tool for analysis in the circumstances needs to be considered and justified within the uncertainty analysis (see Sections 4.1.2 and 4.4.2 for further discussion).

- There is insufficient consideration on what type of modelling and what level of modelling complexity will best meet the objectives of the predictive analysis (Doherty and Moore, 2017). The more complex a model becomes (approximately correlated to the number of parameters used), the greater the uncertainty becomes. A particular issue with complex models is that they can be successfully solved (or calibrated) by any number of combinations of parameter values – one wrong value may produce a plausible answer by being "balanced" by another wrong value for a different parameter. In other words, most solutions are non-unique and may be arrived at using many combinations of conceptualisations and parameters, but this uncertainty is rarely acknowledged or adequately discussed in modelling reports.

- Although calibration of current groundwater models (for example) is apparently undertaken, the methods of calibration are variable (sometimes qualitative, sometimes automated) and poorly documented and disclosed.

- The questions of most importance to regulators or other decision makers are typically not the modeller's primary focus. Emeritus Professor John Doherty argues strongly that "In making the innumerable subjective decisions that the modelling process demands, a modeller's reference point must necessarily be avoidance of failure of the modelling exercise. This occurs if the risk of occurrence of an unwanted event is assessed to be lower than it actually is" (Doherty, 2015). By setting a numerical definition of prediction failure (which can later be translated into a concrete Performance Measure if the proposal is approved), the modelling can be made much stronger and clearer, and uncertainty can be better defined and articulated for decision-making purposes (Doherty & Simmons, 2013).

- Peer reviewing can certainly be helpful in improving the quality of a model report and in reducing the overall uncertainty associated with it. There are examples however, of models that have been peer-reviewed for example in accordance with the Australian Groundwater Modelling Guidelines (Barnett et al, 2012) but where more detailed critiquing has uncovered important gaps (Middlemiss, in prep regarding Hume Coal modelling) – discussed further in Section 4.4.2. Another frequent issue encountered by WaterNSW is that whilst an original modelling report may be peer-reviewed, subsequent revisions rarely are.

4.1.2. Reducing and Clarifying Predictive Uncertainty

As confirmed by a Literature Review commissioned on the topic (Advisian, 2016) and a recent workshop hosted by the BioRegional Assessments (Alluvium, 2017b), one of the defining characteristics of assessing mining-induced subsidence impacts on the Special Area catchments is predictive uncertainty. Another observation is that this uncertainty is only rarely and narrowly discussed when predictions are presented in proposals. WaterNSW suggests that there is considerable room for improving the quality of predictive assessments by articulating and, where possible, reducing uncertainties around effect/impact/consequence predictions.

One consequence of this high level of uncertainty in so many aspects of subsidence impact and consequence assessments is that there is a strong preference to use complex numerical models to attempt to predict key effects, impacts and consequences. With the exception of some aspects of subsidence predictions, the accuracy of these models remains poor, and greater conservatism should accordingly be used in making predictions based on them.

There are many specific sources of uncertainty in assessing how mining-induced subsidence will affect WaterNSW's nominated values in the Special Areas, principally comprising water volumes, water quality and ecological integrity. Key sources of uncertainty in relation to predicting impacts on catchments from undermining are discussed in the Literature Review (Advisian, 2016), and are summarised in the following subsections under the broad analysis groupings of subsidence, surface water and groundwater.

WaterNSW understands and accepts that uncertainty in predicting impacts and consequences from mining on overlying catchments is inevitable. It is misleading to report predicted impacts and consequences as a single value with any degree of confidence, particularly at higher panel width to height ratios and where steep topographical features are undermined.

In many cases it will be more realistic to make predictions in terms of probable ranges of values which might occur (e.g. as probability distributions), and to qualify these ranges by applying statistical measures of confidence or reliability. It is increasingly common and desirable for uncertainties to be accounted for by adopting a probabilistic approach to predictive modelling, in which a likelihood is assigned to less certain subsidence parameters such as strain, valley closure and upsidence.

Whilst it is WaterNSW's clear preference that the maximum possible level of accuracy and certainty is achieved, it is important that the true level of uncertainty be transparently reported within proposals where predictions of uncertain behavior are being made. Parameter accuracy for example, i.e. the inferred accuracy of key prediction parameters such as the depth of surface cracking or horizontal and vertical surface strains, need to be clearly articulated with the prediction.

4.1.3. Recommended improvements in overall modelling approach

WaterNSW recommends the following general improvements in how predictive modelling is performed for the purposes of supporting future mining applications. More subject-specific recommendations are provided under the headings of subsidence, surface water and groundwater in Sections 4.2.3, 4.3.1.4 and 4.4.4 respectively.

- Prior to commencing the analysis, discuss with WaterNSW (and other key stakeholders if appropriate), the proposed impact prediction approach, conceptual understanding of the main processes influencing impacts, how complex does the modelling need to be and what numerical or analytical model(s) are to be used after consideration of all sensible alternatives (Ferre', 2017).

- Start the assessment by defining, in consultation with WaterNSW and other key stakeholders, the potential prediction or development "failures" on which to focus the analysis. In the case of mining proposals submitted within the Special Areas, the key question for surface water prediction analysis from WaterNSW's perspective will be how much water will be diverted out of the harvested catchments and for what duration? For a proposal to undermine a perennial creek or a reservoir within the Special Areas for example, a key prediction failure would be to incorrectly predict that surface water "loss" from that feature will not result in more than a specified rate of leakage or exceed an adopted threshold.

- The next step in the analysis should be consideration of how each potentially consequential prediction failure (i.e. a "False Positive" error where a specified volume of water loss is not predicted but subsequently does occur) will be avoided to an acceptable (e.g. 95%) degree of certainty.

- Make modelling only as complex as is necessary, only proceeding to greater complexity if analysis confirms that it will reduce uncertainty. In some cases, this will mean an iterative approach to check whether uncertainty is reduced by increasing the number of parameters, and in some cases may be achieved by using simpler sub-models or other analysis to check or inform critical components of the larger models.

- Present all relevant parameter values, metadata and key layers to reveal model conceptualisation for all models. A list of suggested data and layers to be exported for rapid importation into visualisation software is provided in Appendix C and discussed further in Section 4.4.4.

- Present uncertainties objectively and transparently, including conceptualisations, parameterisations and assumptions. Use stochastic approaches to parameter estimation and sensitivity analysis wherever it is appropriate to do so. In some cases, this quantification of uncertainty might be performed by comparison of the modelled results with those derived from separate (or ensemble) numerical, analytical or statistical approaches (Ferre', 2017).

- Use the model(s) iteratively to inform future investigations and monitoring, identifying data with maximum "worth" that will fill gaps most effectively (Kikuchi, 2017).

4.2. Subsidence Modelling

4.2.1. Uncertainty in subsidence analysis

The causal relationships between the subsidence effects of underground coal extraction, particularly differential superincumbent rock movements and consequent rock deformation and cracking, and environmental consequences such as diversion of surface water and drying swamps and creeks are conceptually understood but not well quantified. Key elements of current subsidence engineering knowledge and information gaps are described in some detail in our Literature Review (Advisian, 2016). Like many aspects of earth science, only some elements of subsidence can be directly measured using surface measurements and relatively sparse borehole-mounted instruments. Numerous theories have been suggested for how overlying formations respond to having several metres of rock removed at depth (Galvin, 2016a), but due to the difficulties of measurement and the ambiguities of interpreting them, the actual distribution of subsidence-induced deformation and fracturing of superincumbent strata remain highly uncertain.

The difficulties in interpreting subsurface responses to undermining are well shown by attempts over the past decade to predict the height of connective fracturing (HoF) over mined longwalls. The background to this body of work is described in the Literature Review (Advisian, 2016). In summary, numerous theories and analytical techniques have been developed in an effort to predict the height above a mined longwall where connective (at least partly vertical) cracking will effectively cease. This parameter is a key input into hydrogeological models as it is inferred that groundwater below this height will drain relatively rapidly (termed desaturation). Uncertainties around the HoF parameter are currently great, including the question of whether the zonation of fracturing implied by the current theories exists in reality and whether the circumstances and extent to which groundwater within the strata above the HoF will become depressurised and/or desaturated towards the goaf. A major review of the HoF theory and evidence at the Dendrobium Mine was recently completed (PSM 2017, discussed in Section 2.1) which indicates that fracturing is more extensive and less obviously zoned than expected and that neither of the two leading methods for predicting HoF can be relied upon (Galvin, 2016b).

4.2.2. Current practice

The current methods of predicting subsidence effects are described in the Literature Review (Advisian, 2016) and briefly discussed below.

Subsidence prediction methods include physical, graphical, analytical and numerical modelling techniques, but in current Australian practice empirically-based estimates, using back-analysis of large databases of subsidence measurements to deduce likely subsidence behaviors for specific longwall and depth dimensions in various Australian coalfields, have become dominant. The fact that these databases are effectively owned by consulting companies and are considered proprietary and thus non-interrogable makes it difficult for WaterNSW and other authorities to scrutinise these analyses.

Some aspects of subsidence, such as vertical displacement due to "conventional" subsidence mechanisms, can be predicted with a relatively high degree of confidence due to the large body of evidence and monitoring which has been applied to its measurement and prediction (Galvin, 2016). Other aspects, particularly surface strains, "unconventional" subsidence movements and most physical and environmental consequences of subsidence can currently only be predicted with relatively low degrees of confidence.

The empirical approach is much more certain where local precedents exist and less certain where different mine geometries are applied or in a new mining area. An example recently arose in the application for the LW14-18 SMP in Dendrobium Area 3B, where the proponent revealed that subsidence predictions had increased by as much as 30% to 40% from that predicted previously (MSEC, 2015), due at least in part to the lack of empirical data on mining with the unusually high mining width to depth ratios employed in this mine.

A recent advance implemented at Dendrobium Mine is the use of down-hole Time Domain Reflectometry (TDR) tools to monitor ground movements at depth (e.g. Hgeo, 2018). A significant advantage of this technique is that the test hole does not have to be left open, unlike the use of extensometers, and so there is little risk of cross-contamination or "unnatural" flow volumes between aquifers along the drill-hole.

4.2.3. WaterNSW recommendations for improvement

The 30-40% correction made by Dendrobium Mine's subsidence consultants of vertical subsidence magnitude predictions for Longwalls 14-18 (MSEC, 2015) and the currently unexplained drying of much of Eastern Tributary, despite measured subsidence movements for Metropolitan Mine longwalls being consistent with predictions, provides little reassurance to WaterNSW that subsidence engineering science is adequate to enable predictions to be accurately made. Until the knowledge advances to a point where practitioners can reliably and accurately predict the physical and environmental consequences of subsidence from longwalls of specific dimensions and circumstances, WaterNSW believes that a much more precautionary approach should be taken to longwall mining in the Special Areas than is the current practice.

WaterNSW does not profess to be expert in subsidence engineering, but we do support the following recommendations made by Dr Mackie (2017):

Geomechanical modelling incorporating fluid flow in three dimensions with sub-metre discretisation of the physical domain, supported by field and laboratory measurements of rock properties and flow through fractures, is likely to provide a pathway to (stochastically) predict the distribution of connective cracking with reasonable certainty.

Our general observation is that the reliance by current practice towards a purely empirical approach to subsidence prediction appears non-conservative. In a recent paper (Heritage, 2017), consultants SCT noted the inherent value in also using numerical modelling of rock failure to simulate and validate predictions particularly where mining is being extended beyond the limits of empirical databases.

On the basis of the above, WaterNSW's recommendation is that all future geotechnical assessments for mining proposals at least in the Special Areas are undertaken using a combination of methods and that they should be independently peer-reviewed in a manner similar to that currently being undertaken on the Hume Coal mining proposal.

4.3. Surface Water Impact Prediction Modelling

Despite the profound importance of understanding surface water resources in the Special Areas and accurately predicting impacts on these resources likely to occur due to undermining, uncertainties associated with surface water modelling of longwall mining proposals remain unacceptably high in WaterNSW's view. This uncertainty is experienced both in predicting volumetric losses and changes in water quality.

4.3.1. Current practice for surface water modelling

4.3.1.1 Volumetric flow analysis

There are a range of tools which may be used to analyse catchment surface water volume dynamics for various purposes, including water balance models, lumped-parameter rainfall-runoff models (e.g. AWBM), distributed-parameter rainfall-runoff models (e.g. MIKE-SHE) and groundwater flow models (e.g. ModFlow).

The Australian Water Balance Model (AWBM), a lumped-parameter rainfall-runoff model developed by the Cooperative Research Centre for Catchment Hydrology, is used both at Dendrobium and Metropolitan Mines to analyse impacts to undermined streams by comparing flows predicted by AWBM modelling to those recorded at stream gauges. However, these models have not been developed for the purpose of aggregating catchment losses and it is not clear to WaterNSW whether they could be amalgamated and adapted for the purpose of predicting catchment flow losses.

What is used instead to predict catchment losses by the two mining companies for the purpose of licensing by Lands and Water, as required by the *Water Management Act 2000*, is ModFlow, a groundwater flow model. WaterNSW considers this tool inappropriate for this purpose, as the regional groundwater flow models separately developed by the same consultants (HydroSimulations P/L) for the two mines are highly insensitive to recharge dynamics. It is notable in this regard that the founder of HydroSimulations, Dr Noel Merrick recently stated in a conference paper (Merrick, 2017) that the prediction of subsidence-induced surface water losses by ModFlow models "remains aspirational". Based on this paper, WaterNSW's experience and the findings of the HoCR (PSM, 2017 and Mackie, 2017), the predictions of surface flow loss using ModFlow models are not considered credible or conservative.

4.3.1.2 Water quality impact prediction and analysis

Predictions of water quality impacts are currently provided purely as qualitative statements generally indicating that water quality in streams down-gradient of subsided areas is likely to be variably affected by iron staining and precipitates (iron floc), but that the impacts will be localised and won't affect reservoir water quality.

WaterNSW has been examining the impacts of subsidence on water quality since the Waratah Rivulet river bed was extensively fractured following undermining by Metropolitan Mine Longwalls around 2003. Despite the obvious oxidation and mobilisation of large quantities of iron, manganese, aluminum, salts and possibly other compounds due to exposure of freshly cracked rock to diverted surface waters, the measurable downstream water quality impacts have generally been subdued. There are inevitably aquatic ecology impacts in the zone immediately below the cracking where large volumes of iron floc accumulates and radically alters the physico-chemical conditions by reducing oxygen and light, but the extent and severity of these impacts have not been well quantified to date.

Predictions of water quality impacts are currently provided purely as qualitative statements generally indicating that water quality in streams down-gradient of subsided areas is likely to be variably affected by iron staining and precipitates (iron floc), but that the impacts will be localised and won't affect reservoir water quality.

Water quality monitoring in the reservoirs downstream from the impacted zones has not to date confirmed appreciable changes attributable to mining. A disturbing trend has been noted by WaterNSW in broadly comparing iron concentrations in Cataract and Cordeaux Reservoirs (the two dams where active destratification is not practised) over time as shown in Figure 4-1. This data presented is raw and has not been corrected for in-lake physico-chemical processes such as seasonal deoxygenation rates. The Cataract Reservoir has been extensively undermined in the past and at least some of this mining has caused subsidence. It is by no means clear however, whether there is a causative correlation to subsidence between the increasing iron concentrations in Cataract Reservoir relative to the Cordeaux Reservoir.

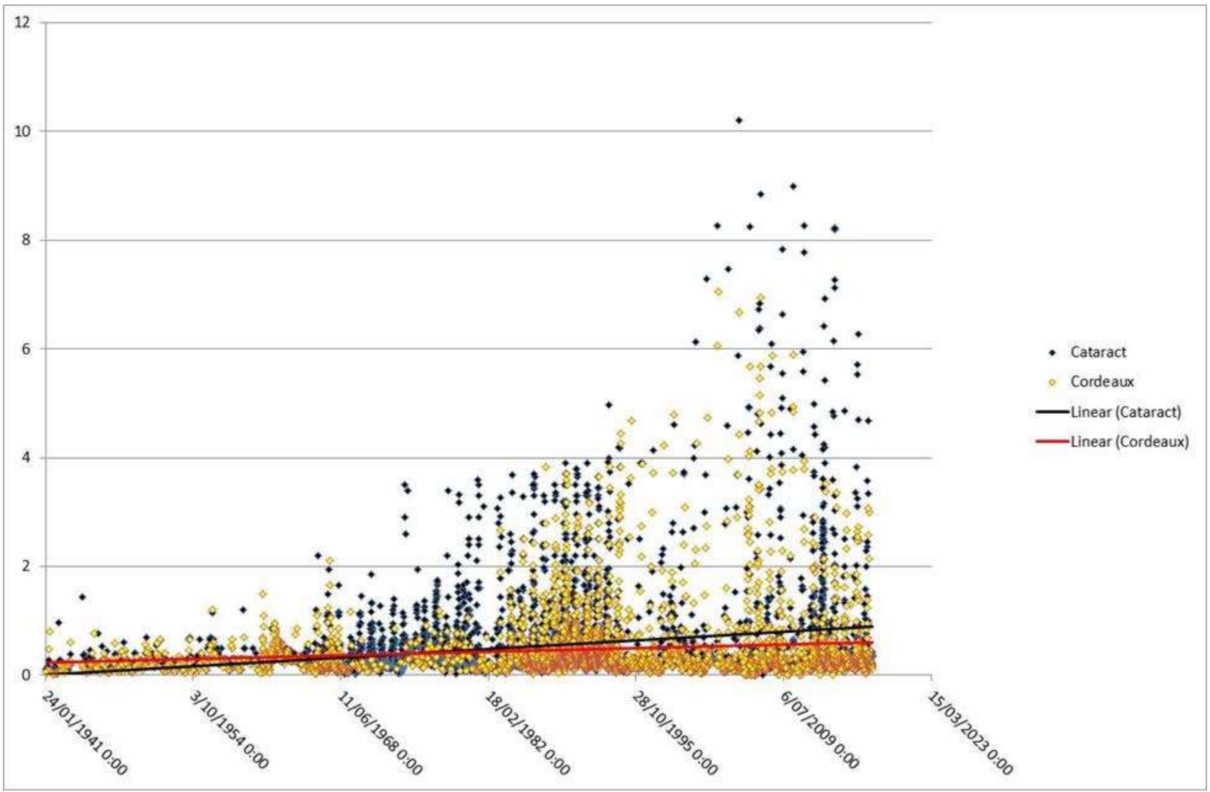

Figure 4-1. Measured iron concentrations in Cataract and Cordeaux Reservoirs

An issue which particularly concerns WaterNSW is that it is anticipated that any additional increases in iron, manganese and possibly aluminum and other species dissolved from undermined catchments will impact on raw water quality delivered to Sydney Water and other customers. WaterNSW applies artificial destratification in most of these storages to manage water quality during summer months. The deep water columns of most reservoirs will seasonally stratify, developing anoxic conditions at depth particularly during summer months. Under anoxic conditions, redox reactions at the sediment-water interface will result in release of iron and manganese from sediments into the water column. These waters with their elevated concentrations of iron and manganese may be brought to the surface during seasonal overturn or mixing induced by strong storms or strong river discharges. Destratification is therefore implemented by WaterNSW in most of the Special Area reservoirs to enable withdrawal of water from medium depths at good quality, avoiding spiky concentrations at "winter overturn" of the water column.

An unintended outcome of this intervention is that metals transported to reservoirs in particulate and/or dissolved forms are more likely to be precipitated and build up in the lake sediments over time. For this reason, WaterNSW considers it important that any assessment of water quality impacts in reservoirs should be performed using a "load-based", rather than dissolved concentration, approach.

4.3.1.3 Uncertainties and issues in surface water volumetric analysis

Besides the use of inappropriate modelling tools currently being applied in the Southern Coalfields, WaterNSW understands that there are inherent uncertainties arising from the dynamic nature and complexity of the catchments within the Special Areas which result in variable catchment hydrology and hydrogeology. Uncertainties arising from complexity of the catchments and their interaction with weather patterns include:

- Topography varies from incised plateaus to steep valley and ridge patterns in the areas being undermined.

- Average rainfall varies remarkably within the Special Areas, from 1,500 mm/annum along the escarpment to 900 mm/annum near the western edge of the Metropolitan Special Area, and has been found to vary substantially from one valley to another due to rain-shadows and similar effects.

- The proportions of rainfall that are diverted into evaporation, transpiration, rapid runoff and baseflow, and infiltrate into superficial and regional groundwater depend on multiple factors such as topography, rainfall distributions in the various valleys, lithology and structural geology, soil depths, canopy cover and vegetation types, antecedent rainfall, stream densities and the presence of swamps and soil storage reservoirs.

- Although some hydrological aspects (e.g. streamflow and rainfall) of the Special Areas are routinely monitored by both WaterNSW and mining companies, a high level of uncertainty is associated with many hydrological characteristics of these catchments, particularly evapotranspiration rates, groundwater interactions with surface flow and baseflow contributions from swamp substrate storages. These parameters are not routinely monitored and some cannot be directly measured.

- There are different hydrogeological regimes within upland swamps across the Special Areas, which are variably sustained by multiple water sources including overland streamflow, rainfall and by perched superficial aquifers, while some wetter swamps also have a regional groundwater contribution. There is also spatial variability associated with rainfall recharge to regional aquifers as indicated above. This variability creates uncertainty which is exacerbated by a lack of long term and targeted groundwater monitoring.

- There is no accurate understanding of the changes in run-off coefficients, and conversely on groundwater recharge rates, across the broad landscape (i.e. except in valley axes) due to subsidence. Some sense of the likely surface water diversion rates can be gained by measuring superficial valley-side swamp sediment water tables, but the losses in overland flow cannot be reliably estimated.

4.3.1.4 WaterNSW recommendations for improvement

The use of limited or inappropriate modelling methods and difficulties in measuring and understanding catchment processes have to date confounded all attempts by WaterNSW to make reliable predictions of project and cumulative surface water losses. Nevertheless, the large volumes of data and ever-improving methods of analysing them provide a good basis for unravelling the complexity and understanding what volumes of water are being permanently diverted from the catchments, and we look forward to working with the Panel and the mining industry to identifying an agreed methodology for doing this.

The general recommendations provided in Section 4.1.3 are particularly relevant to the predictive analysis of volumetric surface water impacts due to subsidence-induced mining. More specific recommendations are provided as follows:

- The choice of modelling tool for predicting surface water quality impacts needs to be critically re-examined. WaterNSW considers the use of groundwater flow models for this purpose inappropriate. More appropriate options include water balance analysis and lumped parameter rainfall-runoff models.
- Distributed parameter rainfall-runoff models should also be considered for impact prediction and detection and could potentially be more directly linked to regional groundwater models. The effort required to set up and run such models would however require a significant step-change in the resources currently applied to surface water analysis, and should probably only be considered if trials of the above options are not considered successful.
- A methodology for measuring or estimating broad-catchment diversion of overland flows needs to be developed. This may include analysis of shallow bedrock water-table analysis to see how recharge dynamics in mined and unmined differ, direct measurement of groundwater or moisture levels above the soil-water interface.

4.4. Predictive Groundwater Modelling

Groundwater in the superficial and regional aquifers forms an important component of the overall water balance for surface catchments across the Special Areas. Groundwater sustains baseflows to streams, and on a local scale supports (or partially supports) a variety of ecosystems, including some upland swamps. In the future it is possible that groundwater from within or around the Special Areas could be harvested for water supplies (e.g. the Kangaloon Borefield), but WaterNSW's priority currently remains on harvesting and protecting surface water resources.

From a WaterNSW perspective, the baseflow contributions to streams from regional groundwater and superficial aquifers (particularly evident following surface runoff events) are important as they are vulnerable to diversion through mine-induced cracking and are seen as an important flow component during droughts. A proportion of quickflow following high rainfall events will also be diverted where cracking and reduced regional groundwater levels are caused by subsidence, as demonstrated by Mackie (2017). Enhanced groundwater recharge to regional aquifers is an inevitable consequence, but whether the diverted surface waters report to the coal seam and/or are detected in mine inflows will vary.

In summary, accurate predictions about how subsidence will affect groundwater levels and, to a lesser extent groundwater quality, in the short and long term are of great importance to WaterNSW.

4.4.1. Current practice in groundwater flow modelling

Although there are other approaches available, current practice in NSW coalfields is invariably to develop numerical groundwater flow models based on either MODFLOW or FEFLOW modelling software. Whilst the underlying code for MODFLOW was developed as "freeware" by the United States Geological Survey (USGS), mining company local and regional groundwater models are generally built within proprietary versions such as Groundwater Vistas, and thus cannot be readily accessed by regulators even if their developers were willing to submit them for scrutiny.

4.4.2. Issues with current groundwater modelling practices

In general, WaterNSW considers that groundwater flow models being used in the Southern Coalfields are suitable for the purpose of estimating drawdown and inflows associated with underground mining, and that much of the reporting is consistent with the Australian Groundwater Modelling Guidelines (Barnett et al, 2012). However, there remains many examples where this modelling has produced spurious or dubious results, generally arising from selective and poorly justified model conceptualisation and parameterisation and a lack of clarity or completeness in reporting results. More specifically:

- Most modelling reports do not provide comprehensive analysis of available monitoring data – current end-of-panel and annual review reports for example provide analysis and commentary on a limited number of piezometers, and no data or discussion is provided on others which may be relevant. In both of the active mines in the Special Areas, water impact analysis focusses only on current mining domains and little or no analysis is provided on groundwater trends in past domains or adjacent historical mines that may be inferred from modelling or long-term monitoring.

- There are disparities between conclusions and interpretations of monitoring data presented by modelling teams engaged by the mining companies and those produced by independent experts or other consultants/investigators (e.g. height of fracturing interpretations above LWs 8-9 at Elouera by Dr Mills; Dendrobium mine inflows assessment by Dr Mackie; PSM conclusions on Dendrobium Area3B connective fracturing).

- There have been a number of cases where modelling techniques have changed without advising stakeholders or providing analysis as to how these changes may have affected the modelling results, other than a presumption of improvement (Mackie, 2016). There was a case in 2014/2015 where the modelling report on which the Dendrobium Mine Area 3B SMP application was based was subsequently replaced without any discussion with WaterNSW. History has shown that in fact the earlier modelling by Coffeys (2012) which predicted surface-to-seam connectivity, appears to have been more appropriate than the subsequent modelling by HydroSimulations (2014).

- Major limitations of the groundwater models are not adequately disclosed or discussed e.g. use of groundwater models for prediction of surface water impacts, availability of monitoring data (e.g. the lack of concern in HydroSimulations [2015] regarding the lack of over-goaf deformation and depressurisation data on which to assess Height of Fracturing), and assumptions about aquifer heterogeneity in which one calibrated value of hydraulic conductivity and porosity is typically used to model each stratigraphic formation.

- Most groundwater modelling reports have limited or no information on uncertainties which have arisen during the development of the groundwater model. What for example are the major issues and challenges in applying modelling tools designed for assessment of groundwater flow in porous aquifers to fractured rock environments that are highly disturbed/modified by mining subsidence? These issues are not generally discussed in modelling reports, which makes it difficult for non-modelling reviewers to gauge the associated uncertainties.

- Over the past decade considerable efforts have been made by the mining companies and researchers to investigate the provenance of mine inflows using geochemical analysis, initially using algae as a tracer for surface waters and more recently using tritium concentrations and ionic balances. The results of these analyses, particularly at Dendrobium Mine, have been consistently at odds with hydrological analyses using correlations between rainfall patterns and mine inflows (Coffeys, 2012; Ziegler and Middleton, 2011). WaterNSW considers that the correlation between rainfall and inflows, such as the analysis performed by Dr Mackie to estimate surface water losses over Dendrobium Mine (Mackie, 2016) is a much more direct and credible method of identifying surface water contributions to mine inflows.

- A separate issue which constrains WaterNSW attempts to scrutinise groundwater flow models in particular arises from the models being generally provided only in a report format (discussed further in Section 4.1.1). Even if the models themselves were provided, the simulations are not readily understood without the full model, their supporting software and a detailed background in how the model has been constructed.

  As noted in Section 3.3.1, one of the recommendations made by the NSW Chief Scientist & Engineer (OCSE, 2014) was that Government should encourage the use of data visualisation tools for examining three-dimensional representations of the Catchment. WaterNSW understands the power of visualisation in developing and examining complex models and strongly supports this recommendation. To assist in such an examination in the future, WaterNSW is compiling a database of environmental and mining impact information, which will include geographical metadata as much as possible.

  WaterNSW is aware that the Australian National Information Communications Technology Research Centre of Excellence (NICTA, now merged with CSIRO to form Data61) has developed a tool in cooperation with the Australian Department of the Environment and Land and Water (LaW) and the Office of the Chief Scientist and Engineer (OCSE) specifically for visualising groundwater situations. WaterNSW is enthusiastic about how this tool could be used in the Special Areas catchments to improve understanding of the way that groundwater responds to longwall mining effects.

4.4.3. Uncertainties in groundwater modelling

A primary source of uncertainty in groundwater impact predictions is the nature and heterogeneity of the rock formations overlying the coal seams. Although the sub-horizontally bedded strata of the Sydney Basin have been extensively investigated by government authorities and mining companies within their exploration and mining tenements, rock formations are formed through complex natural processes and are inherently heterogeneous at various scales.

In intact formations, the heterogeneity of hydrogeological flow fields is largely controlled by the amount and orientation of fine-grained materials within bedding planes which greatly affect horizontal permeability rates, and fractures/faults and other discontinuities in the rock, which largely control vertical permeability. The most fundamental change and ensuing uncertainty regarding the hydrogeological regime in the Special Areas is how much it is modified by subsidence-induced fracturing following undermining. As discussed in Section 2.2, the distribution and orientation of subsidence-induced fracturing is not currently well understood and can't be accurately predicted. In any case, currently used flow models only approximate the fracturing by adjusting the simulated bulk permeability values in each strata grouping.

4.4.4. WaterNSW recommendations for improvement

The general recommendations provided in Section 4.1.3 are particularly relevant to the predictive analysis of volumetric groundwater impacts due to subsidence-induced mining. WaterNSW offers the following additional recommendations:

- WaterNSW recommends that all groundwater models which are prepared to simulate mining consequences in the Special Areas should be required to routinely provide a set of export data and metadata files which can be imported into visualisation software for examination by WaterNSW and other interested stakeholders. The data, export files recommended by WaterNSW for this purpose are provided for the Panel's information as Appendix C (formatting requirements developed by NICTA are also available). The potential value of this information imported into the Groundwater Visualisation Tool is profound, as it would enable WaterNSW, regulators and other stakeholders to rapidly understand key conceptualisations and outputs from the model, including how simulated groundwater recharge, storativity and permeability varies in relation to subsidence effects.

- At this time it appears that geochemical analysis tools are not able to provide accurate or reliable estimates of the contributions of surface water to mine inflows. An independent review into the evidence base, such as was performed by PSM into the height of fracturing (PSM, 2016), may be required to resolve the conflicting lines of evidence. In the meantime, geochemical analysis is considered less reliable than hydrological analysis for this purpose.

WaterNSW further recommends that greater efforts need to be made by modelling experts to provide comprehensive disclosure and/or discussion of the following:

- All piezometer data that is being collected should be reported. Where important trends are discerned, even if they may relate to previous mining, these should be specifically discussed.

- All uncertainties should be clearly presented, including in conceptualisations, choice of model elements, boundary conditions and parameter values. Functionality and calibration of the model should be critically discussed, including whether the model runs reached resolution.

Given the disparities between the results from mining-engaged consultants and independently engaged experts, consideration should be given to alternative models of assessment such as engagement of consultants by regulators at proponent expense. This would particularly apply to periodical audits of compliance with regulatory requirements (currently required in the two active mines in the Special Areas every three years), but should also be considered for annual environmental or end-of-panel reports.

5. IMPROVEMENTS IN MONITORING PRACTICES

WaterNSW's view on current monitoring of mining activities in the Special Areas is that it has improved greatly over the past decade, but that there is a great deal of room for improvement.

Before focusing on monitoring for specific purposes, WaterNSW offers the following general comments and recommendations:

- A key issue which has frequently made it difficult to confirm the magnitude or even existence of mining impacts has been the lack of baseline monitoring. Although it has been recommended in numerous government guidelines, it has been quite rare for there to have been two years of adequate baseline monitoring. The situation is improving however, and we acknowledge that Dendrobium Mine's monitoring system for its proposed domains Areas 5 and 6 are being designed and installed early and with WaterNSW input. As noted in Section 3.3.6, even two years of baseline monitoring won't adequately represent the full seasonal and inter-seasonal range of conditions.

- At least as importantly, monitoring programs are typically ceased prior to establishment of new, post-mining equilibrium in water regimes are established. A particular issue in this regard is the use of vibrating wire piezometers (VWPs), which typically have a maximum service lifetime of no more than 15 years. Once they become inoperational, it is no longer possible to verify subsequent groundwater conditions as the holes are fully grouted. WaterNSW is not aware of any set of longwalls in the Special Areas where post-mining equilibrium conditions have been established and confirmed through adequate surface water and groundwater monitoring.

- WaterNSW recommends that DPE not accept lodgment of an application for planning approval to mine in the Special Areas unless there is, or foreseeably will be, a minimum of two years baseline monitoring prior to mining, and preferably prior to EIS or post-approval assessment. We further recommend that approval conditions should spell out an agreed level of post-mining monitoring which must be continued until new equilibrium conditions have been established and ongoing surface water losses and groundwater level reductions have been adequately accounted for and licensed. If necessary, instruments will need to be replaced until these conditions have been confirmed.

5.1. Subsidence Monitoring

5.1.1. Current practice for subsidence monitoring

Most surface monitoring of subsidence over and around mines in the Special Areas is being undertaken by a combination of:

- GPS monitoring

- Point-to-point transect monitoring along ridges and across valleys and swamps

Dendrobium Mine has also been using airborne Laser Detection and Ranging (LiDAR) remote sensing to better map the three-dimensional nature of subsidence movements in rugged terrain before and after completion of each of the Area 3B longwalls, and Metropolitan Mine has similarly started to use this technology.

There is also limited application of in-hole extensometers to measure strains below the surface, which are particularly helpful in elucidating the height of extensive movement at depth (although extensometers are unable to resolve whether it is primarily vertical or horizontal movement). These extensometer results are infrequently (virtually never) reported to WaterNSW and it is not clear whether they are being routinely undertaken without reporting. A particular issue in this regard was noted in the HoCR (PSM, 2016), where extensometer results quoted by Illawarra Coal's consultants (Parsons Brinckerhoff) was unable to be made available to PSM despite repeated requests. This issue has never been satisfactorily resolved or explained to WaterNSW's knowledge.

It appears that Time Domain Reflectometry (TDR) may replace the use of extensometers. As well as being more accurate about the location where deformation occurs (based on limited applications to date in the Special Areas, e.g. Hgeo, 2018), TDR instruments can be grouted into the hole and therefore do not leave a pathway for rapid water exchanges between aquifers.

5.1.2. Perceived issues

An important source of uncertainty when assessing mining impacts is the coverage and measurement accuracy of subsidence effects and the ensuing impacts and environmental consequences on the values of particular concern to WaterNSW. Many of these phenomena occur sub-surface in difficult terrain, where measurement is invariably limited by spatial and access issues.

Like piezometers, it is generally easier to install in-hole extensometers beneath ridges than beneath valleys and swamps due to rig access issues. Piezometers and geotechnical monitoring is also often preferentially installed in strata locations between longwall panels rather than directly over them, as those directly over longwalls may be destroyed by rock movements which occur soon after extraction. The information from directly over longwalls is much more valuable for impact prediction assessment, but it is more difficult and expensive to obtain.

Even on the surface the understanding of subsidence effects has been limited by measurement methods. For many years subsidence engineers believed that significant surface movements were largely restricted to the vertical dimension. Valley closure and similar horizontal movements were not detected because of limitations in surveying technologies and their environmental consequences were not recognised until the early 1990s (Galvin, 2016). It is possible that similar step-changes in the conceptual understanding of subsidence may be made through, for example, the application of aerial or satellite imagery such as differential radar interferometry (DinSAR) to more accurately measure how subsidence bowls interact with steep topography, but these technologies are not yet widely employed by the mining industry.

A final issue of concern to WaterNSW is the duration of subsidence monitoring. A paper prepared by DSC (Ziegler and Middleton, 2014) noted that significant residual subsidence appeared to have occurred around Cataract Reservoir 25 years after mining ceased, although it is noted that some or all of this may have been related to subsequent pillar extraction in the area. One economical means of investigating this aspect might be to acquire DinSAR imagery over current and historical mines and identify when movements effectively cease. A recent paper from China (Du and Peng, 2016) alternatively suggests that repeated seismic monitoring has value in confirming the extents of subsidence and underground deformation over time.

5.1.3. WaterNSW recommendations for improvement

WaterNSW considers that the most urgent requirement is for detailed studies and ongoing monitoring to be completed directly over completed longwalls to better calibrate fracturing and depressurisation models. The aim of these investigations should be to inform an analytical framework or modelling approach which will enable subsidence impacts and consequences on catchments and groundwater to be predicted with a high degree of accuracy.

We would also encourage the following innovations to be trialed and, if successful in informing the above objective, routinely deployed:

- DinSAR imagery to holistically observe how subsidence bowls develop in the various steep and flat terrains in the Special Areas. Note that SAR imagery has already been collected over the more recent mining domains, so these investigations can readily compare differential movements before and after mining.
- Down-hole TDR imagery to monitor ground deformation over and around goafs.

- Down-hole micro-seismic testing to better delineate the extent and magnitude of cracking in various mining domains.
- Repeated surface seismic (and possibly electrical geophysics?) testing before, during and after mining, again to better delineate extent and magnitude of rock deformation and cracking and possibly changes in hydrogeological conditions.
- Repetition of ground surveys or remote sensing five and ten years after mining is completed to confirm whether there has been any subsequent pillar degradation or other settlement. If such changes are found, periodic surveys need to be repeated until full subsidence stabilisation is confirmed.
- Whilst not strictly a subsidence monitoring technique, WaterNSW wishes to also highlight the profound importance of identifying and understanding structural weaknesses in the ground, such as faults, shear planes at the base of valleys and dominant foliations. It remains an open question for example whether the extreme groundwater level reductions observed beneath WC21 (over Dendrobium 3B longwalls) may be in some way related to structural weakness along the strong lineament which WC21 partially comprises.

5.2. Surface Water Monitoring

5.2.1. Options and current practice for surface water monitoring

In terms of quantifying volumetric changes in surface water, the two primary techniques used in the Special Areas is measurement of pool water levels supported by photographic surveying before and after mining and flow gauging in streams.

Water quality measurement programs are quite varied between the three companies with current operations in the Special Areas, but essentially comprises field parameter testing and collection of samples for laboratory analysis at regular (ranging from weekly to six-monthly) intervals.

Aquatic ecology monitoring is less common amongst the three companies. Where it is undertaken, the approach varies widely between companies, including visual aquatic habitat assessments and surveys of macroinvertebrates and aquatic macrophytes. Some companies also conduct fish and amphibian monitoring – IC for example is currently undertaking a study on the distribution of Giant Dragonflies and Red-Crowned Toadlets in swamps and streams over Dendrobium Mine.

5.2.2. Perceived issues

Current issues with the various monitoring techniques are tabulated below:

Flow gauging	Current flow gauging is being completed primarily by measuring the water level in the pool above a natural rock weir, and developing a gauging curve relationship by measuring flows over the weir on a number of occasions. The following issues with current practice and coverage are as follows: ▪ The accuracy of these gauging techniques is often poor, particularly at high and low flow regimes. The low accuracy is primarily due to the variable manner in which increasing water levels flow over a naturally uneven profile, and in some cases also due to the accuracy of the water level measurement using pressure transducers which are not suited to this particular use. ▪ A common problem has been the lack of suitable sites for gauging in some creeks, such as Wongawilli Creek where the nearest gauging station downstream of the Dendrobium Mine is over two kilometres below the mined area and therefore highly insensitive to detecting mining impacts.

	- WaterNSW considers that it is important to understand the contribution of baseflow to a stream as this affects its significance to supporting catchment yields. We believe that the gaining/losing conditions of all significant streams should be able to be inferred using flow analysis and/or nearby groundwater measurement. - **Flow** gauging is not generally performed at swamp discharge points. The lack of discharge data is preventing water balance analysis of the amount of water which flows from impacted swamps.
Pond level measurement	Pond levels are currently being monitored in a number of pools primarily by means of pressure transducers measuring levels at hourly or longer periods. Three primary issues with pond level measurements are that: - They are not being undertaken in all significant ponds, leading to the current situation in the Eastern Tributary where dry pools may not constitute a TARP trigger exceedance only because they are not being measured. - In general, flow over the downstream (controlling) rockbar of monitored ponds has not been measured, greatly reducing the value of the pond height data. - Subsidence may cause the absolute or the cease-to-flow levels to vary without this necessarily being reported. - In some cases the measurements are being made using pressure transducers which are not sufficiently accurate for this particular use.
Water quality measurements	WaterNSW observes the following issues with water quality testing for the purposes of detecting and measuring mining impacts on streams: - Catchment water quality monitoring programs implemented by operating mining companies in Special Areas differ markedly on spatial and temporal scales, as well as in terms of selection of laboratory analytes. - Implementation of TARPs and selection of water quality triggers for assessment of water quality impacts varies between mining companies. For example, the Metropolitan Colliery uses TARP triggers for dissolved iron and manganese but the Dendrobium Colliery has established triggers based only on field parameters including pH, EC and redox. The underlying logic of these TARP triggers and associated monitoring needs to be clarified and reconsidered. - Assessment of post mining change/impact requires understanding of pre-mining conditions. Often, there is a lack of baseline monitoring or the nearby catchment selected as a reference site may not have the same characteristics. This latter situation has been a particular issue at Metropolitan Mine in the Woronora Reservoir inflow streams. - One of the most visible water quality impacts in undermined streams are orange iron precipitates floating in pools or forming coatings on bedrock and stream bed. Even though a significant portion of metals transported by streams to storages occur in the particulate form, not all routine water quality monitoring for assessment of mining impacts include testing for total metals (using unfiltered samples). - Metal discharges from mining-affected catchments generally increases with increasing flow. As the catchments are closed after rainfall events of greater than 20 mm in a day, water quality is not monitored during periods when the highest discharges are likely to be occurring. - All approvals of mining in Special Areas include a condition of negligible impacts on reservoir water quality. However, there has been no advice on suitable methodology or any guidance how this assessment should be conducted.
Aquatic ecology surveying	WaterNSW note the following current issues: - Some companies employ only qualitative macroinvertebrate sampling techniques (AusRivAS sampling). Qualitative sampling lacks the sensitivity to accurately detect mining impacts, as noted in a recent thesis by Catherine Cunningham (2017).

	▪ Where these studies are quantitative, macroinvertebrate samples are normally identified only to family level. This is an insufficient level of taxonomic resolution to detect mining impacts, particularly for the EPT taxa (Ephemeroptera, Plecoptera and Trichoptera families), which are considered indicators of stream biological health due to their sensitivity to pollution. ▪ Macroinvertebrate sampling does not always include surveys of riffle habitats, which would be the most appropriate habitat type to detect ecological impacts related to changes in river discharge. ▪ Some of the response metrics used to report macroinvertebrate data are not well suited to detection of mining impacts and do not allow for an adequate comparison of control and impact locations.

5.2.3. WaterNSW recommendations for improvement

WaterNSW makes the following recommendations for improving surface water flow and quality monitoring:

- Install and gauge constructed weirs in suitable locations (immediately upstream and downstream of predicted mining areas) to improve accuracy of flow gauging, with sufficient baseline measurement and redundancy to enable adjustments to be made if gauges are moved or damaged by subsidence.
- Clarify zones of stream "significance" by identifying where conditions change from mainly losing to mainly gaining, or alternatively where flows change from permanent to intermittent. This may be resolved through groundwater level monitoring at a number of screened piezometers along the stream length, flow analysis or a combination of the two approaches.
- Undertake flow gauging at any convenient location near the base of swamps to enable volumetric water balance analysis.
- Conduct flow gauging on at least five occasions on selected controlling rock-bars below monitored ponds, in order to build up an understanding of how flow increases progressively downstream and where perenniality of stream ceases.
- Use the above relationships in a landscape-evaluation tool to extrapolate broad trends to unmeasured parts of the catchments.
- Install auto-samplers in key locations, to enable water quality samples to be collected during periods of high rainfall/flow.
- Develop guidance on appropriate water quality monitoring for the purposes of assessing mining impacts using appropriate TARPs, and require that it be followed.
- For aquatic ecology surveying, WaterNSW has reviewed a recent thesis study completed by Catherine Cunningham (2017) and makes the following recommendations based on this review:

– Reference sites should be located away from other potentially confounding landuses where practicable.

– Quantitative macroinvertebrate sampling be undertaken by all companies to ensure data have the sensitivity to detect impacts.

- Macroinvertebrates should be identified to genus level for all EPT (Ephemeroptera, Plecoptera and Trichoptera) taxa, as these are most appropriate indicator taxa for of mining impacts.
- Riffle habitats should be included in macroinvertebrate sampling strategies. In some streams, sections of bedrock may also constitute riffle habitats.
- Macroinvertebrate data should be reported in terms of total family richness, and EPT taxa diversity and abundance, in addition to multivariate analyses of community structure.

5.3. Groundwater Monitoring

As pointed out in the Literature Review (Advisian, 2016), it is inevitable that underground mining, particularly with supercritical subsidence behavior, will result in the formation of an unsaturated zone within and above the mined coal seam. From the point of view of assessing subsidence effects and consequences on water quantity, the most important aspects of groundwater to monitor are how much the water table varies from the pre-mining state (in vertical, areal and temporal dimensions) and how well the upper (Hawkesbury Sandstone) aquifer maintains a natural hydrostatic profile.

From a groundwater chemistry point of view, the most important information is how quickly groundwater is moving through the rock column in mined relative to natural, unmined states. This information can be inferred from such things as the “age” of the water since it was last precipitated, the geochemical signatures and even whether it contains algae or other environmental tracers of surface water.

5.3.1. Current practices in groundwater monitoring

Most of the groundwater level monitoring in the Southern Coalfields is performed by mining companies and is completed by means of vibrating wire piezometers (VWPs). These instruments are typically installed in arrays of up to ten per borehole, and are considered very good at establishing and monitoring vertical hydraulic profiles between a coal seam and the surface.

In a small number of locations within the Special Areas, screened piezometers have also been installed at shallow depths for various reasons, and these are equipped with pressure transducers and dataloggers (generally termed “divers”).

WaterNSW has undertaken extensive testing and has been monitoring a number of wells in the Kangaloon borefield just south of the Metropolitan Special Area (see Figure 1-1). This work was undertaken to investigate the potential for this borefield to provide additional water to Sydney and the Illawarra during periods of extreme drought, but the project has not been fully developed or been awarded planning approval. The associated monitoring provides useful data on the behavior of unmined aquifers close to the Special Areas.

Recognising the lack of baseline monitoring in the Southern Coalfields, WaterNSW has more recently been working with Lands and Water Division to design and install new sentinel groundwater wells in key locations and depths across the Special Areas. These piezometers will provide useful information on the behaviour of unmined aquifers close to the Special Areas. The drilling and refurbishment program is expected to commence in May 2018.

5.3.2. Perceived issues

WaterNSW supports the ongoing use of VWPs for the measurement of vertical hydraulic gradients in and around mined longwalls, however we note that they suffer from the following limitations:

- Their accuracy in measuring groundwater pressure, particularly when the water column is less than 10 m above the instrument is questionable and needs to be rigorously validated by a suitable number of screened piezometers particularly within the upper (Hawkesbury Sandstone) aquifer. An emerging issue in this regard is the question of why routine monitoring failed to identify extraordinary reductions in Hawkesbury Sandstone groundwater levels over Dendrobium Area 3B until specific investigations were sought by WaterNSW in the WC21 valley. One objective of the validation project should be to identify what responses a dry instrument provides so these can be discounted from level analysis.

- VWPs work by regularly "plucking" a taut wire to make a measurement. With current practices of measuring the water level every hour, each instrument has a functional life of up to 10-15 years. As they are grouted in place there is no way that they can be replaced in the same hole. WaterNSW is unaware of any mining domain in the Special Areas where post-mining equilibrium hydrogeological conditions have been confirmed, and considers it unlikely that they will be established within 20 years.

- The current practice of 40-80 m spacings between instruments is causing two issues – firstly that the height of depressurisation above mined longwalls remains only loosely constrained in those few arrays where fracturing doesn't destroy the instrument and secondly that aberrations in instrument readings can't be readily interpreted due to the lack of redundancy in nearby instruments.

- There is a safety issue with the wires potentially forming an ignition source in coal workings from lightning strikes, which means that the deeper arrays need to be decommissioned before they are undermined. Metropolitan Mine has recently commissioned the first set of fiber-optic instruments in an array, and it is hoped that this will resolve the issue and may enable longer groundwater level data recovery.

A particular issue with current company groundwater monitoring programs in the Special Areas is the general lack of screened piezometers to measure shallow groundwater levels beneath streams and swamps. This means that the gaining-losing conditions of most streams and the level of groundwater dependence of most swamp and riparian ecosystems are not known. This is a current problem at both Dendrobium and Metropolitan Mines, both for assessing the level of hydrological change, i.e. quantifying surface water loss, caused by mining and for setting suitable success measures for remedial or mitigation programs.

5.3.3. WaterNSW recommendations for improvement

As well as improving our own network of monitoring piezometers within the Special Areas to inform our understanding of hydrogeological conditions around the dams and to act as sentinel wells in case mining causes a change in these conditions in the future, WaterNSW believes the following groundwater monitoring improvements should be implemented by mining companies.

- Install and instrument adequate numbers of shallow screened piezometers to enable validation of VWP instruments and to assess the level of pre- and post-mining surface water interaction.

- Undertake a scientifically robust evaluation of the accuracy of VWPs installed for the purpose of monitoring and assessing mining impacts on groundwater levels.

- Increase profile density measurements of groundwater levels in locations over and close to longwalls. WaterNSW suggests that the density of instruments, particularly within the arrays within the zone where the upper limit of depressurisation is expected to occur, to intervals of no more than 20-30 m.

5.4. Swamp Monitoring

The NSW Government's Southern Coalfield Strategic Review (2008) noted that the hydrologic properties of the Southern Coalfield swamps are poorly studied, with measurements being restricted to water table monitoring at a few locations. Our literature reviewers (Advisian, 2016) found that the level of knowledge regarding the hydrologic properties and processes in the swamps has not greatly advanced since that Review, although there is certainly much more impact data now available and considerable research is being undertaken. An excellent summary of the current state of knowledge on upland swamps and their interactions with mining was recently published by Dr Young (2017).

WaterNSW supports the Office of Environment and Heritage (OEH, 2016) view that "*hydrological monitoring provides the most useful means for determining impacts within a timeframe suitable for regulatory and operation decision making because changes in hydrology can be detected relatively quickly. Monitoring of shallow groundwater levels in swamps is therefore likely to be the most important measure for early detection of impacts.*" OEH (2016) further stipulates that "*a minimum of two years pre-mining piezometric data should be obtained at both control and potentially impacted upland swamps and used to establish the baseline shallow groundwater regime in every swamp within 400 metres of longwall mining. Where less than two years of pre-mining data is available, then a more conservative assessment of the sensitivity of the feature to potential impacts must be applied.*

A monitoring program that incorporates these elements is referred to as a Before – After – Control – Impact (BACI) design. A BACI design must be used for the monitoring program to distinguish impacts from mining from natural seasonal or climatic variation. The monitoring program should also seek to identify any positive or negative trends in groundwater, particularly in the two years before and 12 months after mining. The use of control sites to understand natural variability should be complemented by mine-site specific rainfall and evaporation data to provide a meteorological context for interpreting swamp groundwater levels."

5.4.1. Current practice for swamp monitoring

A number of approaches are currently taken to hydrological monitoring in swamps by the three mining companies:

- Metropolitan Coal monitors groundwater levels in both swamp substrate and in underlying sandstone at three swamps, and only in swamp substrates at a number of others. Monitoring is undertaken for three reference swamps and seven swamps that have or will be undermined. This monitoring commenced in mid- to late 2010 and provides between 16 and 21 months of monitoring prior to undermining.

- Russell Vale Colliery has monitored swamp substrate piezometers in seven swamps since March/May 2012 (one swamp has two piezometers). These piezometers were all constructed in swamp substrates (0.53 m to 1.6 m deep). An additional 15 piezometers were installed in October 2014.

- At Dendrobium Area 3, IC has installed an extensive network of 39 swamp piezometers and also undertakes deep soil moisture sampling at 17 locations across 12 swamps that overlie the footprint of Longwalls 9 to 18. Three swamps (1a, 1b, and 5) include a series of piezometers across the swamp as well as longitudinally along the gradient of the swamp. In addition, two swamps outside the mining area are also monitored (Swamps 2 and 15a) as reference sites. More recently, IC has installed two shallow bedrock piezometers adjacent to Swamp 14 (which will be undermined by Longwalls 15 and 16), and proposes to install another five shallow bedrock piezometers to investigate cracking responses and the viability of remediation at Swamp 1b.

Some monitoring of the ecology of swamps is also being undertaken by the three companies, focusing on loss or change in vegetation type and impacts on identified upland swamp dependent threatened species or invertebrates. This monitoring is potentially important in improving our understanding of the timing and extent of ecological impacts following changes to the shallow groundwater regime, and inform any adaptive management processes. Dendrobium Mine has recently commissioned separate studies into the distribution of two endangered species, the Giant Dragonfly and the Red-Crowned Toadlet in Area 3B swamps and streams.

5.4.2. Perceived issues

Pells et al (2014) correctly observed that *"Astonishingly, there is no adequate hydrological balance for any of the upland swamps on the Woronora Plateau."* This shortcoming has been addressed to some degree by the research monitoring undertaken by Krogh (2015) and subsequent ongoing research (Glamore and Rayner, 2016). WaterNSW is currently working to support and continue this research to enable a reliable water balance to be developed particularly for Swamp 14, which is programmed to be undermined by Dendrobium Longwalls 15-17 and in an unmined reference swamp (Leech Swamp).

Knowledge gaps noted in the Literature Review (Advisian, 2016) for the upland swamp hydrology and ecosystems include:

- Understanding cumulative impacts across spatial and temporal scales and the hierarchical culmination of consequences.
- Hydrological balance of upland swamps needs to be adequately understood, with adequate baseline data.
- Data that specifically describes the overall ecological response to change in swamp environment is lacking, and the inherent variability of those swamp environments (and the microhabitats within them) making it difficult to model the community as a whole.
- Long-term ecological impact studies using the Before-After-Control-Impact model.
- Swamp wetness as measured by piezometers and soil moisture meters. The key factor driving swamp ecology and geomorphology is water: how wet is the swamp, how does water flow across the surface, what depth is the watertable and how does it respond to rainfall, how far does the capillary fringe rise, what is the swamp water storage capacity, what is the hydraulic conductivity of the swamp substrate, what is the characteristic natural moisture fluctuations of the swamp and what is the degree of moisture heterogeneity of the swamp?

5.4.3. WaterNSW recommendations for improvement

WaterNSW considers that the most urgent improvements required for hydrological monitoring of swamps is to simultaneously monitor shallow groundwater in the swamp substrate and underlying sandstone and to gauge the outflows from swamps at suitable locations. By measuring these parameters, along with weather conditions at a nearby station, it should be possible to undertake simple water balance studies in order to understand the magnitude of hydrological change which occurs after undermining. It should also be possible to develop a scheme for assessing the level of groundwater interaction and importance of downstream morphology (i.e. how important a downstream rockbar may be in maintaining substrate water tables) using superficial groundwater levels. WaterNSW is currently developing a proposal to advance the water balance monitoring and analysis commenced by Krogh (2015) for this purpose, but it is important that this type of study is undertaken more widely both to quantify losses and to inform future rehabilitation efforts.

More detailed monitoring of moisture conditions in swamp substrates before and after mining would also assist in understanding the dynamics of ecological change which transpires after cracking of the bedrock swamp bases.

The monitoring of upland swamp vegetation types and dependent threatened species should focus on those reliant on the shallow groundwater aquifers within swamps, such as those described in the relevant Scientific Committee determinations.

Greater use of ecological investigations (particularly into the presence and response to under-mining by threatened species) and monitoring (e.g. using macro-invertebrate analysis) is recommended. OEH can provide more detailed recommendations in this regard.

Finally, WaterNSW highlights the extreme importance of adequately characterising baseline conditions in order to assess later changes and for assessing the success of any rehabilitation measures. Aerial photography using drones or services such as NearMap is another way to gain a better understanding of variation in swamp condition due to climatic variation.

6. REPORTING

WaterNSW interprets the term “reporting” in the Panel’s Terms of Reference as including the full system of reporting subsidence effect, impact and consequence predictions used to support the proposed mining, through articulation of performance measures and developing Trigger Action Response Plans (TARPs) to regular reporting of impacts, subsidence movement and compliance with specific approval conditions. Although all aspects of this reporting have improved over the past decade, WaterNSW remains frustrated with the large gaps and ambiguities which remain in the system of evaluating and confirming compliance with planning and other approvals.

6.1. Performance Measures

The primary purpose of Performance Measures is to protect significant features within a project areas. WaterNSW supports the inclusion of Performance Measures in both development consents and subsidiary approvals. Performance Measures nominated in primary Planning Approvals have a particular significance and in some cases allow regulatory action to be taken if they are exceeded/not met, whereas those only identified in management plans are assumed to have a lower regulatory status. A third category of thresholds sometimes used in secondary approvals and management plans are termed “Performance Indicators” – these are designed to provide warning a Performance Measure or some adverse outcome may be starting to occur. They are generally not binding from a regulatory perspective.

The primary purpose of these Performance Measures is to enable the proponent and stakeholders to know whether the development is proceeding in accordance with the approving authority’s expectations and that specific adverse outcomes are being adequately avoided.

WaterNSW considers the selection of Performance Measures in current Planning Approvals as being a primary source of ongoing problems both in the design and the regulation of coal mining in the Special Areas. Examples of poorly selected Performance Measures that are of particular concern and frustration to WaterNSW include:

1. At Dendrobium Mine, one of the most important features which was agreed as meriting particular protection is Wongawilli Ck, which delivers an average of approximately 6 GL/year and is classified Class 3 using the Strahler System. Despite what appears to be evidence of significant drying of this stream within and immediately south of Area 3 longwalls, one of the main Performance Measures protecting the creek is based on a gauge located so far downstream of the impacted area that it would be virtually impossible to detect any level of change which occurs around the mining footprint.

2. At Metropolitan Mine the only Performance Measure specifically protecting one of the largest feeder streams of the Woronora Reservoir, known as Eastern Tributary, relates to an arbitrary zone of the creek between Longwall 26 and the Full Supply Level of the reservoir. There are also extensive impacts arising from Longwalls 23-26, which Metropolitan Mine is not legally required to rehabilitate or otherwise address due to their exclusion from Performance Measures.

WaterNSW considers that mining companies should be held to account for ensuring mining does not result in an exceedance of a Performance Measure. An option for attempting rehabilitation of a Performance Measure exceedance should be considered in approvals only as a last resort, with the first option being a change to the mine design or approach, including the options of ceasing to mine where the Performance Measure warrants it.

WaterNSW believes that quantifying levels of consequence within a suitable risk framework could substantially advance the development of Performance Measures, and is working to support this outcome.

6.2. Trigger Action Response Plans

Trigger Action Response Plans (TARPs) are widely applied across NSW mining operations, arising as a key requirement of subsidiary planning approvals called Subsidence Management Plans (SMP) or Extraction Plans (EP).

The typical TARP structure in current mine management plans includes the following key elements:

- **Performance Measures**
  - As discussed above, Performance Measures are designed to enable the performance of a mine operation to be assessed against a particular metric or prediction.
- **Trigger Levels**
  - Most TARPs contain an escalating set of triggers, designed to highlight that a problem may be arising and that additional actions may need to be taken to avoid exceedance of the Performance Measure.
  - Trigger levels are commonly set to be levels 1, 2, 3 and “Exceeding Performance Measure”. In some cases the trigger levels are explicitly linked to Performance Indicators and/or Performance Measures.

- Exceedance of the highest Trigger Level is usually expressed as an exceedance of the Performance Indicator or predicted result for that parameter and/or as an exceedance of a specified rate of change.

- **Actions**

  - Actions are generally nominated for each Trigger Level, which notionally increase effort or level of concern commensurately with the levels.

  - A common issue with Trigger Levels is that it is not clear what happens when they combine or get incrementally worse.

Two of the biggest shortcomings of current TARPs is that they don't spell out what happens if a Performance Measure is exceeded, nor do they nominate impact levels at which mining should be at least temporarily halted.

Another issue with the use of TARPs is that they assume that adaptive management of impacts is at least theoretically possible. This type of approach has worked well in the past for example at Sandy Creek Waterfall, where longwalling was able to be terminated a sufficient distance using subsidence monitoring techniques so that the criteria in the Consent were met, including no rockfalls. There are numerous mining situations however, where adaptive management is not feasible such as where the base of an undermined swamp is predicted to be fractured. Prior to consideration of adaptive management, all efforts should be made to avoid or minimise the advent of subsidence effects and their subsequent consequences on agreed features of importance.

In those situations where adaptive management can be feasibly undertaken, WaterNSW supports the use of reactive TARPs as a management measure once approval has been granted, but highlights that we believe it is equally important that all efforts are made to avoid or minimise the advent of subsidence effects and their subsequent consequences.

WaterNSW further notes that when a TARP is used for managing a significant safety hazard in a coal mine, typically the responsible and accountable persons within the mine's management team are specifically nominated within the TARP. Responsible persons are not typically identified in the TARPs currently in effect in the Special Areas.

6.3. Monitoring, Impact and Consequence Reporting

WaterNSW acknowledges that the three companies operating in the Special Areas do make considerable efforts to report outcomes of monitoring and impact monitoring on a regular basis and in accordance with regulatory requirements. However, we do suggest that there remains a number of issues with the coverage and type of reporting currently occurring.

The biggest difficulty for WaterNSW to satisfy itself, in conformance with our statutory functions described in Section 1.2.1, that our values are being adequately protected is that most reporting is interpretative and is not accompanied by the data which underlies it. WaterNSW does not accept that we should not be able to corroborate and assess the mining company/consultants conclusions with our own data analysis, which is why we have been seeking all company monitoring data gathered in the Special Areas in accordance with Data Sharing Agreements. Significant progress has been made in developing the type of database encouraged in the 2016 Catchment Audit Recommendations (refer to Section 3.2), but it would be much more effective and efficient if provision of the data to ourselves or a central government repository were required in Planning Approvals.

6.4. Recommendations for improving company reporting

In view of the discussion above, WaterNSW recommends the following improvements should be made:

1. As discussed in the 2016 Catchment Audit Recommendations (refer to Section 3.2), WaterNSW believes that all environmental and subsidence monitoring results gathered by mining companies operating in the Special Areas should be fed into a central data repository held and managed by a government agency. In the meantime, WaterNSW is working with mining companies to seek specific data in accordance with data sharing agreements, but without any ability to compel the data provision. We suggest that it would be much more efficient and appropriate if provision of the data to a central government repository or to WaterNSW were required in Planning Approvals.
2. Greater emphasis should be placed on the avoiding, rather than managing, impacts on agreed features. WaterNSW recommends the application of a "bow-tie" risk analysis approach in the analysis of risks, requiring that all future mining applications clearly articulate the means by which exceedances of Performance Measures (or Top Events) will be pro-actively avoided or minimised in its mine design. We believe that this approach will significantly strengthen the rigour and transparency of mining applications in the future.
3. In general, TARPs need to be improved to:
    - clarify what will happen if a Performance Measure is exceeded, and what level of impact would require that mining be at least temporarily stopped and reassessed;
    - make them more specific, quantitative and measurable;
    - clarify their relationship to Performance Measures or Indicators; and
    - identify who has responsibility for implementation.
4. Where they are used, Performance Indicators need to be clearly related to Performance Measures. The trigger levels must be as quantitative as possible, and carefully designed to provide suitable buffers or warning against unacceptable impacts arising.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

Although the Height of Cracking Study focused specifically on evidence at the Dendrobium Mine, the report's findings have implications for the prediction and understanding of surface water, groundwater and ecological impacts throughout the Special Areas of the declared Sydney catchment area. It is also important to understand how different the consequences of mining have been in response to subsidence effects at Metropolitan, Russell Vale and other mine in the Special Area, and thereby to deduce what the key influences on these consequences are.

The HoCR has confirmed WaterNSW suspicions that the subsidence effects observed at Dendrobium Mine are resulting in impacts and consequences more substantial than had been predicted in the mine's planning and post-approval applications. One important observation in this regard is that the Performance Measures identified in the mine's planning approvals have largely failed to identify or prevent the excessive consequences which have since occurred. Another salient observation is that the HoCR (PSM, 2016) findings were very different from those provided by consultants engaged by the company to examine the same evidence (HydroSimulations, 2015; DGS, 2016).

From WaterNSW's viewpoint, the single most important consequence which has been highlighted by the HoCR is that subsidence induced by the Dendrobium Mine longwalls is likely to be resulting in significant diversion of surface water which would otherwise contribute to Greater Sydney's water supply. The associated degradation of water quality and ecological integrity of Special Area catchments are also of concern.

These results suggest that mine dimensions should have been constrained to values where such widespread and extreme consequences did not occur. It will be an important task for the Panel to develop guidance on how to constrain mining dimensions to avoid this scale of subsidence effects in the future.

At the same time, the 2016 Catchment Audit confirms that mining poses a serious risk to the catchments of the Woronora and Metropolitan Special Areas (Figure 1-1) and Sydney's water supplies which are sourced from them. The Auditors make a series of recommendations which are discussed separately in Section 3 and summarised below.

WaterNSW understands that the Panel has also been tasked with reviewing the adequacy of current mine predictive modelling, monitoring and reporting. As these are issues which WaterNSW spends considerable effort in scrutinising, we are able to offer extensive feedback in this submission and make numerous recommendations for improvement, all of which are summarised below.

7.2. Recommendations

WaterNSW makes the following recommendations in relation to topics included in the first group of tasks listed in the IEP's Terms of Reference:

7.2.1. Height of Cracking report (PSM, 2017)

WaterNSW's recommendations in regard to the findings and recommendations of the HoCR (PSM, 2017) are as follows:

1. WaterNSW strongly supports the recommendation to examine the important new information which has come to light since the last Southern Coalfields Inquiry, and will provide ongoing support to the Panel in this regard.

2. Recommendations are made by PSM and the HoCR peer-reviewers on improving predictive modelling approaches. WaterNSW concurs, and provides its comments on how such improvements could be fostered in Section 4.

3. A number of lines of evidence identified in the HoCR suggest that surface water losses are higher than has previously been identified. WaterNSW supports the recommendation to undertake a water balance for Cordeaux Reservoir and investigate the implications of the anomalous recharge patterns in piezometers adjacent to Areas 2 and 3A and Cordeaux Reservoir.

4. More generally, the HoCR concludes with a recommendation that DPE and the major stakeholders consider which impacts need to be better quantified, and what are the appropriate acceptability criteria for these impacts? WaterNSW suggests that the most important impact which needs to be quantified is the volume of surface water being diverted from drinking water catchments. We would be pleased to work with

agencies and the IEP to progress this work and to develop appropriate acceptability criteria.

5. The HoCR also provides a number of recommendations to improve monitoring of subsidence, surface water and groundwater at key locations over the Dendrobium Mine. WaterNSW supports these recommendations, and provides our views on improving monitoring approaches in Section 5 of this submission.

6. WaterNSW supports the HoCR recommendation to verify the location of all projected geological structures prior to the approval of future longwall panels in Area 3B and to leaving a substantial buffer against these structures if there is any possibility that they may directly or indirectly connect with a surface water storage.

7. An important finding arising from the HoCR and associated review reports is that independently engaged studies produce remarkably different results to those engaged by mining proponents. WaterNSW consequently recommends that selected future impact assessment reports should be engaged by government but funded by the mining company (in a similar way to the Catchment Audit discussed below).

7.2.2. Catchment Audit 2016

WaterNSW's recommendations in regard to the findings and recommendations of the 2016 Catchment Audit (Alluvium, 2017a) are as follows:

8. The Auditors' Recommendation M1 to "Establish the scope and commence a state-owned regional surface water and groundwater geotechnical model" is supported, but it needs to be founded on an adequate level of understanding. This task has been examined by WaterNSW and many eminent specialists, including those gathered by the Office of the Chief Scientist (OCSE) and the national Office of Water Science (OWS) in recent workshops. The current conclusion is that such an integrated model cannot be reliably developed until a sufficient database of monitoring information across the Special Areas has been compiled and the causative relationships between subsidence effects, impact and consequences have been more accurately quantified. WaterNSW will support any process that works towards the eventual completion of this recommended task.

9. WaterNSW is working with NSW Lands and Water in an effort to implement the Auditors' Recommendation M2 to "Activate licensing under Section 60I of the Water Management Act 2000 in accordance with the NSW Aquifer Interference Policy to regulate surface water loss to mine workings". Current licensing arrangements are considered unsatisfactory in a number of respects.

10. WaterNSW commends DPE and the NSW government for implementing the recommendation to establish the Independent Expert Panel to review the monitoring, analysis and reporting program relevant to mines operating in the Catchment.

11. The fourth recommendation by the Auditors is to "investigate thresholds at which mining activities cause loss of surface water to mine workings, and impact the yield of individual Sydney catchment water supply systems. Results to be considered in the Metropolitan Water Plan." WaterNSW looks forward to working with the Panel, Metropolitan Water Directorate and other stakeholders to develop appropriate thresholds.

12. The Auditors tasked DPE with "identifying surface water flow monitoring requirements in mining approval conditions". Whilst some requirements are already identified in current mining approval conditions, WaterNSW has observed numerous opportunities for improvement – see Section 5.2. The goal from WaterNSW's

perspective should be to enable sufficient data to enable water balance or some other type of modelling to make and assess accurate predictions of surface water take.

13. The final recommendation about mining made by the Auditors is to "Compile all empirical evidence of mining impacts in the Sydney Drinking Water Catchment in a regional cumulative impact assessment." WaterNSW strongly supports this objective, and considers that the first step towards it is to require mining companies to provide the government with all impact and environmental monitoring data in electronic format for ingestion in a government database (i.e. by extending the SEED database to include industry data).

7.2.3. Predictive Modelling Improvements

General improvements which WaterNSW recommends to the modelling and analysis used for predicting consequences of mining are summarised as follows:

14. Prior to commencing the analysis, discuss with WaterNSW (and other key stakeholders if appropriate), the proposed impact prediction approach, conceptual understanding of the main processes influencing impacts, how complex does the modelling need to be and what numerical or analytical model(s) are to be used after consideration of all sensible alternatives. The opportunity for early stakeholder consultation and justification of modelling approach is strongly encouraged by WaterNSW.

15. Start the assessment by defining, in consultation with WaterNSW and other key stakeholders, the potential prediction or development "failures" on which modelling will focus. In the case of mining proposals submitted within the Special Areas, the key question for surface water prediction analysis from WaterNSW's perspective will be how much water will be diverted out of the harvested catchments and for what duration? For a proposal to undermine a perennial creek or a reservoir within the Special Areas for example, a key prediction failure would be to incorrectly predict that surface water "loss" from that feature will not result in more than a specified rate of leakage or exceed an adopted threshold.

16. The next step in the analysis should be consideration of how each potentially consequential prediction failure (i.e. a "False Positive" error where a specified volume of water loss is not predicted but subsequently does occur) will be avoided to an acceptable (e.g. 95%) degree of certainty.

17. Make modelling only as complex as is necessary, proceeding to greater complexity only if it will reduce uncertainty. In some cases, this will mean an iterative approach to check whether uncertainty is reduced by increasing the number of parameters, and in some cases may be achieved by using simpler sub-models or other analysis to check or inform critical components of the larger models (Doherty and Moore, 2017; Ferre', 2017).

18. Present key layers and parameters to reveal model conceptualisation for all models. A list of suggested data and layers to be exported for easy importation into visualisation software is provided in Appendix C and discussed further in Section 4.4.4.

19. Present uncertainties objectively and transparently, including conceptualisations, parameterisations and assumptions. Use stochastic approaches to parameter estimation and sensitivity analysis where appropriate. WaterNSW encourages innovative approaches to the quantification of uncertainty, e.g. by comparison of the

modelled results with those derived from separate (or ensemble) numerical, analytical or statistical approaches.

20. Use the model(s) iteratively to inform future investigations and monitoring, identifying data with maximum “worth” that will fill key information gaps most effectively.

More specific recommendations for predictive modelling of surface water, groundwater and other potential impacts are as follows:

21. Surface water catchment impact analysis tools need to be improved. WaterNSW considers the use of groundwater flow models for the purpose of estimating surface water losses inaccurate and inappropriate, and that water balance analysis and lumped parameter rainfall-runoff models should be trialed and implemented in preference.

22. A methodology for measuring or estimating broad-catchment diversion of overland flows also needs to be developed in order to inform estimates of catchment surface water losses induced by mining. WaterNSW recommends that analysis of shallow bedrock water-table analysis to see how recharge dynamics in mined and unmined differ should be trialled, as well as trialling direct measurement of groundwater or moisture levels above the soil-water interface.

23. The ongoing use of groundwater flow models for hydrogeological assessment and prediction is broadly supported. However, WaterNSW considers it important that, in addition to the general improvements for analysis discussed above, each model used to support proposals is able to be scrutinised by regulators and other informed stakeholders. We recommend that proponents should be required to routinely provide a set of export data and metadata files (see Appendix C) which can be readily imported into visualisation software and examined by WaterNSW and other interested stakeholders.

24. At this time it appears that geochemical analysis tools are not able to provide accurate or reliable estimates of the contributions of surface water to mine inflows. An independent review into the evidence base, such as was performed by PSM into the height of fracturing (PSM, 2016), may be required to resolve the conflicting lines of evidence. In the meantime, geochemical analysis is considered less reliable than hydrological analysis for this purpose.

25. All piezometer data that is being collected should be reported. Where important trends are discerned, even if they may relate more to previous mining, these should be specifically discussed.

26. All uncertainties should be clearly presented, including in conceptualisations, choice of model elements, boundary conditions and parameter values. Functionality and calibration of the model should be critically discussed, including whether all model runs reached resolution or convergence.

27. Given the disparities between the results from mining-engaged consultants and independently engaged experts, consideration should be given to alternative assessment paradigms such as engagement of consultants by regulators at proponent expense. This would particularly apply to periodical audits of compliance with regulatory requirements (currently required in the two active mines in the Special Areas every three years), but should also be considered for annual environmental or end-of-panel reports.

7.2.4. Monitoring Improvements

28. WaterNSW recommends that all future approvals should include a requirement for at least two years baseline monitoring prior to commencement (and preferably prior to EIS or post-approval assessment). We further recommend that an agreed level of monitoring must continue until new equilibrium conditions have been established and ongoing surface water losses and groundwater level reductions have been adequately accounted for and licensed. If necessary, instruments will need to be replaced until these conditions have been confirmed.

29. Greater implementation of focused investigations and monitoring of subsidence and groundwater behavior directly over longwall goafs is strongly encouraged, with the purpose of informing impact assessment and prediction methodologies.

30. Trial the use of DinSAR imagery to holistically observe how subsidence bowls develop in the various steep and flat terrains in the Special Areas. Note that SAR imagery has already been collected over recent mining domains, so these investigations can readily compare differential movements before and after mining.

31. Expand the use of down-hole Time Domain Reflectometry imagery to monitor ground movements.

32. Trial the use of down-hole micro-seismic testing to better delineate the extent and magnitude of cracking in various mining domains.

33. Trial the use of repeated surface seismic (and possibly electrical geophysics?) testing before, during and after mining, again to better delineate extent and magnitude of rock deformation and cracking and possibly changes in hydrogeological conditions.

34. Periodical ground surveys to continue until full subsidence stabilisation is confirmed.

35. Install and gauge constructed weirs in suitable locations (immediately upstream and downstream of predicted mining areas) to improve accuracy of flow gauging, with sufficient baseline measurement and redundancy to enable adjustments to be made if gauges are moved or damaged by subsidence.

36. Clarify zones of stream "significance" by identifying where conditions change from mainly losing to mainly gaining, or alternatively where flows change from permanent to intermittent. This may be resolved through groundwater level monitoring at a number of screened piezometers along the stream length, additional gauging of flow below monitored ponds with flow analysis or various other approaches.

37. Use the above relationships in a landscape-evaluation tool to extrapolate broad trends to unmeasured parts of the catchments.

38. Install auto-samplers in key locations, to enable water quality samples to be collected during periods of high rainfall/flow.

39. Develop guidance on appropriate water quality monitoring for the purposes of assessing mining impacts using appropriate TARPs, and require that it be followed.

40. For aquatic ecology surveying, WaterNSW recommends that macroinvertebrate sampling should be undertaken by companies working near or above perennial streams, that riffle sites should be preferentially selected for surveying, that reference sites should be located away from other potentially confounding landuses where practicable. Macroinvertebrates should be identified to genus level and survey data

should be reported in terms of total family richness and taxa diversity and abundance, in addition to conducting multivariate analyses of community structure.

41. Install and instrument adequate numbers of shallow screened piezometers to enable validation of VWP instruments and to assess the level of pre- and post-mining surface water interaction.

42. Undertake an evaluation of the accuracy of VWPs installed for the purpose of monitoring and assessing mining impacts on groundwater levels.

43. Increased profile density measurements of groundwater levels in locations over and close to longwalls. WaterNSW suggests that the density of instruments, particularly within the arrays within the zone where the upper limit of depressurisation is expected to occur, to intervals of no more than 20-30 m.

44. Requirement for sufficient hydrological monitoring in significant upland swamps, including downstream flow-gauging, to a sufficient quality and coverage to support water balance assessments.

45. More detailed monitoring of moisture conditions in swamp substrates before and after mining would also assist in understanding the dynamics of ecological change which transpires after cracking of the bedrock swamp bases.

46. The monitoring of upland swamp vegetation types and dependent threatened species should focus on endangered species and those reliant on the shallow groundwater aquifers within swamps.

47. Greater use of ecological investigations (particularly into the presence and response to under-mining by threatened species) and monitoring (e.g. using macro-invertebrate analysis) is recommended. OEH should be consulted for more detailed recommendations in this regard.

48. Finally, WaterNSW highlights the imperative of adequately characterising baseline conditions in order to assess later changes and for assessing the success of any rehabilitation measures. Aerial photography using drones or services such as NearMap is another way to gain a better understanding of variation in swamp condition due to climatic variation.

7.2.5. Reporting Improvements

49. WaterNSW believes that all environmental and subsidence monitoring results gathered by mining companies operating in the Special Areas should be required in Planning Approvals and fed into a central data (e.g. SEED) repository held by the NSW Government.

50. Greater emphasis should be placed on the avoiding, rather than managing, impacts on agreed features. WaterNSW recommends the application of a “bow-tie” risk analysis approach in the analysis of risks, requiring that all future mining applications clearly articulate the means by which exceedances of Performance Measures (or Top Events) will be pro-actively avoided or minimised in its mine design. We believe that this approach will significantly strengthen the rigour and transparency of mining applications in the future.

51. In general, TARPs need to be improved to:

    - clarify what will happen if a Performance Measure is exceeded, and what level of impact would require that mining be at least temporarily stopped and reassessed;

- make them more specific, quantitative and measurable;
- clarify their relationship to Performance Measures or Indicators; and
- identify who has responsibility for implementation.

52. Where they are used, Performance Indicators need to be clearly related to Performance Measures. The trigger levels must be as quantitative as possible, and carefully designed to provide suitable buffers or warning against unacceptable impacts arising.

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9. APPENDICES

Appendix A - Summary of the Literature Review (Advisian, 2016) report

Appendix B – Surface water-loss from Illawarra escarpment - pre- and post-mining figures

Appendix C - Recommended data, export files and formatting requirements for groundwater flow models to be examined in NICTA Visualisation Software.

Appendix A

Summary of literature Review report (Advisian, 2016)

1. BACKGROUND

1.1. Approach

This Appendix summarises the outcomes of a Literature Review carried out by a consultant team commissioned by WaterNSW. The Literature Review report (Advisian, 2016) summarises the key findings of relevant studies and documents. This review was undertaken with a preference for peer-reviewed national and international publications that have been published in the last 10 years and that relate directly to mining in high value water catchments or under waterbodies. In addition, the review included relevant documentation identified by WaterNSW relating to the Southern Coalfield.

The aim of the Literature Review was to attempt to:

- Establish a direct causal link between subsidence effects, subsidence impacts and any environmental consequences;
- Quantify the magnitude and risk of an environmental consequence;
- Identify subsidence effects, impacts and/or consequences and how interrelationships between these elements can be predicted; and
- Identify limits for subsidence impacts below which the risk of environmental consequences is negligible.

A summary of the current literature relating to subsidence effects and impacts is presented in Section 2 below. A summary of the current literature relating to environmental consequences is presented under the headings of surface water, ecology and groundwater (refer Sections 3, 4 and 6 respectively). Gaps in the existing knowledge base for each of these areas are also identified.

It was found that very little of the available documentation on mining and subsidence effects, impacts and consequences have been peer-reviewed. This is particularly evident in work undertaken as part of the Australian black coal industry's research program, now known as the Australian Coal Association Research Program (ACARP). ACARP progress research on issues of common interest, including publication of a number of documents setting out prediction methods for subsidence effects from longwall mining (e.g. *ACARP C18015, 2014 - Effects of Mine Subsidence, Geology and Surface Topography on Observed Valley Closure Movements and Development of an Updated Valley Closure Prediction Method*). In general, these reports have been prepared by specialist consultants on a commercial basis and have not been technically peer-reviewed. Another example is the various "Information Reports" published by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC), which generally comprise literature reviews. It is important to note that information cited within these documents does not infer "government endorsed" or "peer-reviewed" status.

Further, much of the key documentation examined in the Literature Review comprises consultants' reports prepared on behalf of mining companies to support mining applications or interpretative reports of how the mine has "performed" relative to its approval conditions. Virtually none of these reports have been peer-reviewed.

Other important sources of documentation are the submissions made by WaterNSW and assessment and interpretative reports on mining applications prepared by other government agencies for the Department of Planning & Environment (DPE) and the Planning Assessment Commission (PAC).

1.1.1. Sydney Drinking Water Catchment and Special Areas

Many of the major dams, reservoirs and canals used for drinking water supply are surrounded by 'Special Areas' established under the *Water NSW Act, 2014)*, within which certain types of activity and access are restricted. This creates a buffer zone from human activity to reduce the risks from contamination and to protect Sydney's drinking water. The Project focused on the catchments within Metropolitan and Woronora Special Areas which overlie the coal measures of the Southern Coalfield. These catchments drain to the reservoirs and weirs as listed in Table 1-1.

Table 1-1: Reservoirs within the Metropolitan and Woronora Special Areas

Storage	Total Operating Capacity (ML)	Security Yield (ML/a)	Water Surface Area at Full Supply (ha)	Catchment Area (ha)	Approximate Elevation (m AHD)
Woronora	71,790	9,500	400	7,225	180
Cataract	97,190	20,000	850	12,618	280
Cordeaux	93,640	14,000	780	8,684	320
Avon	146,700	20,800	1,050	14,256	330
Nepean	67,730	19,000	330	31,824	320
Broughtons Pass Weir	50	NA	1.31	8,169	230
Pheasants Nest Weir	25	NA	0.25	13,596	210

1.1.2. History of Water Supply and Mining Activities in the Special Areas

Table 1-2 summarises the history of mining and water supply activities in the Metropolitan and Woronora Special Areas.

Table 1-2: History of Water Supply and Mining Activities in the Special Areas

Pre-1800	▪ Aboriginal occupation of area - Dharawal, Wadi and Gundurngurra people estimated to go back at least 15,000 years ▪ 1788 First European settlement in the Sydney area
1800s	▪ 1800s Increased "hand-got" method of longwall mining in Australia ▪ 1857 Commercial quantities of coal produced at Kemira Colliery ▪ 1850-1988 Kemira/Mt Keira ▪ 1878-1991 Coal Cliff Colliery (bord and pillar) operated ▪ 1861-1955 Mt Pleasant Colliery ▪ 1861-2004 South Bulli (Bellambi) Colliery ▪ 1865-1970? Mt Kembla Colliery ▪ 1878-1991 Coal Cliff (bord and pillar) operated ▪ 1880 Metropolitan Special Area declared to protect Upper Nepean catchment ▪ 1888 Metropolitan Colliery opened at Helensburgh ▪ 1888 Prospect Reservoir, Broughton's Pass Weir, Pheasants Nest Weir and the Upper Canal completed ▪ 1892-1983 South Clifton Colliery

1900 - 1950	▪ 1900-1962 Excelsior No. 1 and No. 2 Collieries ▪ 1907 Construction of Cataract Dam complete ▪ 1910-1983 Avondale Colliery ▪ 1916-1993 Wongawilli Colliery ▪ 1926 Cordeaux Dam completed ▪ 1927 Avon Dam completed ▪ 1930-1980 Old Wollondilly Coal Mine (Warragamba Special Areas) ▪ 1935 Completion of Nepean Dam ▪ 1935-1973 Wollondilly Extended Coal Mine (Warragamba Special Areas) ▪ 1941 Woronora Dam completed; Woronora Special Area declared ▪ 1942-1973 North Bulli Colliery ▪ 1946-1989 Huntley Colliery ▪ 1946-1993 Nebo Colliery ▪ 1947-1985 Corrimal Colliery
1950 - 2000	▪ 1955-1996 Oakdale Colliery (Warragamba Special Areas) ▪ 1957-1982 Valley No. 1 (Warragamba Special Areas) ▪ 1961 Mechanised longwall mining introduced ▪ 1971-1999 Avon Colliery ▪ 1971-1991 Darkes Forest Colliery ▪ 1972-1981 Bulli Colliery ▪ 1976-1986 Nattai North Colliery (Warragamba Special Areas) ▪ 1968-1981 Brimstone Colliery (Warragamba Special Areas) ▪ 1980-2001 Cordeaux Colliery ▪ 1988-1991 Kemira Colliery (longwall in Wongawilli Seam) ▪ 1993-2007 Wongawilli Colliery consolidated with Kemira and Nebo Collieries to become Elouera Colliery ▪ 1999 Sydney Catchment Authority become operational
2000-present	▪ 2004 South Bulli Colliery (subsequently also known as Bellambi Colliery, Belpac No.1 Colliery) become NRE No.1 Colliery and recently Russell Vale Colliery ▪ 2005 Longwall mining commences at Dendrobium Coal Mine ▪ 2007 Elouera Colliery sold and renamed NRE Wongawilli Mine ▪ 2015 WaterNSW becomes operational (replaces Sydney Catchment Authority)

Source: Modified from NSW Chief Scientist & Engineer (2014); Galvin (pers comm 2016)

The current and historic underground mines located under the catchments of WaterNSW's storages are listed in Table 1-3.

Table 1-3: Mines Located under WaterNSW Storage Catchments

Storage	Underground Mines			
	Current Operation	Care & Maintenance	Proposed	Historic
Nepean	-	-	-	-
Avon	Dendrobium Area 3B Wongawilli	-	-	Avon, Avondale, Huntley, Wongawilli, Elouera
Cordeaux	Dendrobium Areas 2 & 3A	-	-	Kemira/ Mt Keira, Mt Kembla, Mt Pleasant, Nebo, Cordeaux
Cataract	-	Russell Vale	Russell Vale	Bulli, Cordeaux, Corrimal, Excelsior No.1 & No.2, North Bulli, South Bulli, South Clifton
Woronora	Metropolitan	-	-	Darkes Forest, Coalcliff

Mines in the Woronora and Metropolitan Special Areas are all underground. Both bord and pillar mining and longwall mining are used in the region, although longwall mining predominates. Both methods leave behind goaves which tend to fill with collapsed rock and overburden material as the longwall progresses. Subsidence effects tend to be substantially greater over longwall mines.

2. SUBSIDENCE

2.1. General

Mining-induced subsidence effects and impacts are a function of a number of mechanisms and likely to be affected by many factors, the most important of which are geology, mining depth, extraction height, excavation width, individual excavation width-to-depth ratio, overall extraction width-to-depth ratio and pre-mining horizontal to vertical stress ratio. Each of these factors can affect subsidence both directly and indirectly in a number of different ways.

The factors thought to that have the largest influence over subsidence effects are extraction height (h), mining depth (H), excavation width (W), and overall extraction width (W_o). These factors combine to affect subsidence as follows:

- The extraction height primarily controls the magnitude of potential surface subsidence;
- The proportion of the extraction height that translates to surface subsidence depends on the manner and magnitude with which the roof sags or collapses after the void has been formed and on how much the roof, floor and coal strata of the interpanel pillar system compress;
- The proportion of both strata collapse and interpanel pillar system compression are dependent on the width of individual panels, the overall extent of extraction and the width and strength of intervening coal pillars between the panels, as well as the depth of mining.

As an individual excavation is made wider relative to depth, the stiffness of the overburden is reduced, resulting in increased vertical surface displacement to some limiting value. The individual panel span-to-depth ratio, W/H, at which the stiffness of the overburden is reduced to zero corresponds with the vertical surface displacement above an isolated panel reaching its maximum possible value and is referred to as the critical width-to-depth ratio, W/H. Larger panel width-to-depth ratios are referred to as being supercritical and smaller panel width-to-depth ratios as being subcritical (Galvin, 2016). Depending on the panel width-to-depth ratio, multiple adjacent panels may need to be extracted before the stiffness of the overburden is reduced to a limiting value. In these situations, surface movements develop incrementally with the extraction of each panel.

Geology affects subsidence by controlling the amount of deformation experienced by overlying strata. If the geology comprises multiple relatively thin beds then this material will more readily cave and fall like a deck of cards to result in a low bulking factor. The upper roof strata may also more readily flex and conform to the void shape than overlying massive strata. In some cases, subsidence can be dramatically reduced due to the presence of these massive spanning units, such as thick beds of intrusives found in South Africa or conglomerates found in the Newcastle region. Conversely, any structural weaknesses in the rock such as faults or jointing may result in uneven and locally pronounced subsidence effects.

Intuitively, the wider the extraction and shallower the workings the more likely that a longwall panel will reach a supercritical state in its own right. In these situations, the development of vertical surface displacement is often represented by plotting the ratio of maximum subsidence to the extraction height, S_{max}/h, against the ratio of individual panel width to mining depth, W/H. This is shown in Figure 2-1 for the case where extraction height is taken to be equal to seam thickness.

For a given geological setting, this type of relationship is used to estimate maximum vertical displacement above an isolated panel based on key geometric factors. This is shown in Figure 2-1 for the case where extraction height is taken to be equal to seam thickness. For a given geological setting, this type of relationship is used to estimate maximum vertical displacement above an isolated panel based on key geometric factors.

Curves created for isolated panels in the Southern, Western and Newcastle Coalfields of NSW are shown in Figure 2-1 where NCB refers to the UK National Coal Board and DMR refers to the NSW Department of Mineral Resources.

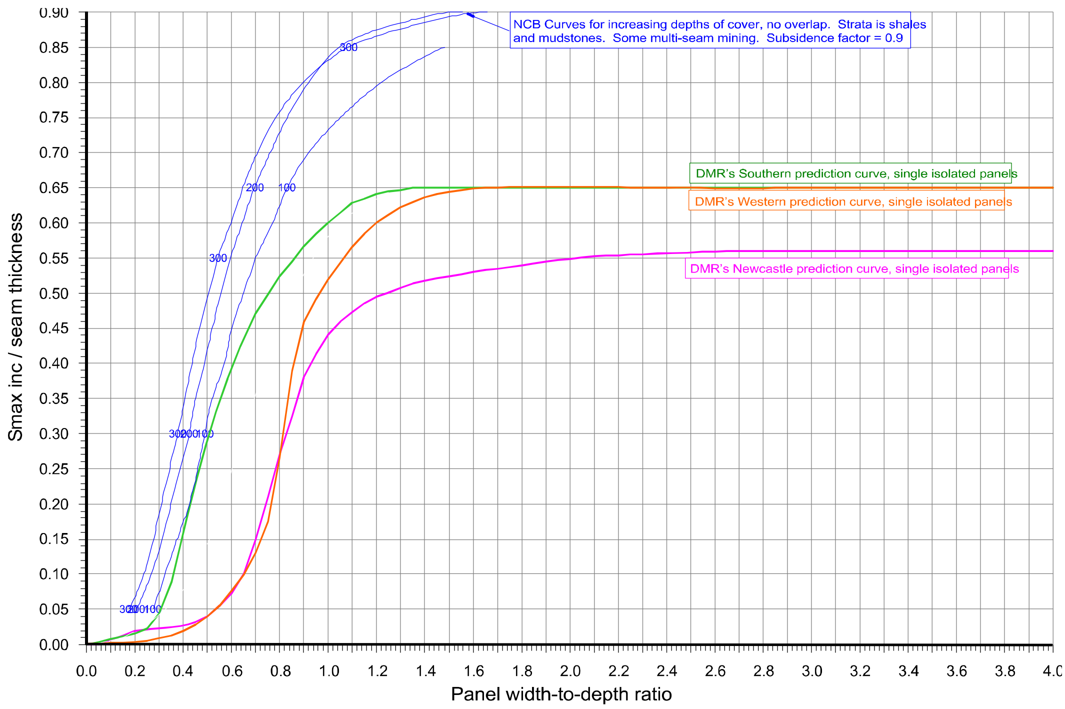


Figure 2-1: Ratio of S_{max} to seam thickness versus panel width-to-depth ratio (modified from MSEC (2007)

Profiles of vertical displacement at the surface are a reflection of the stiffness of the superincumbent strata and, therefore, give valuable insight into the distribution of superincumbent strata load (Galvin, 2016). This is illustrated by the vertical surface displacement profiles shown in Figure 2-2 and Figure 2-3. Figure 2-2 provides vertical surface displacement profiles over 210 m wide longwall panels at a depth of around 80 m (W/H=2.6) showing how maximum surface displacement develops virtually independently of subsequent panel extraction at shallow depth, consistent with tributary area load (TAL) based on the concept of an abutment angle (Galvin, 2016). Figure 2-3 provides vertical surface displacement profiles over 210 m wide longwall panels at a depth of around 500 m (W/H=0.42) showing how maximum vertical surface displacement develops incrementally at depth as subsequent panels are extracted and not in accordance with TAL.

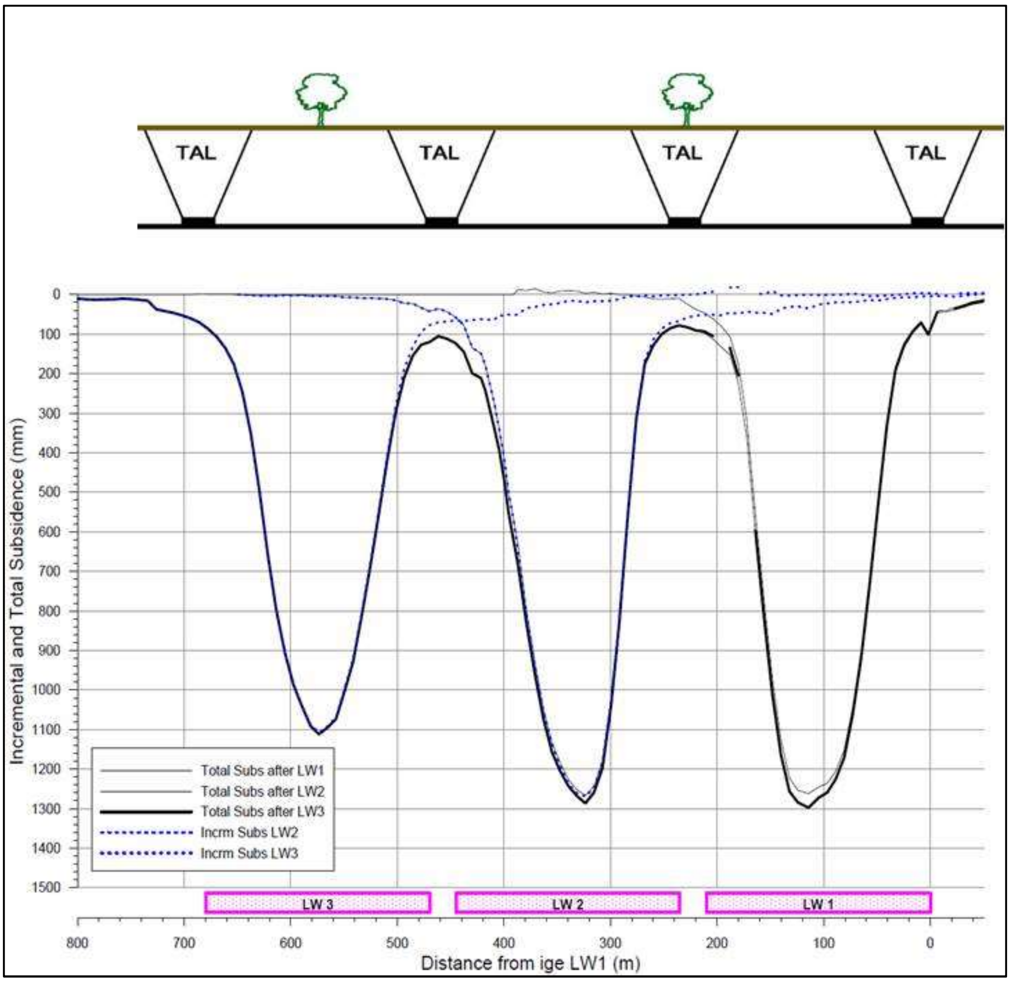


Figure 2-2: Vertical surface displacement profiles over 210 m wide longwall panels at a depth of around 80 m

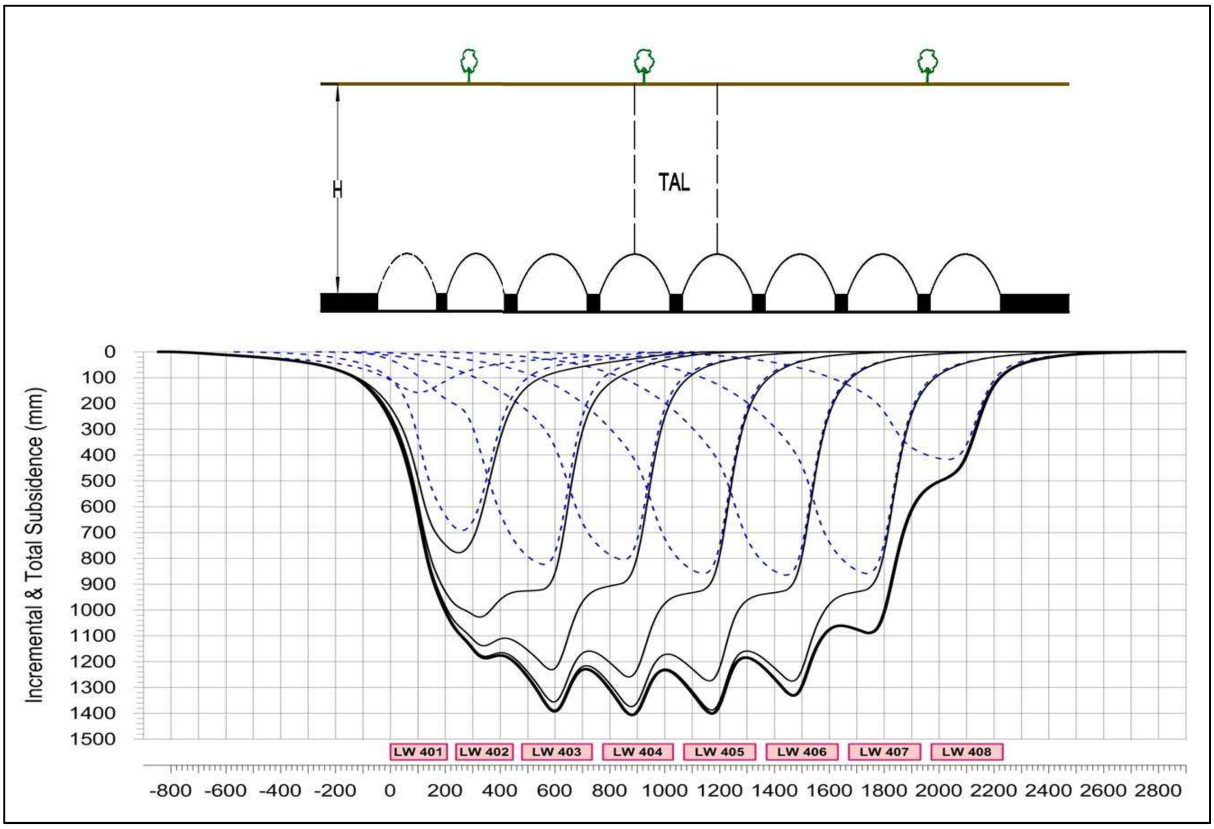


Figure 2-3: Vertical surface displacement profiles over 210 m wide longwall panels at a depth of around 500 m

As described by Galvin (2016), when the depth of cover is low (typically less than 150 m) and the total excavation width-to-depth ratio, W/H, for an individual panel is high (typically, at least one and often higher), the stiffness of the superincumbent strata over a shallow excavation can reduce to zero as it is being extracted, resulting in vertical surface displacement over that panel developing virtually independently of that over adjacent panels. The abutment load on the interpanel pillars is relatively low because the depth of cover is shallow and because the superincumbent strata over the flanking excavations do not dome and form a bridge. This results in near symmetrical profiles of vertical surface displacement, such as those shown in Figure 2-2, as soon as each panel is extracted. In these circumstances, compression of the interpanel pillars (chain pillars) and their immediate roof and floor strata makes only a minor contribution to vertical displacement and over 90% of the final vertical displacement at a surface point is usually reached within weeks of it being undermined. The measured vertical surface displacement above interpanel pillars in these circumstances may largely reflect interaction of neighboring subsidence troughs rather than compression of the pillar system and surrounding strata.

The situation is quite different at depth, as shown in Figure 2-3, which illustrates conditions for a mine in the Southern Coalfield of NSW. This figure shows that limited vertical surface displacement occurred over the first longwall panel, being LW 401, when it was extracted. Extraction of LW 402 resulted in a large step increase in vertical displacement over LW 401. The overall vertical surface displacement profile is found by summing the incremental displacement profiles. This type of subsidence development is more typical of mines in the Woronora and Metropolitan Special Areas.

2.1.1. Type of Subsidence Effects

Subsidence is the term given to the deformation of the ground in response to underground mining. Originally subsidence engineering was only concerned with downward vertical movement of the ground. This view of subsidence affected the way it was measured and the assumed extent of impacts. Commonly the zone of influence was assumed to be limited laterally out to where an imaginary line drawn upwards from the edge of the workings intersected the surface at a point where negligible downward movement had occurred. The angle was found to vary between coalfields and commonly referred to as the angle of draw.

The Literature Review focused on subsidence as a consequence of large scale voids due to longwall mining at depth (at least 100 m below surface). This type of subsidence is commonly divided into one of two components:

Systematic Subsidence - also known as conventional or classical subsidence. This describes the expected ground behavior in the absence of 'anomalous' influences such as valley effects. It also excludes the influence of any specific geological structure such as faults or dykes.

Non Systematic Subsidence - also known as non-conventional or site-centric subsidence. This describes the unexpected ground behaviors that cause a deviation from the expected systematic behavior, i.e. closure, upsidence (reduced vertical displacements), movement on geological structures and far field movements.

The ground movements which occur due to subsidence are typically described using a set of parameters which include:

- **Vertical displacement**, of a point, usually expressed in mm;
- **Horizontal displacement**, of a point, usually expressed in mm;
- **Tilt**, which is the change in the slope of the ground surface between two points induced by differential vertical displacement between these points; that is; tilt is the difference in vertical displacement between two points divided by the distance between the two points. It is usually expressed in units of mm/m;
- **Curvature**, which is the rate of change of tilt, and is calculated as the change in tilt between two adjacent points divided by the distance between the two points. Curvature is usually expressed in units of km^{-1} (that is, 1/km)*;*
- **Strain**, which is calculated as the change in horizontal displacement between two points on the ground, divided by the original horizontal distance between them. Strain is typically expressed in units of mm/m, and is termed tensile (positive strain) if the distance between two points increases, and compressive (negative strain) if the distance between two points decreases;
- **Angle of draw**, which defines the angle from the horizontal projected from the panel edge to the surface, such that vertical displacement is considered negligible (typically less than 20 mm) outside of this angle. In the Southern Coalfield, this angle has been considered to be approximately 26.5°, however much larger angles are commonly measured.

Tilt and curvature can be derived mathematically directly from vertical displacement using differentiation. Tilt is the first derivative of vertical displacement and curvature is the second derivative. As strain is a measure of differential horizontal displacement, it cannot be derived mathematically from vertical displacement. Empirical subsidence prediction methods typically rely on a correlation with either vertical displacement or curvature to estimate strain. In most cases this correlation is simply a fixed multiplier of curvature. Strains (in mm/m) in the Southern Coalfield are commonly estimated as 10 to 25 times the curvature (in 1/km), with the most commonly assigned value being 15.

The magnitude and extent of subsidence at the surface due to longwall mining is largely thought to be controlled by panel width, overburden thickness, and the extracted coal seam thickness and overburden geology.

Systematic subsidence theory is based on the following assumptions:

- The surface topography is relatively flat;
- The rock mass is uniform with no influence from large scale structures;
- The surrounding rock mass does not contain any extremely strong or extremely weak strata. Where these strata types are present, the strong or weak strata may modify the magnitude of the subsidence, which still develops systematically.

Non-systematic subsidence is irregular mining induced effects that occur when the ground conditions do not fit those expected for systematic prediction. These conditions include:

- Valleys and gorges that may alter the in-situ stress regime and cause bulging, cracking and shearing in the valley floors, inward and downslope movement of the valley sides (walls), and tensile cracking/opening of joints in the valley sides.
- Massive overburden that may span tens to hundreds of metres with minimal deflection and without failing, causing increased abutment stress and strata compression over, under and within abutment and chain pillars. Massive strata may also cave cyclically (periodically) or sporadically rather than regularly to produce an irregular profile of vertical displacement at the surface, or they may result in zones of reduced vertical displacement. Surface uplift of the order of tens of millimeters can also occur around the edges of excavations due to rotation of thick beds over the panel abutments.
- Compression and/or failure of the chain pillar system (comprising the floor strata beneath a pillar, the coal element of the pillar system and the strata overlying the pillar for many tens of metres into the super-incumbent strata) may occur due to various mechanisms. Chain pillar system failure can take a considerable period of time to develop, especially where it is associated with swelling, creep or breakdown of soft or weak roof or floor strata. Mining may have been completed in the area many years earlier and that area, or even the mine, abandoned before instability becomes apparent.
- A steep or sloping surface above a panel can cause surface cracking on the topographical high sides of the mine workings and compression humps in topographical low sides.
- Far field horizontal movements that occur beyond the angle of draw, these being mainly horizontal.

Major irregularities in subsidence effects can often be attributed to the presence of surface incisions such as gorges, river valleys and creeks. Mining induced valley movements are typically described using the following measures:

- **Upsidence**, which is an expression of reduced vertical displacement or relative uplift within a valley compared to systematic (conventional) subsidence behavior. Upsidence is a result of anticlinal bulge beneath the valley, which may spread out on each side of the valley axis for a considerable distance, and, localised buckling in the base of the valley due to compressive failure or shear of the surface and near-surface strata.

- **Closure**, which is the reduction in the horizontal distance between the sides of a valley or depression. Observed closure movements across a valley are the total movement resulting from various mechanisms, including systematic mining induced movements, valley closure movements, far-field effects and other possible strata mechanisms such as downhill soil slumping of unconsolidated deposits.

- **Compressive strains**, which occur at the base of valleys as a combined result of conventional subsidence, valley closure, the buckling or shearing of the near surface strata, and the downhill movement of valley sides under the effect of gravity.

- **Tensile strains**, which occur in the crests of the valleys as a combined result of conventional subsidence, valley closure and the downhill movement valley sides under the effects of gravity.

Far-field horizontal surface displacements have been detected in the Southern Coalfield for up to several kilometres from the limits of mining. These regional-scale movements are generally greatest at the goaf edge and decrease with increasing distance from the goaf. Although this behavior is not fully understood by subsidence engineers, possible causes include:

- Simple elastic horizontal deformation of the strata within the exponential 'tail' of the subsidence profile that applies in conventional circumstances;

- Influence of valleys and other topographical features which remove existing constraints to lateral movement and permit the overburden to move 'en masse' towards the goaf area, possibly sliding on underlying weak strata;

- Unclamping of existing near-surface horizontal shear planes;

- Influence of unusual geological strata which exhibit elasto-plastic or time dependent deformation;

- Stress relaxation towards mining excavations;

- Horizontal movements aligned with the principal in-situ compressive stress direction;

- Valley-notch stress concentrations;

- Movements along regional joint sets and faults; and

- Unclamping of regional geological plates.

2.1.2. Effects of Subsidence on Hydrogeological Conditions

Subsidence is known to affect hydrogeological conditions in a number of ways including changes to hydraulic conductivity, permeability and porosity. Of particular relevance to hydrogeological conditions is the vertical and lateral extent of new fracturing in response to extraction as well as the areal extent, frequency and orientation of new fractures. These fractures increase both the permeability and storativity of the affected rockmass, and both are liable to lower water tables and divert surface waters.

Field studies on fracturing and hydrogeological affects are limited due to cost limitations and difficulties in instruments surviving the direct effects of subsidence. Historically, utilising arrays of surface to seam extensometers and drilling piezometers has played an important role in assessing the impacts of fracturing. Increasingly the analysis of these effects is based on laboratory or numerical models. The validation of these models is limited as very few sites are extensively calibrated with field measurements.

A commonly adopted approach to characterising the fracturing above an extracted longwall panel is to divide the rock mass into conceptual zones and assume that each zone has a different degree and type of fracturing as a result of subsidence. Four zones are commonly recognised (from the mined seam upwards) in these models:

- **Caved or collapsed zone** - comprised of loose blocks of rock detached from the roof and occupying the cavity formed by mining. This zone can contain large voids. Some authors differentiate between primary and secondary caved zones.

- **Disturbed or fractured zone** - basically in-situ material lying immediately above the caved zone which has sagged downwards and consequently suffered significant bending, fracturing, joint opening and bed separation. Some authors include a secondary caving zone within this zone.

- **Constrained zone** - also called the intermediate or aquitard zone. Comprises rock strata above the disturbed zone which have sagged slightly but are assumed to be laterally constrained by surrounding rock mass, and have absorbed most of the strain energy without suffering significant fracturing or alteration to the original physical properties. Some bed separation or slippage is expected as well as limited and discontinuous vertical cracks (primarily on the underside of thick strong beds). Weak or soft beds in this zone may suffer plastic deformation.

- **Surface Zone** - unconfined strata at the ground surface in which mining induced tensile and compressive strains may result in the formation of near-surface cracking or ground heaving.

It is commonly perceived in Australian practice that claystone bands and/or rocks in compression in the constrained zone form “aquitards” to protect near-surface aquifers from depressurisation. There is limited field data to support this, and some data from investigations at Dendrobium Mine suggest the opposite (Parsons Brinckerhoff, 2015).

Galvin (2016) concludes that zoned models may be useful conceptually; however the end user must be aware of important limitations, being:

- None account for the effects of horizontal-to-vertical stress ratio and the important impact this can have on permeability, conductivity and the formation of a constrained zone;

- None account for discontinuous subsidence associated with bridging strata;

- In reality, behavior types, permeability and the lateral extents of affected areas is likely to change the conceptually arched top of the “disturbed zone” and base of the “constrained zone” gradationally as depth of mining increases relative to panel width.

More recently there has been a focus on Height of Connected Fracturing or more commonly termed Height of Connective Fracturing (HoF), as this parameter is used as a proxy for the base of the “constrained zone” in groundwater flow models and can be inferred from direct measurement of impacts. The most common means of measuring HoF is from down-hole extensometer measurements but it has also been inferred from pore pressure responses in piezometers. The vertical extent of HoF is inferred from interpolation between data points while the lateral extent is assumed based on some limited measurements, but largely based on conceptual models of the extent of impacts. Most of the existing methods for predicting HoF in NSW are empirical, based on extrapolation of limited observations and approximations.

In areas close to the zone of extraction i.e. the goaf and caved zones, both vertical and horizontal cracking is thought to be substantial and therefore rapid increases in vertical and horizontal permeability are expected, as well as increases in storativity of the rock mass. However, it is suggested by Booth (2002), ACARP (2008) and others that higher within the profile there is limited vertical connectivity within the fractured or constrained zone, which is argued to result in little to no increase in vertical permeability or vertical fluid flow in what is commonly referred to as the “constrained zone”. This restricted flow condition is assumed to be maintained even though increases in horizontal permeability may be substantial. This inference has prompted some researchers to adopt the term Height of Connected Fracturing (HoCF) by to differentiate between fracturing that is vertically connected, and hence likely to cause an increase in vertical permeability and flow, from the zone nearer the surface where vertical fractures may be prominent but are not inferred to be connected to the goaf (sometimes termed the “surface fracturing zone”.

As stated above, extensometer and piezometer measurements are the most common approaches to measuring inferred HoF however both methods have limitations in this regard. Extensometers provide some information on deformations at discrete points, which is often assumed to be due to vertical movement alone. However, they also respond to anchor slippage and other deformations such as horizontal and shear movement. Therefore, they should be regarded as only providing an indirect measurement of HoF. Piezometers provide an indirect measurement of the effects of HoF. However, they react to connectivity both vertically and horizontally and therefore do not represent a direct measure of HoF as depressurisation may be the result of increased horizontal permeability alone. Another issue is that the groundwater regime in mined overburden strata is likely to be in an unstable (transient) state for many months after mining, and piezometric levels need to stabilised before the height of desaturation (inferred to broadly coincide with HoF) can be reasonably inferred.

A key assumption in height of fracturing conceptual models is the effect of anisotropy. In the Caved Zone, the effects of fracturing and change in permeability are assumed to be similar in both the vertical and horizontal directions. In the Constrained Zone, however, the vast majority of the fracturing is assumed to be horizontal and not vertical as discussed above. Consequently, groundwater models that attempt to mimic this behavior simulate significant increases in horizontal permeability but little to no change in the vertical permeability. This is despite the limited ability for measuring instrumentation to differentiate between vertical and horizontal effects.

There are currently two models being commonly used to predict height of fracturing for subsidence impact assessment (Tammetta (2013) and Ditton and Merrick (2014)). These models have the following characteristics:

- They are empirical models designed to give a best fit of their respective databases using correlations of simple geometric measures (height of extraction, panel width and depth of cover);
- They are limited by the coverage of their databases (for example the maximum panel width in the Tammetta (2013) database is 260 m while Ditton and Merrick (2014) have only three panels out of 34 greater than 300 m wide);
- They ignore any site specific geological conditions;

- They require significant error corrections to encapsulate all of the input observations; and
- The observations on which empirical relationships have been derived are not absolute but are based on interpretation.

The impact of longwall-induced fracturing on hydraulic properties has been examined by several studies. A recent study conducted by Parsons Brinkerhoff (2015) investigated the permeability changes due to longwall mining by conducting pre and post-mining packer testing above an extracted longwall panel at the Dendrobium Mine in the Southern Coalfield of NSW. The results from this testing are summarised as:

- Mining increased the mean permeability in each unit by 1.5 to 3.5 orders of magnitude;
- Deeper units typically experienced a greater increase in permeability;
- More permeable zones appeared to correspond to zones with higher pre-mining bedding plane frequencies;
- A down-hole video survey showed a number of large open fractures above the water table. Most were sub-horizontal, but some inclined to sub vertical fractures were noted;
- At depths below 100 m, water was observed cascading out of some fractures at an estimated rate of around 1 L/s.

At this point in time it can be concluded that our understanding of subsidence on overburden strata is not complete. Further it can be concluded that our ability to accurately predict HoF (or HoCF) is poor.

2.1.3. Mining near Water Bodies

Holla and Barclay (2000) provide a review of requirements for total panel extraction beneath water bodies in different countries around the world. In many countries the requirements are said to be almost solely based on limiting vertical tensile strains in the overlying rock, typically to be within the range of 5 mm/m to 10 mm/m. These values are, on average, approximately double the strain limit of 4 mm/m that SCA (2013) suggested as the limit below which water inflow is unlikely to occur, based on experience with UK and Australian undersea mining.

There has been an ongoing debate on mining near Sydney water catchments areas since at least the 1880s. The Reynolds Commission (1973) concluded that mining should be allowed beneath the stored waters with the following conditions:

- The marginal zone around stored waters could be defined using and angle of draw equal to 26.5°;
- There should be no mining or driving of access roads beneath a dam structure closer than 200 m away from the edge of the structure or within an angle of draw of 35°;
- No mining in areas with less than 60 m of cover;
- Bord and pillar mining restricted to depths greater than 60 m with restrictions placed on pillar dimensions;

- Panel and pillar mining restricted to depths greater than 120 m with restrictions placed on mine dimensions.

An outcome of the Reynolds Inquiry was the creation of the *Dams Safety Act 1978* and the Dams Safety Committee (DSC) which was responsible for administering the Act. At the inception of the DSC, extra buffer zones additional to the Reynolds Inquiry recommendations of 0.5 times depth were used as the basis for defining where mining activity adjacent to stored waters may need to be controlled although extractive mining was still permitted within this zone. This zone was called a restricted zone and was equal in size to 1.2 times the seam depth. These offset distances, known as Notification Areas, are essentially still in effect today and are currently administered by the DSC.

2.1.4. Gaps in Existing Knowledge

Key gaps in existing knowledge identified from the Literature Review on subsidence effects, impacts and consequences are:

- The fundamental basis upon which HoF models have been developed is that there is a discrete height of complete desaturation above which there is a constrained zone where groundwater levels will be permanently sustained, which does not appear to apply in many cases. In reality, groundwater depressurisation seems to occur as a gradual continuum of effect; greatest at the seam level and reducing upwards and not necessarily to a level that causes desaturation in the short term. The controls and mechanisms of desaturation are key data gaps.

- There are no reliable methods for detecting the true spatial extent and height of connected fracturing, this being a critical parameter for predictive modelling and one that may greatly affect losses of surface or groundwater.

- Piezometric and extensometer data are the most common means of inferring HoF, and should continue to be used, although their interpretation needs to be careful and consistent.

- Microseismic investigations can usefully identify where major cracking is occurring within overburden formations, but cannot discern their geometry. This technique should be more widely used.

- Despite the application of numerous empirical, analytical and, less commonly, numerical theoretical models, there are currently no reliable methods for the prediction of HoF in the Southern Coalfield. More use could potentially be made of a combination of models to check and calibrate predictions and inferred mechanical processes.

- Current methods for HoF prediction do not include the effects of geology or material properties such as rockmass strength or stiffness.

- HoF prediction methods are focused on data obtained directly above a longwall panel with limited data away from the center upon which spatial variation can be correlated against.

- HoF prediction methods assume a degree of fracture anisotropy that cannot be verified by readily available means of detecting impacts. Neither extensometers nor piezometers can distinguish between horizontal and vertical movements.

- There are no established methods for reliably predicting safe offset distance for water bodies. Any such “buffer zone” approaches would need to incorporate an adequate knowledge of the location and potential interconnections between basal shear planes and zones of vertically connective fracturing.

- Insufficient knowledge of how subsidence interacts with complex topographical landforms is currently available. It is suggested that both LIDAR and DinSAR remote sensing technologies should be trialed to enable subsidence bowls in complex terrains to be progressively mapped and their impacts studied.

3. SURFACE WATER

3.1. Surface Water Catchments and Drainage Systems

3.1.1. Topography

The Metropolitan and Woronora Special Areas are located within the Woronora Plateau, which is a deeply dissected sandstone plateau. There is significant topographic relief within the Plateau and the landform varies from gently sloping broad ridges and plateaux to steep-sided slopes along incised gullies. The topography broadly coincides with Hawkesbury Sandstone dip slopes falling to the north-west.

3.1.2. Streams and Swamps

The Woronora Plateau has a relatively high drainage density which reflects the erodibility of the soils, hydrologic character of the system, and the size and quantity of sediment load moved from the basin. The high drainage density in the Woronora Plateau is also related to the weathering resistance of the sandstone formations and its relative weakness along joints and other discontinuities. The main drainage lines on the plateau are the Woronora, Cataract, Cordeaux and Avon Rivers and O'Hares Creek. These major streams flow to the northwest down the elevation gradient, which is broadly coincident with geological bedding planes.

Upland swamps are a significant feature of the catchments within the Metropolitan and Woronora Special Areas, making up approximately 5% of the combined reservoir catchment areas. The four types of upland swamps that occur within the Special Areas and their key features are summarised as follows:

- Headwater swamps

– Comprise the majority of upland swamps and are often large or are represented by clusters of swamps where they occur in the headwaters or elevated sections of the Woronora Plateau.

– Usually occupy broad, shallow, trough-shaped valleys on first-order and sometimes second-order drainage lines.

– Most are inferred to be fed from a perched water table within the sediments that are independent of the natural regional water table.

– Usually terminate at points where the watercourse suddenly steepens or drops away at a 'terminal step'.

- Valley-side swamps

– Relatively uncommon in the Special Areas.

– Occur on steeper terrain than headwater swamps and are sustained by small horizontal aquifers that seep from the sandstone strata and flow over unbroken outcropping rock masses. This swamp type has comparatively shallow soils because the gradient usually limits sediment accumulation.

- Can be disconnected vegetatively from headwater swamps. Occur as pockets on the sides of valleys surrounded by terrestrial vegetation.

- Valley infill swamps

  - Less common than headwater swamps and occur on relatively flat sections of more deeply incised second and third order watercourses. They tend to be elongated downstream.

  - Fed from multiple sources of water with the primary source derived from overland streamflow with other contributions from through-flow and direct precipitation. Generally, the swamp is independent of the deeper regional water table. Due to their relatively large catchment areas these swamps tend to be wetter than many headwater and valley-side swamps.

- Hanging swamps

  - Very few in the Special Areas due to the low incidence of cliff lines and paucity of ironstone or often impermeable horizontal surfaces. Examples have been identified in the Bargo and Cataract gorges on the Woronora Plateau.

  - Fed by seepage through the sandstone, which then emerges on the cliff face or valley side when it reaches less permeable horizontal planes such as ironstone or claystone. They have only shallow or minimal sediment and are essentially a thick mat of shrub and fern vegetation.

3.1.3. Regional Climate and Hydrology

3.1.3.1 Climate

Analysis of the data shows that there is a marked decreasing rainfall gradient from east to west. The Woronora and Nepean catchments receive less annual rainfall than the other catchments. Areal actual average annual evapotranspiration generally decreases from south to north.

3.1.3.2 Flow Regime

A number of stream flow gauges are located on the watercourses within the study area, although very few of these gauges are designed to provide precise measurements in low flow periods. Data obtained from these gauges shows relatively high runoff per unit area in the headwater catchments of the Cataract Reservoir, moderate runoff in the headwater catchments of the Cordeaux, Avon and Nepean Reservoirs and relatively low runoff from the other catchments. The areas of higher runoff per unit area naturally correspond to the areas of higher rainfall.

3.1.3.3 Baseflow

From a surface water perspective, the term ‘baseflow’ is ill defined and there remains considerable debate amongst surface water hydrologists regarding an appropriate definition and any physical processes that can be attributed to baseflow derived from analysis of flow records alone. Within the RBMAF study, baseflow is defined as delayed discharge to permanent streams from regional aquifers, superficial aquifers (swamps) and saturated soil/ weathered rock.

The issue regarding the definition of ‘baseflow’ is further compounded by the fact that different methods of analysis lead to different estimates of baseflow as a proportion of total flow. In addition, the available methods do not adequately distinguish the relatively slow delayed outflow (such as flow from regional groundwater and superficial aquifers) from other components of flow during surface runoff events. In the context of understanding and quantifying processes that might be impacted by mining, it would be desirable to be able to discriminate between the various processes that contribute to the components of 'baseflow' and to define the contribution of each process to the total water resource.

3.1.3.4 Upland Swamp Hydrology

There is a range of processes that occur in different swamps. In the case of swamps monitored by Metropolitan Coal for example, one swamp demonstrated a consistent hydraulic gradient indicating flow from the swamp to the sandstone while another swamp demonstrated the reverse relationship. After an initial rise due to rainfall, many swamps demonstrate a relatively constant rate of water level decline, which can be mainly attributed to evapotranspiration and possibly some drainage to the underlying sandstone. A smaller number of swamps demonstrate water level decline representative of a recession curve characteristic of a water storage draining to a fixed outlet level such as a rockbar.

3.1.3.5 Water Quality

Water quality in the Special Areas is protected by buffer zones of pristine bushland around the dams and their immediate catchment areas. As a result, water quality in the Special Areas is generally of very high quality.

WaterNSW monitors water quality within reservoirs and declared catchments streams. The mining companies undertake routine water quality monitoring on the major watercourses within each project area as well as in selected control catchments in the Special Areas. The available water quality data demonstrate that there are wide variations in water quality along each of the monitored rivers, including control catchments, as well as over time.

Water quality of both quick flow and baseflow in stream runoff is influenced by a number of factors including the organic and inorganic fabrics within swamps and groundwater-rock interactions in shallow and deep aquifers. Monitored water quality is highly variable in space and time.

There has been limited study of groundwater quality associated with swamps in the Southern Coalfield. Water quality of swamps is normally reflected in the water quality of the drainages immediately downstream, which generally exhibit very low dissolved salts.

WaterNSW's main concern relates to the water quality in the reservoirs and the requirement to meet its obligations in relation to the water quality of its water supply customers. WaterNSW routinely collects water quality samples within the catchment, at the reservoirs and at the pre-treatment phase.

3.1.4. Impacts and Consequences of Coal Mining

3.1.4.1 Surface Water Quantity

A summary of the impacts and potential consequences of subsidence on surface water quantity in the Special Area catchments is provided below.

Table 3-1: Impacts and Consequences of Subsidence on Surface Water Quantity (based on NSW Government, 2008)

Physical Subsidence Impacts	Potential Consequences
▪ Cracking of stream rock bars; ▪ Tensile/shear movement of joint and bedding planes in the stream bed ▪ Localised uplift and buckling of strata in the stream bed (e.g. lifting/ mobilising of stream bed rock plates)	▪ Loss of surface water flow into subsurface flow path ▪ Loss of standing pools/connectivity ▪ Additional groundwater inflows and outflows ▪ Changes in water supply yields

Physical Subsidence Impacts	Potential Consequences
▪ Tilting of stream beds (both dynamic/ incremental and final outcome)	▪ Stream bank and bed erosion, migration of flow channels ▪ Changes in flow rates ▪ Reduction in water supply yields (not currently confirmed whether by significant volumes)

3.1.4.2 Surface Water Quality

A summary of the impacts and potential consequences of subsidence on surface water quality is provided in Table 3-2.

Table 3-2: Impacts and Consequences of Subsidence on Surface Water Quality

Physical Subsidence Impact	Potential Consequences
▪ Tensile cracking of stream rock bars ▪ Tensile/shear movement of joint and bedding planes in the stream bed ▪ Localised uplift and buckling of strata in the stream bed (e.g. lifting/ mobilising of stream bed rock plates	▪ Localised changes in stream water chemistry due to water-rock interactions along new flow pathways caused by subsidence ▪ Increases in iron, manganese, aluminum, sodium, calcium, barium, chloride and sulphate in surface water ▪ Increases in iron, barium, strontium and calcium together with the bicarbonate anion in surface water ▪ Mobilisation of carbonates to give bicarbonate ions ▪ Orange discoloration of surface water due to dissolved iron ▪ Growth of bacterially-mediated iron mats and blooms in rock pools ▪ Reduction in dissolved oxygen and related eco toxic impacts ▪ Increases in alkalinity and salinity ▪ Consequences are likely to be sporadic, localised in nature and have had no detectable influence on water quality in downstream reservoirs

NSW Chief Scientist & Engineer (2014) found that although the impact of underground longwall mining in the catchment could lead to small changes in the levels of impurities in water entering WaterNSW's dams, these changes can be coped with by Sydney Water's treatment plants. In an attachment to the above-cited report, Professor Chris Fell stated that "*There is insufficient evidence at present of any soluble organic impact on water resulting from the subsidence caused by long-wall mining.*" Professor Fells concluded that raw water quality issues in the Special Areas can largely be managed through existing treatment works, although "*any new developments in catchments should be preceded by a careful investigation of their likely effect on the surface water in catchments, both in normal conditions and in extreme weather event*s".

3.1.4.3 Upland Swamps

Table 3-3 summarises the potential subsidence impacts and potential consequences for swamps.

Table 3-3: Impacts and Consequences of Subsidence on Swamps

Physical Subsidence Impacts	Potential Consequences
Valley infill swamps	

Physical Subsidence Impacts	Potential Consequences
Tensile cracking, tensile/ shear movement of joint and bedding planes, and buckling and localised upsidence in the stream bed below the swamp	Draining of swamps, leading to: ▪ drying and potential erosion and scouring of dry swamps ▪ loss of standing pools within swamps ▪ vulnerability to fire damage of dry swamps ▪ change to swamp vegetation communities ▪ adverse water quality impacts, e.g. iron bacterial matting Loss of stream baseflow Loss of swamp ecology (terrestrial and aquatic) Reduction or loss of flow leads to a range of downstream consequences
Headwater swamps	
Tensile cracking and tensile/ shear movement of joint and bedding planes in the rocks below the swamp	Potential drop in perched water tables, leading to draining of swamps Impacts are likely to be similar in character but less extensive and significant than for valley infill swamps Loss of swamp ecology (terrestrial and aquatic) Loss of flow can lead to a range of downstream consequences

Sources: NSW Government (2008) and Commonwealth of Australia (2014)

3.1.5. Gaps in Existing Knowledge

Water resources and hydrological processes are not understood in sufficient detail to allow a cause and effect relationship to be quantified between mine subsidence effects, impacts and consequences for flow in the creeks and the available water in the reservoirs. At the catchment-wide scale, the reservoirs in the Metropolitan and Woronora Special Areas have been in existence for long enough for those public authorities responsible for water supply to have a good understanding of the available resource and the variability from year to year. However at the smaller spatial and time scales more likely to reflect consequences of mining there is insufficient detailed understanding of the following key parameters and processes.

3.1.5.1 Baseflow

Baseflow is considered by WaterNSW to be an important contribution to the reservoirs during extended dry periods. This flow is sustained by drainage from the regional groundwater and, to some extent, by outflow from headwater swamps, both of which are vulnerable to the effects of subsidence (lowering of the regional groundwater or drying of headwater swamps). However, different analytical approaches to defining baseflow produce vastly different estimates of the proportion of total flow into the reservoirs that constitutes baseflow.

- The current flow monitoring network is focused largely on measurement of flow in the major river systems. In order to be able to better define the baseflow component it would be necessary to:

– ensure the accuracy of water level measurement and the rating for very low flows;

  - continuously monitor salinity as a tracer in accordance with the recommendation from SKM & CSIRO (2012);

- The current assumptions adopted for purposes of estimating baseflow are based on the gauging of the major river systems. However, because the reservoirs are long and narrow a large proportion of the catchment area constitutes small catchments draining directly into the reservoirs. These small catchments behave differently to the larger catchments and can be expected to have a smaller proportion of baseflow than the major catchments. Monitoring of examples of these types of catchments would help to clarify the overall magnitude of baseflow to the reservoirs.

3.1.5.2 Near Surface Hydraulic Gradients

There is a paucity of firm evidence regarding the fate of water lost from swamps and watercourses, which is dependent on the position and hydraulic gradient of the underlying regional aquifer water table. Loss volumes are also affected by the relative magnitude of any changes in horizontal and vertical hydraulic conductivity.

Metropolitan Coal has contributed to developing an understanding of the relative water levels in swamps and shallow groundwater in the sandstone beneath swamps. The evidence from the monitoring undertaken to date is that hydraulic gradients leading to flow towards and away from some swamps have been observed. This infers that there is some direct or indirect connectivity (being local discharge or enhanced recharge) between some swamps and the regional aquifer water table. Similar shallow bedrock monitoring in other swamps that are currently monitored only for swamp-sediment water levels is required to improve the understanding of the interactions between swamps and the underlying groundwater systems. Further understanding of the fate of water lost from swamps and cracked creek beds could also be gained by the installation of a line of piezometers down slope of an impacted area in order to determine the magnitude of any induced changes in the hydraulic gradient.

3.1.5.3 Near Surface Hydraulic Conductivity

A commonly observed mine-induced subsidence effect in the Special Areas is fracturing within the “surface zone”, which may be tensile or compressive depending on the relative geometry of the longwalls and the overlying valleys and ridges. Information on the depth to which cracking occurs below the surface and relative magnitude of changes in the horizontal and vertical permeability in this zone and the underlying constrained zone are critical to an understanding of the fate of water that is lost from surface water and shallow groundwater systems. Given that the vertical hydraulic gradient is usually downwards, the relative magnitude of changes in horizontal and vertical hydraulic conductivity in the surface fracture zone will affect the direction of flow of water lost from the surface. Another unknown factor is the effect of down-slope rock that has not been impacted by subsidence on groundwater flow patterns and the quantity and quality of returning water to the surface.

3.1.5.4 Climatic Effects on Swamps

Direct rainfall is a major contribution to water in swamps. Measurement of rainfall at the swamp is undertaken in very few instances, and virtually nothing is currently known of true evapotranspiration rates.

Evapotranspiration is a function of the atmospheric conditions, the available soil moisture and the vegetation type. A key data gap for swamp hydrology is an understanding of how the actual evapotranspiration rate changes as the swamp soils dry out.

3.1.5.5 Measurement and Modelling

Issues of concern to WaterNSW are the maintenance of water supply (and quality) and the preservation of the ecological functioning of the catchments. In relation to water supply, the key concerns relate to the magnitude of any loss of supply to the reservoirs. Two issues common to monitoring and modelling to be resolved are:

- Is the monitoring system capable of detecting change at a time and spatial scale that is important for water supply, and if so can it distinguish mining impacts from climate and catchment ranges of variability?
- Does any hydrologic model contain the relevant structure to adequately represent the physical processes that may change as a result of mining and can the parameters needed for such a model be determined with sufficient spatial discrimination?

Current catchment models and monitoring systems do not appear capable of detecting or representing the detailed hydrologic processes that occur at a local catchment scale.

4. ECOLOGY

The maintenance and protection of the ecological integrity of the Special Areas is a key principle of WaterNSW. The environments of consideration for the RBMAF include upland swamps, streams and the broader terrestrial landscapes. The ecological integrity (**loosely** referred to as biodiversity if the latter term is used in its contemporary context) comprises all living things and the environments in which they live, and recognises genetic diversity, ecosystem diversity, the range of ecosystem processes across landscapes and the environmental services they provide. The ecological component of the RBMAF has been addressed under three broad ecosystem types found in the Special Areas: aquatic biodiversity (streams), upland swamps and terrestrial biodiversity.

4.1. Aquatic Biodiversity

The aquatic environments in the Special Areas comprise a complex network of rivers, streams, standing water and upland swamps, and the biota dependent on these systems are equally diverse. Surface aquatic environments have attracted most of the attention in the literature, however an increasing awareness of subterranean ecosystems and groundwater dependent ecosystems is evolving.

Aquatic invertebrates include several species of freshwater crayfish and a diverse range of smaller taxa, including freshwater shrimp, molluscs, worms and aquatic macroinvertebrates. Aquatic macroinvertebrates studies indicate that regulated flow has a profound impact on assemblages that threatened species were not generally observed, and that species assemblages were indicative of different river health conditions and showed significant within stream and between river variations.

A number of native fish have also been recorded along with six alien species. The distribution and abundance of fishes, like the aquatic flora, are poorly researched in the Special Areas. The headwater storages of Avon, Nepean, Cordeaux and Woronora are barriers to fish that spawn in the estuaries or at sea and then are unable to make recolonising migrations upstream of these impoundments. The Macquarie Perch is the only fish species listed as threatened that is known to occur in the Special Areas and it is listed as endangered under the *Fisheries Management Act* 1994 and the *Environment Protection and Biodiversity Conservation Act* 1999 (EPBC Act). Macquarie Perch have been observed in Wongawilli Creek at the crossing of Fire-Road 6 (Krogh, 2008).

4.2. Upland Swamps

There are more than 1,400 upland swamps located in the Special Areas. They comprise terrestrial vegetation that are generally treeless heaths and sedgelands and are home to many terrestrial faunal species. Many provide critical habitat for biota that are wholly, partially or opportunistically groundwater dependent. Upland swamps, as 'priority fauna habitat,' are listed as key habitat for at least 12 priority fauna species as well as habitat for the threatened Prickly Bush-pea. In addition, there are the key obligate, groundwater dependent fauna species/communities including the Giant Dragonfly, the stygofauna and the freshwater burrowing crayfish. The four types of upland swamps that occur within the Special Areas are described in Section 3.1.2.

4.3. Terrestrial Biodiversity

4.3.1.1 Terrestrial Vegetation

The Special Areas contain a diversity of terrestrial ecosystems and habitats, and the variation in the geological, topographical and hydrological environments allow for many different vegetation communities to evolve. They include open forests, rainforests, woodlands, heaths and uplands swamps.

A number of vegetation communities which are known to occur or may occur in the Special Areas are recognised as endangered populations or endangered ecological communities listed under the *Threatened Species Conservation Act* 1995 (TSC Act) and also, for some, the EPBC Act. These include the Woronora Plateau population of *Callitris endlicheri* (a tree), Coastal Upland Swamp in the Sydney Basin Bioregion, Cumberland Plain Woodland in the Sydney Basin Bioregion, Southern Sydney Sheltered Forest on Transitional Sandstone soils in the Sydney Basin Bioregion, O'Hares Creek Shale Forest Community, Robertson Rainforest in the Sydney Basin Bioregion, Robertson Basalt Tall Open-forest in the Sydney Basin Bioregion, Shale Sandstone Transition Forest in the Sydney Basin Bioregion. In addition, there are a large number of threatened floral species known or likely to occur in the Special Areas.

Recognition that longwall mining, such as in the Southern Coalfield, can have adverse consequences on surface and groundwater hydrology, physical features, streams, swamps and biodiversity and has led to the 'Alteration of habitat following subsidence due to longwall mining' being listed as a Key Threatening Process under the TSC Act.

Terrestrial Fauna Habitat

Five broad habitat types were identified in the Woronora Special Area, comprising forest, heath and mallee, riparian and associated watercourse and upland swamp habitats. From these broad habitat types, three are recognised as being 'priority fauna habitat' for the Greater Southern Sydney Region. These include 'upland swamps', 'grassy Box Woodlands' and 'alluvial woodlands and forests'.

Cliffs, rock benches, rock overhangs and elevated sandstone ledges also provide shelter and nesting sites for threatened, protected and regionally significant species. Water in streams and pools provide critical habitat for threatened, protected and regionally significant terrestrial species.

The number of threatened fauna species that are likely to utilise habitats in the Woronora and Metropolitan Special Areas are in the order of 30 or more. Of particular interest are the threatened terrestrial species that are dependent on surface or groundwater for part of their life-cycle including the Giant Burrowing Frog, Red-crowned Toadlet, Giant Dragonfly and the Littlejohn's Tree Frog.

5. IMPACTS AND CONSEQUENCES OF COAL MINING

Significant (and comparatively subtler) changes to the environment can impact on biodiversity either directly or indirectly, over different time and space scales and cumulatively. The time and space relationship adds an additional dimension to evaluating impacts as ecological, hydrological and geomorphic processes can operate with considerable lag, are interdependent, have within and outside system influences and importantly have different ecosystem-resilience and recovery potentials following impact. Further, a number of reported 'minor' impacts can culminate into a more regionally significant impact with largely indeterminate long-term consequences.

5.1. Impacts and Consequences on Terrestrial Biodiversity

There are little to no known records of direct impacts on biodiversity associated with the terrestrial ecosystems on slopes and ridgetops. There is, however, evidence of short-term vegetation dieback as a result of temporary gas releases from near surface strata in the Upper Cataract River gorge and dieback of riparian vegetation on the Waratah Rivulet River/Eastern Tributary.

Despite the low recorded incidence of impacts on terrestrial biodiversity (either through lack of observed impacts or lack of targeted surveys), there is an ongoing risk that impacts and consequences, such as bedrock cracking, diversion of overland runoff to underlying strata, cliff falls and the lowering of the water table may present in the future with adverse potential consequences to fauna habitat and groundwater dependent ecosystems.

Factors that can influence the duration, intensity and probability of impact and their related consequences include degree of impact, ecosystem recovery potential and resilience, groundwater dependency, past disturbance history and the future short and long-term climatic conditions.

5.1.1. Impacts and Consequences on Aquatic Biodiversity

Reported consequences of subsidence impacts have include draining of pools, iron staining, alteration in macroinvertebrate assemblages, alteration of surface flows, flow diversion and dieback of gas-affected vegetation.

Ecological consequences on aquatic biodiversity may reasonably be predicted in any stream which experiences rapid changes in pool depth, flow rates, physical alteration of the stream bed, alteration of the subterranean zone or a change in water quality.

The factors that can influence the degree of impact include stream flow, type of stream bed substrate, geomorphic character of the stream, catchment area, persistence of iron springs, characteristics of instream pools, ecosystem recovery potential, past disturbance history, groundwater dependency and the ability of aquatic organisms to mobilise and recolonise.

5.1.2. Impacts and Consequences on Upland Swamp Ecosystems

A number of upland swamps have reportedly been impacted by mining in the Special Areas with the main recorded consequences relating to swamp drying, change in perched water tables, erosion and the alteration of baseflow contributions downstream. Impacts on ecosystems within the swamp may also ensue after several years of altered hydrological conditions, but are more difficult to measure and analyse.

The primary driver of upland swamp geomorphology and ecology processes is water derived from surface and groundwater sources. Longwall mining-related subsidence impacts that result in an alteration to swamp hydrology outside expected natural variation can adversely affect key biophysical and chemical processes.

Swamps can be differentially impacted depending on swamp ‘type’. However, across all swamp types, except hanging swamps, the primary consequences relate to swamp drying, peat desiccation and an increase in fire risk. The secondary consequences are complex and can include the alteration of vegetation structure and composition, loss of geomorphic stability, loss of habitat for fauna and groundwater dependent ecosystems, adverse consequences to downstream reaches and the alteration of nutrient and water cycles.

Factors influencing impacts and consequences include ecosystem recovery potential, groundwater dependency, degree of groundwater alteration, past disturbance history, fire history, prevailing climate and the type of impact or disturbance.

5.1.2.1 Gaps in Existing Knowledge

General data gaps include:

- Much of the data, analysis and reporting of impacts pertaining to longwall mining is in the ‘grey’ literature[2] and is project-specific; hence the studies are undertaken over different time and space scales, report at different levels of detail, the parameters measured vary and the scale of study may have varying usefulness for a ‘whole of area’ assessment. Further, the data is not always readily accessible to WaterNSW or in the public domain.

- There is a lack of a comprehensive, centralised data system that records, characterises, maps and quantifies mining-related impacts to the natural environment across the Special Areas.

5.1.2.2 Aquatic Biodiversity

Aquatic ecosystems are very diverse in the Special Areas and the general knowledge gaps as outlined above are applicable. Adequate long-term ecological impact studies using the Before-After-Control-Impact model is a recognised knowledge gap.

5.1.2.3 Upland Swamps

Knowledge gaps for the upland swamp ecosystems include:

- Where cracking of swamp substrates occurs, it is almost always masked by the swamp sediments. Use of geophysical or other techniques to map the cracking is not routinely undertaken and may or may not be effective, and the viability of rehabilitating swamps by sealing the substrate remains unknown.

- Understanding cumulative impacts across spatial and temporal scales and the hierarchical culmination of consequences.

- Hydrological balance of upland swamps with adequate baseline data.

- Data that specifically describes the overall ecological response to change in swamp environment is lacking, and the inherent variability of those swamp environments (and the microhabitats within them) make it difficult to model the community as a whole.

- Long-term ecological impact studies using the Before-After-Control-Impact model.

[2] The grey literature referred to in this report relates to material produced by organisations outside of the traditional commercial or academic publishing and distribution channels and includes government and industry reports, fact sheets and policy documents.

- Swamp wetness as measured by piezometers and soil moisture meters. The key factor driving swamp ecology and geomorphology is water: how wet is the swamp, is the superficial aquifer replenished by regional groundwater, how does water flow across the surface, what depth is the water table and how does it respond to rainfall, how far does the capillary fringe rise, what is the swamp water storage capacity, what is the hydraulic conductivity of the swamp substrate, what is the characteristic natural moisture fluctuations of the swamp and what is the degree of moisture heterogeneity of the swamp? Despite several years of extensive monitoring, answers to these questions are not consistently available.

5.1.2.4 Terrestrial Biodiversity

The dependency of the broad vegetation groups or site-specific vegetation communities on the regional groundwater is largely unknown, as is their resilience to withstand changes in regional water tables. Dependency (if any) is expected to be highly variable across the diversity of regional landscapes, leading to a major constraint in surveying and monitoring these attributes.

6. GROUNDWATER

6.1. Groundwater Systems

The groundwater systems underlying the Metropolitan and Woronora Special Areas are features of the natural environment and are important components of the catchment water cycle.

There are three primary groundwater systems across the area:

- Superficial aquifers (colluvium and minor alluvium).
- Regional aquifers (sandstone and minor volcanics).
- Deeper groundwater systems (comprising minor aquifers and aquitards in a variety of sedimentary rock types).

Groundwater in the superficial and regional aquifers forms a small but important component of the overall water balance for surface catchments across the Special Areas. Groundwater sustains baseflows to streams, and on a local scale supports (or partially supports) a variety of ecosystems. In the regions outside the Special Areas, groundwater is considered an important water resource. In the future it is possible that groundwater from within the Special Areas could be harvested for water supplies, but WaterNSW's priority currently remains on harvesting and protecting surface water resources.

Baseflow is typically defined as delayed discharge to permanent streams from regional aquifers, superficial aquifers (swamps) and saturated soil/ weathered rock. Baseflow is characterised by an exponential decay curve following the cessation of surface runoff. In addition, many hydrology texts and methods of hydrograph analysis also include baseflow that occurs during a surface runoff event.

From a WaterNSW perspective, the baseflow contribution to streams from regional groundwater and superficial aquifers (particularly evident following surface runoff events) are important as they are vulnerable to diversion through mine-induced cracking and are seen as an important flow component during droughts. These baseflow contributions are particularly at risk from longwall mining as groundwater levels typically reduce, sometimes by as much as 90 m, following undermining and it is not certain whether long-term recoveries will ever return to pre-mining levels.

A proportion of quickflow following high rainfall events will also be diverted where cracking and reduced regional groundwater levels are caused by subsidence. Enhanced groundwater recharge to regional aquifers is a likely consequence.

6.2. Impacts and Consequences of Coal Mining

The following **impacts on groundwater systems** may occur as a result of underground coal mining activities. Many of these have been recognised on a local scale in the Special Areas:

- Falling groundwater levels (also referred to as piezometric pressures);
- Loss of stored water;
- Changes in groundwater storage characteristics (porosity, permeability and capacity);
- Increased recharge rates in subsided areas and discharges in different parts of the landscape;
- Increased secondary porosity and permeability of consolidated rocks;
- Increased vertical flow and diminished horizontal flow;
- Interconnection of previously non-connected (or poorly connected) groundwater systems;
- Changed groundwater flow patterns;
- Changed geochemistry and salinity distributions within all groundwater systems;
- Drainage of superficial aquifers;
- Loss of streamflow to shallow aquifers;
- Poorer quality baseflow discharges (particularly pH and iron) to streams;
- Loss of groundwater to areas outside of the drinking water catchments;
- Creation of artificial groundwater storages in abandoned mine workings.

The **resulting consequences of these impacts** vary with the sensitivity of catchment features and each groundwater system and depth but can be summarised as:

- Loss of headwater and hillside swamps, and changed terrestrial and riverine ecosystems that are partially groundwater dependent;
- Loss of hillside springs and stream baseflow;
- More rapid and extended drying cycles in affected swamps;
- Changed flora and fauna composition of affected swamps, and terrestrial and riverine ecosystems that are partially groundwater dependent;
- Where large headwater swamps previously supplied baseflow to streams during dry periods, there will be smaller (or no) baseflow contribution as water is diverted into the regional sandstone aquifer;

- Increased recharge to the regional sandstone aquifer (with consequently reduced surface runoff) where extensional cracking occurs at surface;
- reduction in storage capacity in the regional sandstone aquifer where local groundwater levels fall and there is increased discharge into surrounding creeks (even with increased recharge);
- Reduced groundwater resource potential;
- Loss of high quality (low salinity) groundwater into the poorer quality Narrabeen Group groundwater system;
- Loss of groundwater discharge to stream sections that previously provided important baseflow contributions;
- (Slight) reduction in overall streamflow volumes;
- Stream losses will locally increase groundwater storage volumes, although a proportion of this water may return as stream baseflow lower in the catchment;
- Increased concentrations of low pH and high iron groundwater to streams;
- Smothering effect of colloidal and bacterial iron affecting riverine ecosystems;
- Groundwater gradients could flatten or reverse in the vicinity of the artificial lakes with potentially increased water losses;
- Increased flows to mining voids, which becomes sinks for surrounding groundwater;
- After the cessation of mining, abandoned mine workings will provide large artificial (sub-surface), low quality water storages.

Issues of most concern to WaterNSW are the impacts to surficial and regional aquifers and the resultant consequences that affect baseflows, water quality, associated ecosystems and catchment yield.

6.3. Gaps in Existing Knowledge

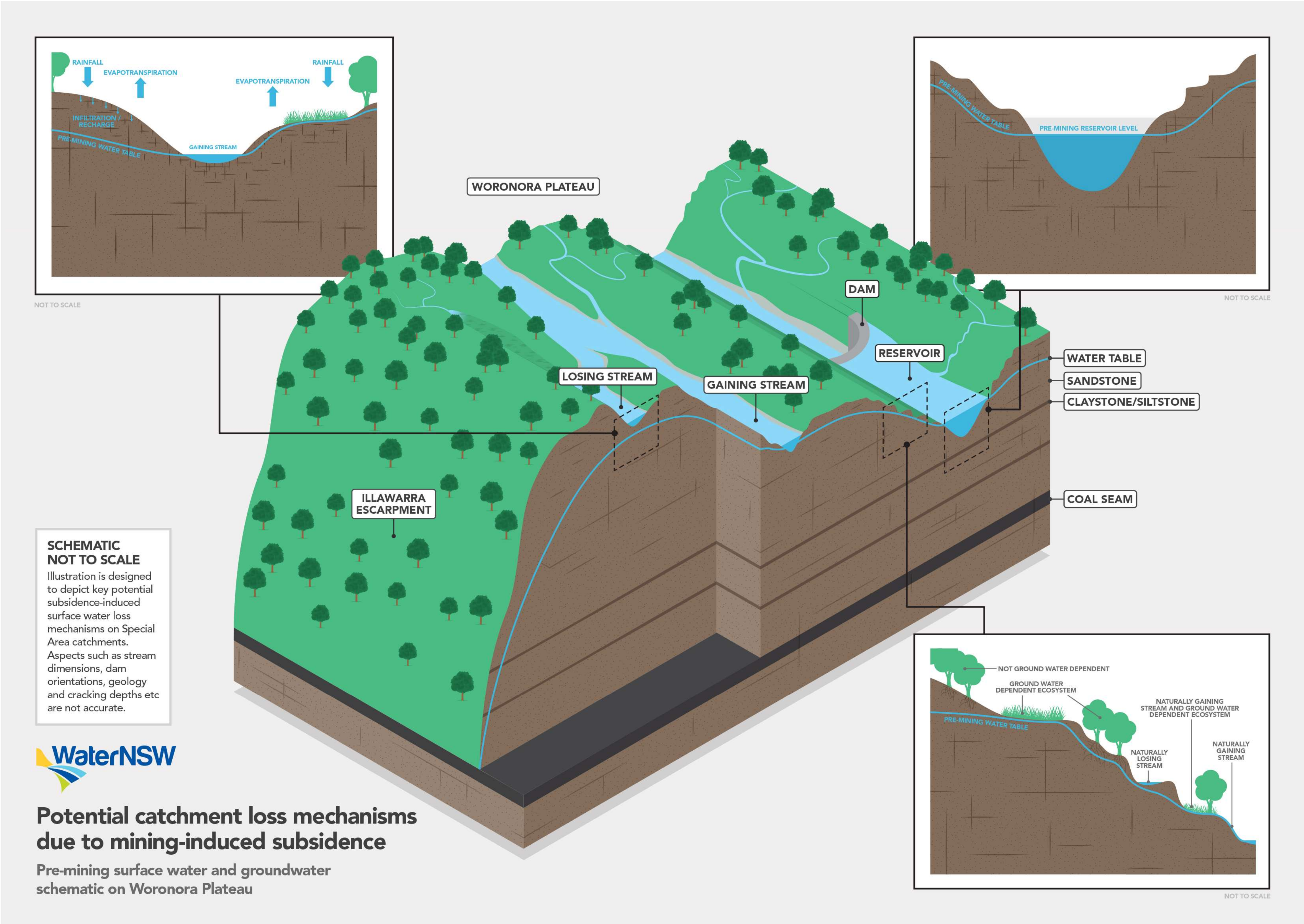
To fully assess the impacts and consequences of longwall mining on different groundwater systems, it is important to have a good spatial and temporal groundwater monitoring network for water levels/piezometric pressures and water quality. This requirement applies to both mining impacted areas and control sites. Groundwater responses and trends can take many years to comprehend and fully assess so the early establishment of networks is an important consideration. In many mining domains, current groundwater monitoring coverage and duration is inadequate, and the short and long-term trends for mining-induced changes particularly in the superficial and regional aquifers are not adequately known.

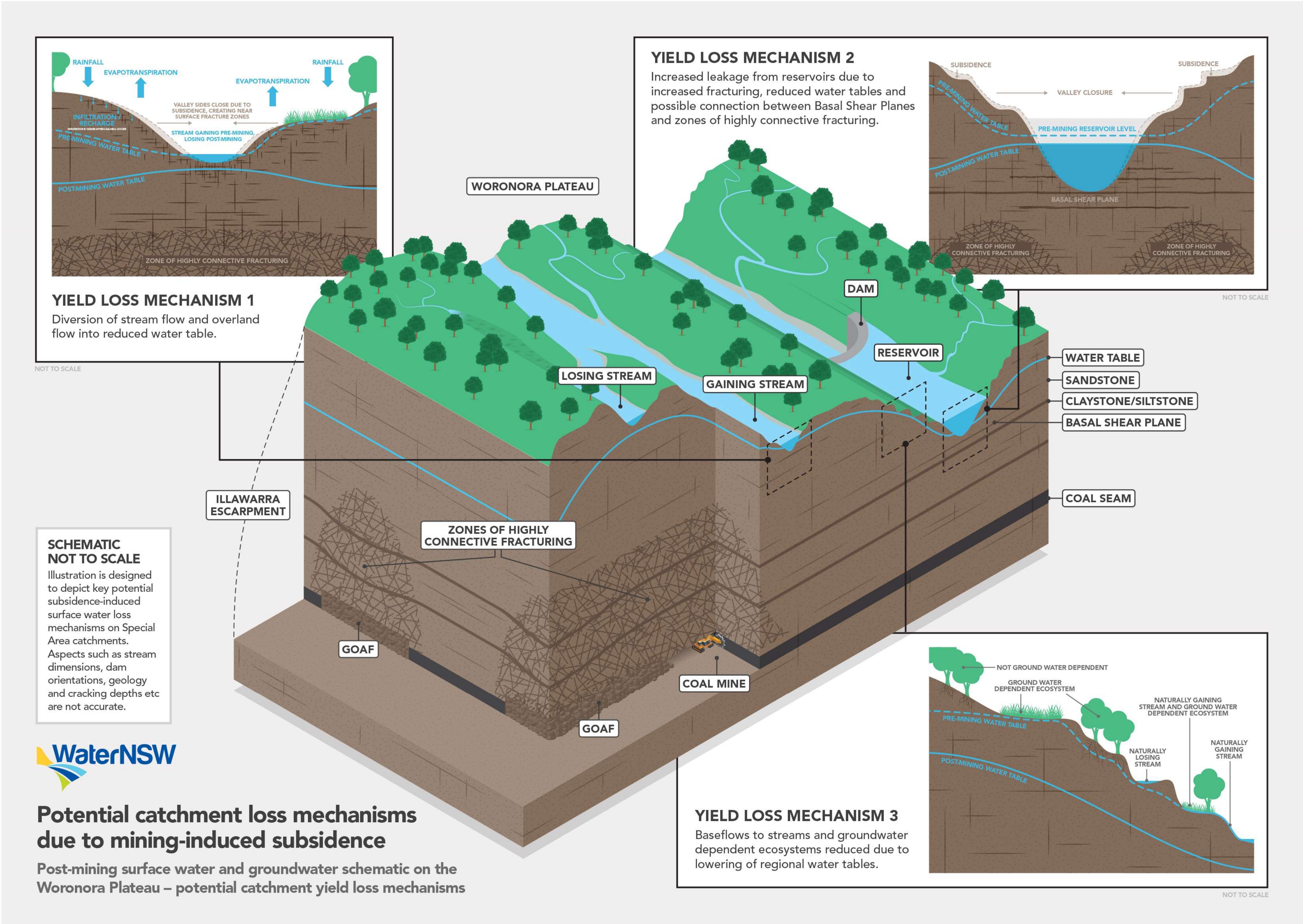
Baseline groundwater monitoring data is currently inadequate, with monitoring networks rarely providing more than 12 months of data prior to longwall mining. However, on a local scale there are now a number of project networks designed to assess short-term groundwater and baseflow trends resulting from mining.

The inability to compare mining trends with natural ‘pre-mining’ seasonal trends is a problem for WaterNSW, and on a regional scale it is consequently not yet possible to integrate data and trends or to evaluate the long term and cumulative consequences of induced groundwater system changes.

Appendix B

Diagrams showing key surface water diversions in pre- and post-mining scenarios on Illawarra Plateau


RAINFALL
EVAPOTRANSPIRATION
EVAPOTRANSPIRATION
RAINFALL
INFILTRATION / RECHARGE
PRE-MINING WATER TABLE
GAINING STREAM
NOT TO SCALE
PRE-MINING WATER TABLE
PRE-MINING RESERVOIR LEVEL
NOT TO SCALE
WORONORA PLATEAU
DAM
RESERVOIR
LOSING STREAM
GAINING STREAM
WATER TABLE
SANDSTONE
CLAYSTONE/SILTSTONE
COAL SEAM
ILLAWARRA ESCARPMENT
SCHEMATIC NOT TO SCALE
Illustration is designed to depict key potential subsidence-induced surface water loss mechanisms on Special Area catchments. Aspects such as stream dimensions, dam orientations, geology and cracking depths etc are not accurate.
WaterNSW
Potential catchment loss mechanisms due to mining-induced subsidence
Pre-mining surface water and groundwater schematic on Woronora Plateau
NOT GROUND WATER DEPENDENT
GROUND WATER DEPENDENT ECOSYSTEM
PRE-MINING WATER TABLE
NATURALLY GAINING STREAM AND GROUND WATER DEPENDENT ECOSYSTEM
NATURALLY LOSING STREAM
NATURALLY GAINING STREAM
NOT TO SCALE


RAINFALL
EVAPOTRANSPIRATION
RAINFALL
EVAPOTRANSPIRATION
VALLEY SIDES CLOSE DUE TO SUBSIDENCE, CREATING NEAR SURFACE FRACTURE ZONES
INFILTRATION / RECHARGE
INFILTRATION IS HIGHER AFTER CRACKING OCCURS
STREAM GAINING PRE-MINING, LOSING POST-MINING
PRE-MINING WATER TABLE
POST-MINING WATER TABLE
ZONE OF HIGHLY CONNECTIVE FRACTURING
YIELD LOSS MECHANISM 1
Diversion of stream flow and overland flow into reduced water table.
NOT TO SCALE
YIELD LOSS MECHANISM 2
Increased leakage from reservoirs due to increased fracturing, reduced water tables and possible connection between Basal Shear Planes and zones of highly connective fracturing.
SUBSIDENCE
SUBSIDENCE
VALLEY CLOSURE
PRE-MINING WATER TABLE
PRE-MINING RESERVOIR LEVEL
POST-MINING WATER TABLE
BASAL SHEAR PLANE
ZONE OF HIGHLY CONNECTIVE FRACTURING
ZONE OF HIGHLY CONNECTIVE FRACTURING
NOT TO SCALE
WORONORA PLATEAU
DAM
RESERVOIR
LOSING STREAM
GAINING STREAM
WATER TABLE
SANDSTONE
CLAYSTONE/SILTSTONE
BASAL SHEAR PLANE
COAL SEAM
ILLAWARRA ESCARPMENT
ZONES OF HIGHLY CONNECTIVE FRACTURING
GOAF
COAL MINE
GOAF
SCHEMATIC NOT TO SCALE
Illustration is designed to depict key potential subsidence-induced surface water loss mechanisms on Special Area catchments. Aspects such as stream dimensions, dam orientations, geology and cracking depths etc are not accurate.
WaterNSW
Potential catchment loss mechanisms due to mining-induced subsidence
Post-mining surface water and groundwater schematic on the Woronora Plateau – potential catchment yield loss mechanisms
NOT GROUND WATER DEPENDENT
GROUND WATER DEPENDENT ECOSYSTEM
NATURALLY GAINING STREAM AND GROUND WATER DEPENDENT ECOSYSTEM
PRE-MINING WATER TABLE
NATURALLY LOSING STREAM
NATURALLY GAINING STREAM
POST-MINING WATER TABLE
YIELD LOSS MECHANISM 3
Baseflows to streams and groundwater dependent ecosystems reduced due to lowering of regional water tables.
NOT TO SCALE

Appendix C

Recommended data and export file requirements for groundwater flow models to be examined in Ground Visualisation Software

As set out in main submission, WaterNSW recommends that the following list of information should accompany any groundwater model submitted in support of mining proposals in the Special Areas.

The list is broken into two tables below; Table C1 contains the metadata and information that can be communicated outside a graphical environment, whilst Table C2 lists those attributes that are better understood in a spatial context, and are better represented by importing into a groundwater visualisation package.

Table C1. Standard model information to be provided in electronic text or spreadsheet files

Property/ Parameter	*Description*
Model Objectives	A clear statement of the purpose of the model and what decisions the model seeks to address, as discussed in the Australian Modelling Guidelines (Barnett et al, 2012).
Model Metadata	Single text file that stores the high level model metadata as a .json object file. Any number of attributes may be specified in this file, e.g. model/run name, created date, author etc.
Grid Definition	Multiple text files exported as .json files, describing the 3D grid used by the model and its position in space.
Groundwater Pumping/Extraction Rates Applied	Excel table summarising predicted groundwater pumping or other discharge rates applied in model
Scenario Properties	Excel table explaining variables used in each scenario presented in report.
Receptors	Excel table summarising locations and types of key receptors considered in modelling
Water Budget	Excel table summarising key volumetric flows (water budget components) across the model space at key time slices*, both within model domain and through external boundaries.

Table C2 presents the layers and parameters which should be routinely exported from the model, using the formats provided in the appended guidance prepared by NICTA (Tabs B and C).

Table C2. Minimum model layers and parameters to be exported from model

Property Parameter	*Description*
Stratigraphy	3D representation of key stratigraphic layers (with labels based on Geoscience Australia stratigraphic names)
Hydraulic Properties	Key hydraulic properties generated following calibration, specifically vertical and horizontal hydraulic conductivity (K_v & K_h), storativity [s] at key time slices*.
Rainfall & Evapotrans.	A map summarising annual rainfall and evapostranspiration rates if areally varied.
Groundwater Recharge	Map layer showing inferred recharge rates and spatio-temporal variability (if any applied) for shallowest aquifer for each main time step*.
Borehole Data	Stratigraphic or lithological logs and temporal water level measurements of key monitoring wells.
Structural Geology	Major faults, shear zones or joint sets incorporated into model (if any applied).
Topography	Surface topography (presented as a digital elevation model)
Boundary Conditions	Graphical representation of the boundary conditions applied to each edge of the model.
Surface Water Features	Stream/lake bottom elevations and heads, streambed conductance.
Surface Water Interaction	Fluxes at base of stream/lake/drain features at key time slices*.
Receptors	Map layer showing location of main receptors, with legend denoting receptor types.
Predicted Heads	Separate contoured layers showing groundwater (and surface water if relevant) heads at current conditions, predicted at key time slices*.
Certainty	Level of model certainty/confidence associated with spatial data. As described in Section 8.5.7 and Figure 8-6 of the Australian Groundwater Modelling Guidelines (Barnett et al, 2012), one option is to present certainty as a colour density or by varying the transparency of a layer to indicate the level of uncertainty.

*** Note**

Where the parameters are requested in terms of key time slices, the default set of events for which those parameter should be provided are as follows:

1. Predicted conditions at commencement of the activity
2. Predicted conditions at “peak impact” for that parameter
3. Predicted conditions at completion of the activity

Predicted conditions once steady-state water conditions have returned following project closure