

# Literature Review of Underground Mining Beneath Catchments and Water Bodies

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Prepared for WaterNSW by:



**Advisian**

WorleyParsons Group

In collaboration with:



**John Ross**



**Mactaggart**

Natural Resource Management

**Grant Sutton & Associates**



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### WaterNSW – Literature Review of Underground Mining Beneath Catchments and Water Bodies

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# Executive Summary - Literature Review of Underground Mining beneath Catchments and Water Bodies

## S1. Introduction

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### S1.1 Approach

The Literature Review aims to summarise the key findings of all relevant studies and documents, with a preference to use 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, as well as relevant documentation identified by WaterNSW relating to the Southern Coalfield.

It is noted that very little of the available documentation on mining and subsidence effects, impacts and consequences has been peer-reviewed. The mining industry has co-operated through the Australian Coal Industry's Research Program (ACARP) organisation to 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 key documentation examined in this 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 which 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 (DP&E) and the Planning Assessment Commission (PAC).

### S1.2 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 *Sydney Water Catchment Management Act 1998*, 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 protect Sydney's drinking water. The Project focusses 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 S1.1.



**Table S1.1: Reservoirs within the Metropolitan and Woronora Special Areas**

Storage	Total Operating Capacity (ML)	Water Surface Area at Full Supply (ha) <sup>***</sup>	Water Storage Area at Full Supply (km <sup>2</sup> )	Catchment Area (ha)	Approximate Elevation (m AHD)
Woronora	71,790	400	4.0	7,225	180
Cataract	97,190	850	8.5	12,618	280
Cordeaux	93,640	780	7.8	8,684	320
Avon	146,700	1,050	10.5	14,256	330
Nepean	67,730	330	3.3	31,824	320
Broughtons Pass Weir	50	1.31		8,169	
Pheasants Nest Weir	25	0.25		13,596	

### S1.3 History of Water Supply and Mining Activities in the Special Areas

Table S1.2 summarises the history of mining and water supply activities in the Metropolitan and Woronora Special Areas.

**Table S1.2: History of Water Supply and Mining Activities in the Special Areas**

<b>Pre-1800</b>	<ul style="list-style-type: none"> <li>▪ Aboriginal occupation of area - Dharawal, Wadi Wadi and Gundurngurra people estimated to go back at least 15,000 years</li> <li>▪ 1788 First European settlement in the Sydney area</li> </ul>
<b>1800s</b>	<ul style="list-style-type: none"> <li>▪ 1800s Hand-got longwall mining on the advance in use in Australia</li> <li>▪ 1857 Commercial quantities of coal produced at Kemira Colliery 1850-1988 Kemira/Mt Keira</li> <li>▪ 1878-1991 Coal Cliff Colliery (bord and pillar) operated</li> <li>▪ 1861-1955 Mt Pleasant Colliery</li> <li>▪ 1861-2004 South Bulli (Bellambi) Colliery</li> <li>▪ 1865-1970? Mt Kembla Colliery</li> <li>▪ 1878-1991 Coal Cliff (bord and pillar) operated</li> <li>▪ 1880 Metropolitan Special Area declared to protect Upper Nepean catchment</li> <li>▪ 1888 Metropolitan Colliery opened at Helensburgh</li> <li>▪ 1888 Prospect Reservoir, Broughton's Pass Weir, Pheasants Nest Weir and the Upper Canal completed</li> <li>▪ 1892-1983 South Clifton Colliery</li> </ul>



<b>1900 - 1950</b>	<ul style="list-style-type: none"> <li>▪ 1900-1962 Excelsior No. 1 and No.2</li> <li>▪ 1907 Construction of Cataract Dam complete</li> <li>▪ 1910-1983 Avondale Colliery</li> <li>▪ 1916-1993 Wongawilli Colliery</li> <li>▪ 1926 Cordeaux Dam completed</li> <li>▪ 1927 Avon Dam completed</li> <li>▪ 1930-1980 Old Wollondilly Coal Mine (Warragamba Special Areas)</li> <li>▪ 1935 Completion of Nepean Dam</li> <li>▪ 1935-1973 Wollondilly Extended Coal Mine (Warragamba Special Areas)</li> <li>▪ 1941 Woronora Dam completed; Woronora Special Area declared</li> <li>▪ 1942-1973 North Bulli Colliery</li> <li>▪ 1946-1989 Huntley Colliery</li> <li>▪ 1946-1993 Nebo Colliery</li> <li>▪ 1947-1985 Corrimal Colliery</li> </ul>
<b>1950 - 2000</b>	<ul style="list-style-type: none"> <li>▪ 1955-1996 Oakdale Colliery (Warragamba Special Areas)</li> <li>▪ 1957-1982 Valley No. 1 (Warragamba Special Areas)</li> <li>▪ 1961 Mechanised longwall mining introduced</li> <li>▪ 1971-1999 Avon Colliery</li> <li>▪ 1971-1991 Darkes Forest Colliery</li> <li>▪ 1972-1981 Bulli Colliery</li> <li>▪ 1976-1986 Nattai North Colliery (Warragamba Special Areas)</li> <li>▪ 1968-1981 Brimstone Colliery (Warragamba Special Areas)</li> <li>▪ 1980-2001 Cordeaux Colliery</li> <li>▪ 1988-1991 Kemira Colliery (longwall in Wongawilli Seam)</li> <li>▪ 1993-2007 Wongawilli Colliery consolidated with Kemira and Nebo mines to become Elouera Colliery</li> <li>▪ 1999 Sydney Catchment Authority become operational</li> </ul>
<b>2000-present</b>	<ul style="list-style-type: none"> <li>▪ 2004 South Bulli (also known as Bellambi, Belpac No.1) become NRE No.1 and recently Russell Vale</li> <li>▪ 2005 Longwall mining commences at Dendrobium Coal Mine</li> <li>▪ 2007 Elouera Mine sold and renamed NRE Wongawilli Mine</li> <li>▪ 2015 WaterNSW becomes operational (replaces Sydney Catchment Authority)</li> </ul>

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 S1.3.

**Table S1.3: 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 from which the coal has been extracted, which tend to fill with collapsed rock and overburden material as the longwall progresses. Subsidence rates tend to be substantially greater over longwall mines.

## S2. Subsidence

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### S2.1 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 review is focussed 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:

1. **Systematic Subsidence** - also known as conventional or classical subsidence. This describes the expected ground behaviour 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.
2. **Non Systematic Subsidence** - also known as non-conventional or site-centric subsidence. This describes the unexpected ground behaviours that cause a deviation from the expected systematic behaviour, i.e. closure, upsidence, 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 subsidence**, which is vertical or horizontal movement of a point, usually expressed in mm;
- **Horizontal movement**, which is horizontal movement of a point, usually expressed in mm;
- **Tilt**, which is the change in the slope of the ground surface as a result of differential vertical subsidence, usually expressed in mm/m;
- **Curvature**, which is the rate of change of tilt, and is calculated as the change in tilt between two adjacent points. Curvature is usually expressed in units of 1/km;
- **Strain**, which is calculated as the change in horizontal movement between two points on the ground, divided by the original horizontal distance between them. Strain is typically expressed in units of mm/m, and are termed tensile (positive strain) if the distance between two points increases, or 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 subsidence is 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 are derived directly from subsidence using differentiation. Strain is differential horizontal movement and therefore is not directly derived from subsidence. Empirical methods

typically rely on a correlation with subsidence or subsidence derivative to estimate strain. In most cases this correlation is simply a linear proportion of curvature. Strains in the Southern Coalfield are commonly estimated as 10 to 25 times the curvature (measured in mm/m). The most common factor adopted for estimation using this method is 15.

The magnitude and extent of subsidence at the surface due to longwall mining is 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 rockmass is uniform with no influence from large scale structures;
- The surrounding rock mass does not contain any extremely strong or extremely weak strata.

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

- Valleys and gorges may alter the in situ stress regime and cause bulging, cracking and shearing in the valley floors, downslope movement of the walls, and tensile cracking/opening of joints in the valley walls.
- Massive overburden may sag and span tens to hundreds of metres without failing, causing increased abutment/gate road compression. Massive strata may also cave sporadically rather than regularly to produce vertical steps in the subsidence profile. Surface uplift of the order of tens of millimetres can also occur around the edges of excavations due to rotation of thick beds over the goaf.
- Gate road foundation settlement or failure may occur due to various mechanisms. Gate road system failure may take a considerable period of time to develop, especially where it is associated with 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. This behaviour is mainly confined to bord and pillar based systems.
- 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 movements that occur beyond the angle of draw.

Major irregularities in subsidence profiles 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 the reduced subsidence or the relative uplift within a valley compared to conventional subsidence behaviour. Upsidence is a result of anticlinal bulge beneath the valley, which spreads out on each side of the valley 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 result of valley closure and the buckling or shearing of the near surface strata.
- **Tensile strains**, which occur in the crests of the valleys as the result of valley closure movements.

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 behaviour is not fully understood by subsidence engineers, a range of 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.

## S2.2 Effects of Subsidence on Hydrogeological Conditions

Subsidence is known to affect hydrological conditions in a number of ways including changes to hydraulic conductivity 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 frequency and orientation of new fractures.

Field studies on fracturing and hydrogeological effects are limited due to cost limitations and difficulties in instruments surviving the direct effects of subsidence. Consequently much of the current theory of these effects is based on laboratory or numerical models. These models are a presentation of reality and very few are extensively calibrated with field measurements

A commonly adopted approach to characterising the fracturing above an extracted longwall panel is to divide the rockmass 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 discontinuous vertical cracks (usually 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.

Galvin (2016) concludes that zoned models may be very 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, behaviour types, permeability and the lateral extents of affected areas changes gradationally as depth of mining increases relative to panel width.

More recently there has been a focus on height of fracturing (HoF) as a measure of these impacts. HoF is primarily assessed from direct measurement of impacts. The most common means of assessing HoF data is predominantly from extensometer measurements but has also been inferred from pore pressure response 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 from conceptual models of the lateral extent of impacts. Most of the existing methods for predicting HoF are typically empirical and based on observations and approximations.

In areas nearer the zone of extraction, such as the caved zone, both vertical and horizontal cracking is thought to be substantial and therefore significant increases in vertical and horizontal permeability are expected, as well as increases in porosity. However it is suggested by ACARP (2008) and others that higher within the profile there may be limited vertical connectivity within the fractured or constrained zone which is argued to result in little to no increase in vertical permeability and therefore vertical fluid flow even though increases in horizontal permeability may be substantial. This observation has prompted the use of the term Height of Connected Fracturing (HoCF) by some researchers to differentiate between fracturing that is vertically connected and hence has an increase in vertical permeability. This is different to HoF which includes regions nearer the surface where vertical fractures may form but may not be connected and therefore vertical permeability is relatively unchanged.

Extensometer and piezometer measurements are common approaches to inferring HoF and HoCF however both methods are limited. Extensometers provide some information on vertical deformations at discrete points. However they also respond to anchor slippage and other deformations such as horizontal movement. Therefore they should be regarded as only providing an indirect measurement of HoF. They do not provide direct information of HoCF. 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 HoCF as depressurisation may be the result of increased horizontal permeability alone.

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. Consequently groundwater models that attempt to mimic this behaviour simulate significant increases in horizontal permeability but little to no change in the vertical permeability. This is despite the limited ability by instrumentation 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;
- They ignore any site specific geological conditions;
- They require significant error corrections to encapsulate all of the input observations; and
- The observations upon 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 Brinckerhoff (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.

## **S2.3 Mining near Water Bodies and Major Aquifers**

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).

In Australia there has been an ongoing debate on mining near Sydney catchments areas since 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 should be defined using an 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 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 are essentially still in effect today, but are essential on a case by case basis.

## S2.4 Gaps in Existing Knowledge

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

- There are no reliable methods for detecting the 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. Microseismic investigations can usefully identify where major cracking is occurring within overburden formations, but cannot discern their geometry. Piezometric and extensometer data are also important in inferring HoCF and should be routinely used;
- Despite the application of numerous empirical, analytical and, less commonly, numerical theoretical models, there are no current 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.
- HoF prediction methods are focussed on data obtained directly above a longwall panel with limited data away from the centre 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.
- 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. Instead, groundwater depressurisation occurs 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;
- There are no established methods for reliably predicting safe offset distance for water bodies.
- 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 trialled to enable subsidence bowls in complex terrains to be progressively mapped and their impacts studied.

## S3. Groundwater

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### S3.1 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. Groundwater forms a small but important component of the overall water balance for 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.

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.

The following groundwater systems (in order of likely baseflow volume contributions) are considered the most important for sustaining baseflow contributions to the drinking water catchments:

- Hawkesbury Sandstone and Gosford Sub-Group rocks;
- Colluvium (swamp substrate);
- Basalts;
- Alluvium (in creeks).

## S3.2 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 areas and discharge 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 (as described in Tables 5.1 to 5.4 of the main report) 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;
- Large wetting and 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.

It is the impacts to surficial and regional aquifers and the resultant consequences that affect baseflows, water quality, associated ecosystems and catchment yield that are the issues most important to WaterNSW.

### **S3.3 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 both 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.

Baseline groundwater monitoring data is poor 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.



## **S4. Surface Water**

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### **S4.1 Surface Water Catchments and Drainage Systems**

#### **S4.1.1 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.

#### **S4.1.2 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 may be summarised as follows:

- **Headwater swamps**
  - These 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.
  - They 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 is independent of the natural regional water table; and
  - 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; and
  - Valley-side swamps can be disconnected vegetatively from headwater swamps – occurring 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; and



- Valley infill swamps have multiple sources of water including by stream flow along distinct channels and supplemented by rain infiltration and seepage from the swamp is independent of the deeper regional water table in the underlying Hawkesbury Sandstone. Because of their relatively large catchment areas these swamps and their direct connection to flowing streams tend to be wetter than many headwater and valley-side swamps.
- **Hanging swamps**
  - There are very few hanging swamps in the Special Areas due to the low incidence of cliff lines. Examples have been identified in the Bargo and Cataract gorges on the Woronora Plateau; and
  - These swamps are fed by seepage through the sandstone, which then emerges on the cliff face or valley side when it reaches much less permeable underlying claystone. They have only shallow or minimal sediment and are essentially a thick mat of shrub and fern vegetation.

## **S4.2 Regional Climate and Hydrology**

### **S4.2.1 Climate**

Rainfall and evaporation data are provided in the main report. 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.

### **S4.2.2 Flow Regime**

A number of stream flow gauges are located on the watercourses within the study area, although none 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.

### **S4.2.3 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. Typically, baseflow is considered to comprise a number of components such those outlined in Section S3.1.

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.

### **S4.2.4 Upland Swamp Hydrology**

Based on the monitoring data analysed for the study, there is a range of processes that occur in different swamps. In the case of swamps monitored by Metropolitan Coal, one swamp demonstrated a consistent hydraulic gradient indicating flow from the swamp to the sandstone, while another swamp

demonstrated the reverse. Many swamps demonstrate a relatively constant rate of water level decline following rainfall, which can be mainly attributed to evapotranspiration and possibly some drainage to the underlying sandstone. A minority 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 rock bar.

### S4.2.5 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.

The mining companies undertake routine 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 monitored river as well as over time including control catchments.

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.

The main concern of WaterNSW 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 obligations. WaterNSW routinely collects water quality samples within the catchment, at the reservoirs, and at the pre-treatment and post treatment phases.

## S4.3 Impacts and Consequences of Coal Mining

### S4.3.1 Surface Water Quantity

A summary of the impacts and consequences of subsidence on surface water quantity is provided in Table S4.1.

**Table S4.1: Impacts and Consequences of Subsidence on Surface Water Quantity**

Physical Subsidence Impacts	Consequences
<ul style="list-style-type: none"> <li>▪ Tensile cracking of stream rock bars;</li> <li>▪ Tensile/shear movement of joint and bedding planes in the stream bed</li> <li>▪ Localised uplift and buckling of strata in the stream bed (e.g. lifting/ mobilising of stream bed rock plates)</li> </ul>	<ul style="list-style-type: none"> <li>▪ Loss of surface water flow into subsurface flow path</li> <li>▪ Loss of standing pools/connectivity</li> <li>▪ Additional groundwater inflows, commonly carrying ferrous iron from freshly broken rock</li> <li>▪ Reduction in water supply yields (not currently confirmed whether by significant volumes)</li> </ul>
<ul style="list-style-type: none"> <li>▪ Tilting of stream beds (both dynamic/ incremental and final outcome)</li> </ul>	<ul style="list-style-type: none"> <li>▪ Stream bank and bed erosion, migration of flow channels</li> <li>▪ Changes in flow rates</li> <li>▪ Reduction in water supply yields (not currently confirmed whether by significant volumes)</li> </ul>

Source: based on NSW Government, 2008

### S4.3.2 Surface Water Quality

A summary of the impacts and consequences of subsidence on surface water quality is provided in Table S4.2.

**Table S4.2: Impacts and Consequences of Subsidence on Surface Water Quality**

Physical Subsidence Impact	Potential Consequences
<ul style="list-style-type: none"> <li>▪ Tensile cracking of stream rock bars;</li> <li>▪ Tensile/shear movement of joint and bedding planes in the stream bed;</li> <li>▪ Localised uplift and buckling of strata in the stream bed (e.g. lifting/ mobilising of stream bed rock plates.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Localised changes in stream water chemistry due to water-rock interactions along new flow pathways to subsidence;</li> <li>▪ Increases in iron, manganese, aluminium, sodium, calcium, barium, chloride and sulphate in surface water;</li> <li>▪ Increases in iron, barium, strontium and calcium together with the bicarbonate anion in surface water;</li> <li>▪ Mobilisation of carbonates to give bicarbonate ions;</li> <li>▪ Orange discolouration of surface water due to dissolved iron;</li> <li>▪ Growth of bacterially-mediated iron mats and blooms in rock pools;</li> <li>▪ Reduction in dissolved oxygen and related eco toxic impacts;</li> <li>▪ Increases in alkalinity and salinity;</li> <li>▪ Consequences are likely to be sporadic, localised in nature and have had no detectable influence on water quality in downstream reservoirs;</li> <li>▪ Water quality consequences associated with the sub-surface flow through fresh fracture networks ameliorate over a 5 to 10 year period.</li> </ul>

NSW Government (2014) found that although the impact of underground long-wall mining in the catchment could lead to small changes in the levels of impurities in water entering WaterNSW's dams, these changes could be adequately addressed by Sydney Water's treatment plants. Evidence to date does not suggest a sufficiently large change in soluble organic concentrations to be of concern to WaterNSW values. Water quality issues in the Special Areas can largely be managed through existing treatment works, although an upgrade to infrastructure may be required to sustain this capability.

### S4.3.3 Upland Swamps

Table S4.3 summarises the potential subsidence impacts and consequences for swamps.

**Table S4.3: Impacts and Consequences of Subsidence on Swamps**

Physical Subsidence Impacts	Consequences
<b>Valley infill swamps</b>	
<ul style="list-style-type: none"> <li>▪ Tensile cracking, tensile/ shear movement of joint and bedding planes, and buckling and localised upsidence in the stream bed below the swamp</li> </ul>	<ul style="list-style-type: none"> <li>▪ Draining of swamps, leading to:               <ul style="list-style-type: none"> <li>- drying and potential erosion and scouring of dry swamps</li> <li>- loss of standing pools within swamps</li> <li>- vulnerability to fire damage of dry swamps</li> <li>- change to swamp vegetation communities</li> <li>- adverse water quality impacts, e.g. iron bacterial matting</li> </ul> </li> <li>▪ Loss of stream baseflow</li> <li>▪ Loss of swamp ecology (terrestrial and aquatic)</li> <li>▪ Loss of flow leads to the full range of downstream consequences</li> </ul>



Physical Subsidence Impacts	Consequences
<b>Headwater swamps</b>	
<ul style="list-style-type: none"> <li>Tensile cracking and tensile/ shear movement of joint and bedding planes in the rocks below the swamp</li> </ul>	<ul style="list-style-type: none"> <li>Potential drop in perched water tables, leading to draining of swamps</li> <li>Impacts are likely to be similar in character but less extensive and significant than for valley infill swamps</li> <li>Loss of swamp ecology (terrestrial and aquatic)</li> <li>Loss of flow leads to the full range of downstream consequences</li> </ul>

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

## S4.4 Gaps in Existing Knowledge

Water resources and hydrological processes are poorly understood in sufficient detail to allow a cause and effect relationship to be quantified between mine subsidence effects 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 responsible for water supply to have a good understanding of the available resource and the variability from year to year. However at smaller spatial and time scales more likely to reflect any consequences of mining there is insufficient of detailed understanding of a number of the following key parameters and processes.

### S4.4.1 Baseflow

Baseflow following significant flow events 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 largely focussed 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 level measurement and the rating for very low flows;
  - continuously monitor salinity as a tracer in accordance with the recommendation from SKM and 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 will 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 catchments would help to clarify the overall magnitude of baseflow to the reservoirs.

### S4.4.2 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 hydraulic gradient in the shallow bedrock and relative magnitude in any changes in hydraulic conductivity.

Metropolitan Coal has contributed to an understanding of the relative piezometric levels in swamps and shallow groundwater in the sandstone beneath the swamp. The evidence from the monitoring undertaken to date is that hydraulic gradients leading to flow towards and away from swamps have been observed. Further monitoring in other swamps that are currently monitored for swamp piezometric levels would assist in understanding the interactions between swamps and the any shallow

groundwater system. Further understanding of the fate of water lost from swamps and cracked creek beds could be gained by the installation of a line of piezometers down slope of an impacted area in order to determine the magnitude of any change in the hydraulic gradient.

#### **S4.4.3 Near Surface Hydraulic Conductivity**

An effect of mine induced subsidence is considered to be tensile fracturing within the “surface zone”. 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 the surface water system. Given that the hydraulic gradient will usually be 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. The other unknown factor is the effect of down-slope rock that has not been impacted by subsidence.

#### **S4.4.4 Hydrology of Headwater Swamps**

A key missing element is an understanding of how the actual evapotranspiration rate changes as the swamp soils dry out. The other missing element is monitoring of groundwater levels beneath the swamp in order to understand the changes in hydraulic gradient that occur as a result of subsidence.

#### **S4.4.5 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 issues relate to the magnitude of any loss of supply to the reservoirs. Two issues that are common to monitoring and modelling to be resolved are:

- Is the monitoring system capable of detecting change at a time and space 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 process that may change as a result of mining and can the parameters needed for such a model be determined with sufficient spatial discrimination?

Based on preliminary analysis of available literature, 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.

## **S5. Ecology**

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The maintenance and protection of the ecological integrity of the Special Areas is a key principle of WaterNSW, and the environments of concern 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 this Review has been addressed under three broad ecosystem types: terrestrial biodiversity, aquatic biodiversity (streams) and upland swamps.

## **S5.1 Terrestrial Biodiversity**

### **S5.1.1 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 *Environment Protection and Biodiversity Conservation Act 1999* (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 consequences on surface and groundwater hydrology, physical features, streams, swamps and biodiversity has led to the *Alteration of habitat following subsidence due to longwall mining* being listed as a Key Threatening Process under the TSC Act.

### **S5.1.2 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 for WaterNSW 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.

## **S5.2 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 variation.

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 EPBC Act.

### **S5.3 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; however, many provide critical habitat for biota that are wholly, partially or opportunistically groundwater dependent. Upland swamps, as 'priority fauna habitat,' are 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 S4.1.2 above.

### **S5.4 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.

#### **S5.4.1 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, such as cliff falls, bedrock cracking 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.

#### **S5.4.2 Impacts and Consequences on Aquatic Biodiversity**

Reported consequences of impacts have included 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 can be attributed to a change in stream flow and flow rate, physical alteration of the stream bed, alteration of the subterranean zone and 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.

### **S5.4.3 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 consequences relating to swamp drying, change in perched water tables, erosion and the alteration of baseflow contributions downstream.

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.

## **S5.5 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 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.

### **S5.5.1 Terrestrial Biodiversity**

The dependency of the broad vegetation groups or site-specific vegetation communities on the regional groundwater is unknown, as is their resilience to withstand change. It is also expected that it would be highly variable across the diversity of regional landscapes, leading to a major constraint in surveying and monitoring these attributes.

### S5.5.2 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.

### S5.5.3 Upland Swamps

Knowledge gaps for the upland swamp ecosystems include:

- 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) 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?

## S6. Risk Assessment

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A review of risk related documents is provided in Appendix E. The reviewed documents refer to *ISO 31000: 2009 Risk Management Principles and Guidelines* (or its predecessor standards). The following aspects of the specific risk assessments reviewed in Appendix E will be included for consideration:

- Use of an event tree template to assist in the initial identification of risks relevant to the individual mining application.
- Development of a more detailed consequence table separately addressing water quality, water quantity, ecological risk etc. The ranges/thresholds for each level of consequence will be agreed with WaterNSW e.g. what loss of water yield is considered as a moderate consequence.
- Consideration of the change in risk consequence over time.
- Development of a standard likelihood table and risk matrix in accordance with the standard WaterNSW templates. All future risk assessments should adopt the same templates for consistency, particularly when assessing cumulative impacts.
- Consideration of cumulative impacts of multiple mining applications within the one catchment area.
- Development of a consistent standard risk management framework for reviewing risk assessments and particularly when assessing cumulative impacts.
- Identification of appropriate mitigation strategies that can be implemented before and/or after the risk occurs.



**Advisian**

WorleyParsons Group



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## Abbreviations

ACARP	Australian Coal Association Research Program
AHD	Australian Height Datum
ANZECC	Australian and New Zealand Environment Conservation Council
ARMCANZ	Agriculture and Resources Management Council of Australia and New Zealand
AS/NZS ISO	Australian and New Zealand, International Organisation for Standardisation
AWBM	Australian Water Balance Model
BFI	Baseflow Index
BoM	Bureau of Meteorology
BP	Before present, used to define the age of groundwater in years
BVG	Broad Vegetation Groups
CL	Coal Lease
CSIRO	Commonwealth Scientific & Industrial Research Organisation
DEC	Department of Environment and Conservation
DECC	Department of Environment and Climate Change (now known as Department of Environment and Conservation)
Dol	NSW Department of Industry (Resources and Energy)
DoP	NSW Department of Planning (now known as NSW Department of Planning and Environment)
DP&E	NSW Department of Planning and Environment
DPI-Water	NSW Department of Primary Industries – Water (formerly NSW Office of Water (NOW))
DSC	Dam Safety Committee
EC	Electrical Conductivity, a measure of the total dissolved solids in water, measured as $\mu\text{S/cm}$
EIA	Environmental Impact Assessment
EIS	Environmental Impact Statement
EPA	NSW Environment Protection Authority
EP&A Act	Environmental Planning and Assessment Act 1979
EPBC Act	Environment Protection and Biodiversity Conservation Act 1999 (Commonwealth)
ERA	Environmental Risk Assessment
ET	Evapotranspiration
FSL	Full Supply Level
GDE	Groundwater Dependent Ecosystem
HoCF	Height of Connected Fracturing
HoF	Height of Fracturing
IESC	Commonwealth Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development
IMMCP	Impact Monitoring, Management and Contingency Plan
Kh	Horizontal Permeability
Kv	Vertical Permeability
KTP	Key Threatening Process
LLL	Lidsdale Lithgow Seam
L/s	Litres per second



LTA	Long-Term Average (rainfall)
LTAEL	Long-Term Average Annual Extraction Limits
LW	Longwall
mbgl	Metres below Ground Level
ML	Megalitres
NOW	NSW Office of Water (now known as NSW Department of Primary Industries – Water)
NPWS	National Parks and Wildlife Service
NRM	Natural Resource Management
NSW	New South Wales
NTU	Nephelometric Turbidity Units
OEH	NSW Government, Office of Environment and Heritage
PAC	Planning Assessment Commission
POEO Act	Protection of the Environment Operations Act 1997
PSM	Pells Sullivan Meynink
SCA	Sydney Catchment Authority (now known as WaterNSW)
SEARs	Secretary of the Department of Planning and Environment's Environmental Assessment Requirements
SEPP	State Environmental Planning Policy
SSDs	State Significant Developments
TARP	Trigger Action Response Plan
TDS	Total Dissolved Solids
TSC Act	Threatened Species Conservation Act 1995
TSS	Total Suspended Solids
U/S	Upstream
D/S	Downstream
VWP	Vibrating Wire Piezometer
WAL	Water Access Licence
WMA	Water Management Act 2000
WMP	Water Management Plan
WSP	Water Sharing Plan



## Glossary

Alluvium	Unconsolidated sediments (clays, sands, gravels and other materials) deposited by flowing water.
Alluvial Aquifer	Aquifers that are permeable zones that store and produce groundwater from unconsolidated alluvial deposits. Shallow alluvial aquifers are generally unconfined aquifers.
Aquatic Macroinvertebrates	Organisms without backbones, which are visible to the eye without the aid of a microscope that live on, under and around rocks and sediments on the bottoms of lakes, rivers and streams
Aquatic Macrophyte	Plants that grow in or near water and are either emergent, submerged or floating
Aquifer <sup>1,4</sup>	'Aquifer' means a geological structure or formation, or an artificial landfill, that is permeated with water or is capable of being permeated with water. NOTE: For this project, the term is applied to those formations that can yield useful volumes that contribute to stream baseflow or useful volumes for abstraction.
Aquifer, Confined	An aquifer that is overlain by low permeability strata. The hydraulic conductivity of the confining bed is significantly lower than that of the aquifer.
Aquifer, Semi-Confined	An aquifer overlain by a low-permeability layer that permits water to slowly flow through it. During pumping, recharge to the aquifer can occur across the confining layer – also known as a leaky artesian or leaky confined aquifer.
Aquifer, Unconfined	Also known as a water table aquifer. An aquifer in which there are no confining beds between the zone of saturation and the surface. The water table is the upper boundary of an unconfined aquifer.
Aquitard <sup>4</sup>	A low-permeability unit that can store groundwater and also transmit it slowly from one aquifer to another. Aquitards retard but do not prevent the movement of water to or from an adjacent aquifer.
Areal Actual Evapotranspiration	The ET that actually takes place, under the condition of existing water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average.
Areal Potential Evapotranspiration	The ET that would take place, under the condition of unlimited water supply, from an area so large that the effects of any upwind boundary transitions are negligible and local variations are integrated to an areal average.
Baseflow	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.
Colluvium	Unconsolidated sediments that have been deposited at the base of hillslopes by either runoff, sheet wash, slow continuous downslope creep, or a variable combination of these processes.
Depressurisation	The lowering of hydrostatic water pressure in an aquifer or aquitard.
Discharge	The volume of water flowing in a stream or through an aquifer past a specific point in a given period of time.
Dual permeability aquifer	An aquifer in which groundwater flow is through both the primary porosity of the rock matrix and the secondary porosity of fractures and fissures.



Evapotranspiration	A collective term for the transfer of water, as water vapour, to the atmosphere from both vegetated and un-vegetated land surfaces. It is affected by climate, availability of water and vegetation characteristics.
Fractured Rock Aquifer	Aquifers that occur in sedimentary, igneous and metamorphosed rocks which have been subjected to disturbance, deformation, or weathering, and which allow water to move through joints, bedding planes, fractures and faults.
Fracturing	Breakage in a rock or mineral along a direction or directions that are not cleavage or fissility directions.
Goaf	An area in which mining has been completed and left in a partially or totally collapsed state or in an inadequately supported state to assure safe entry. An abandoned area.
Groundwater <sup>2</sup>	Groundwater is the water contained within rocks and sediments below the ground's surface in the saturated zone, including perched systems above the regional water table.
Groundwater Dependent Ecosystems	Ecosystems which have their species composition and natural ecological processes wholly or partially determined by groundwater.
Groundwater Dependent Wetland	Land, in the context of the GDE, permanently or temporarily under water or waterlogged with a known or likely component of groundwater discharge in its hydrologic cycle (Serov et al, 2012)
Groundwater System <sup>2</sup>	A groundwater system is any type of saturated sequence of rocks or sediments that has similar hydrogeological characteristics and is in hydraulic connection. The characteristics can range from low yielding and high salinity water to high yielding and low salinity water.
Highly Productive Groundwater <sup>3</sup>	A groundwater source (as defined in each Water Sharing Plan and declared in the Regulations) that has the following criteria: (a) total dissolved solids of less than 1,500 mg/L and (b) water supply works that can yield water at a rate greater than 5 L/sec.
Hyporheic Zone	The region beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface water.
Hydrophytic	A plant that is adapted to living in waterlogged soil or wholly or partially submerged in water.
Less Productive Groundwater <sup>3</sup>	All other groundwater sources (as defined in WSPs) that are not defined as highly productive groundwater.
Macrophyte	Plant that grows in or near water and is either emergent, submerged or floating.
Macroinvertebrate	Organism without a backbone that is visible to the eye without the aid of a microscope and lives on, under and around rocks and sediments on the bottoms of lakes, rivers and streams.
Permeability	The ability of a substance to allow another substance to pass through it, especially the ability of a porous rock, sediment, or soil to transmit water through pores and cracks.
Point Potential Evapotranspiration	The ET that would take place, under the condition of unlimited water supply, from an area so small that the local ET effects do not alter local air mass properties. It is assumed that latent and sensible heat transfers within the height of measurement are through convection only.
Porosity	The proportion of open space within an aquifer or aquitard, comprised of intergranular space, pores, vesicles and fractures.
Recharge	The process which replenishes groundwater, usually by rainfall infiltrating from the ground surface to the water table and by river water reaching the water table or exposed aquifers.



Regional Aquifer	<p>For this project, the regional aquifers are:</p> <ul style="list-style-type: none"> <li>(a) Hawkesbury Sandstone aquifers (dual permeability, sedimentary rock aquifers), and</li> <li>(b) Volcanic aquifers (fractured rock aquifers)</li> </ul> <p>They are generally unconfined or semi-confined aquifers.</p>
Retreat Mining	<p>Mining which retreats towards the main headings leaving behind a collapsed goaf (eg longwall mining or pillar extraction)</p>
Salinity Classification	<p><b>Fresh water quality</b> – water with EC less than 800 <math>\mu\text{S/cm}</math>.</p> <p><b>Marginal water quality</b> – water that is more saline than freshwater and generally waters with EC between 800 and 1,600 <math>\mu\text{S/cm}</math>.</p> <p><b>Brackish quality</b> – water that is more saline than freshwater and generally waters with EC between 1,600 and 4,800 <math>\mu\text{S/cm}</math>.</p> <p><b>Slightly saline quality</b> – water that is more saline than brackish water and generally waters with EC between 4,800 and 10,000 <math>\mu\text{S/cm}</math>.</p> <p><b>Moderately saline quality</b> – water that is more saline than slightly saline water and generally waters with EC between 10,000 and 20,000 <math>\mu\text{S/cm}</math>.</p> <p><b>Saline quality</b> – water that is almost as saline as seawater and generally waters with EC greater than 20,000 <math>\mu\text{S/cm}</math>.</p> <p><b>Seawater quality</b> – water with EC generally around 55,000 <math>\mu\text{S/cm}</math>.</p>
Sedimentary Rock Aquifer	<p>These aquifers occur in consolidated sediments such as porous sandstones and conglomerates, in which water is stored in the intergranular pores, and limestone, in which water is stored in solution cavities and joints.</p>
Stream Power	<p>Rate of energy dissipation against the bed and bank of a stream per unit downstream length</p>
Storage Capacity	<p>When used in a surface water context means the storage volume of a reservoir or weir pool. When used in a groundwater context means the volume of water stored or able to be stored in a groundwater system.</p>
Storativity	<p>The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storativity is equivalent to specific yield.</p>
Subsidence Effect	<p>The nature of a particular mining-induced ground movement.</p>
Subsidence Impact	<p>Any physical change to the fabric of the ground, its surface or a man-made feature resulting from a subsidence effect.</p>
Subsidence Consequence	<p>Any change in amenity, function or risk profile of a natural or man-made feature due to a subsidence impact.</p>
Superficial Aquifer	<p>Thin aquifers associated with upland swamps that are permeable zones contained within colluvial deposits. These aquifers can be ephemeral and are always unconfined.</p>
Toposequence	<p>A sequence of soils in which distinctive soil characteristics are related to topographic situation</p>
Vibrating Wire Piezometer (VWP)	<p>An instrument consisting of a vibrating wire element connected to a sensitive diaphragm; designed to measure pore pressures in fully and partially saturated soils and rock in boreholes.</p>
Water Bearing Zone <sup>4</sup>	<p>Geological strata that are saturated with groundwater but not of sufficient permeability to be called an aquifer.</p>
Water Table	<p>The top of an unconfined aquifer. It is at atmospheric pressure and indicates the level below which soil and rock are saturated with water.</p>



## NOTES

1. *Water Management Act (2000)* definition
2. Plain English definitions from DPI Water's website  
(reference <http://www.water.nsw.gov.au/water-management/groundwater> )
3. Criteria from *NSW Aquifer Interference Policy* (NOW, 2012)
4. In this Review report, the term 'aquifer' is used for those groundwater systems with relatively high permeability and the terms 'aquitard' and 'water bearing zone' are used for portions of those deeper groundwater systems that exhibit low or very low permeability.



**Advisian**

WorleyParsons Group



## 1 Introduction

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### 1.1 Background

This Review has been undertaken to assist WaterNSW develop a scientifically robust and defensible policy position for consistent and transparent assessment of the individual and cumulative risks arising from underground coal mining proposals within the Sydney Drinking Water Catchment Special Areas (the Special Areas), particularly the Metropolitan and Woronora Special Areas which overlie the coal measures of the Southern Coalfield. The Review focusses on the following values within the Special Areas:

- WaterNSW's water supply infrastructure;
- Water quantity and quality;
- Human health; and
- Ecosystem health.

### 1.2 Terminology

It is noted that different disciplines use the same term differently. The definitions used in this report are those set out in the glossary. In particular, the following subsidence related definitions provided in Galvin (2016) have been adopted within this Literature Review.

- **Subsidence effects:** the nature of a particular mining-induced ground movement.
- **Subsidence impacts:** any physical change to the fabric of the ground, its surface or a man-made feature resulting from a subsidence effect.
- **Consequences:** any change in amenity, function or risk profile of a natural or man-made feature due to a subsidence impact.

For purposes of this report, the 'study area' comprises the Metropolitan and Woronora Special Areas upstream of Broughtons Pass and Pheasants Nest Weirs.

### 1.3 Key Risks

The focus of this Project is on the consequences for water supply, water quality and the ecological integrity of the Special Areas. The key technical issues for WaterNSW relate to:

- The risk of connective cracking and the resulting magnitude of any water lost from reservoirs and catchments into underlying groundwater systems and mine voids, without these flows returning to reservoirs or downstream watercourses;
- The level of protection that can be provided through longwall setbacks and other mitigation measures to minimise the risk of natural and mining-induced connective and non-connective cracking and its effect on surface water resources including water stored in reservoirs and contributions from regional aquifers and near-surface aquifers (swamps) to baseflow in streams and swamps;
- The local consequences for water quantity, quality (or ecosystem health) of subsidence impacts from individual mines and the cumulative long term catchment scale impacts of historic and current mining;
- The potential long term environmental consequences for ecosystem health, particularly to streams and swamps within the Special Areas.



## 1.4 Approach

The Literature Review aims to summarise the key findings of all relevant studies and documents, with a preference to use peer-reviewed national and international publications that have been published in the last ten years and that relate directly to mining in high value water catchments or under waterbodies, as well as relevant documentation identified by WaterNSW relating to the Southern Coalfield.

It is noted that very little of the available documentation on mining and subsidence effects, impacts and consequences has been peer-reviewed. The mining industry has co-operated through the Australian Coal Industry's Research Program (ACARP) organisation to 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 key documentation examined in this 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 which 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 (DP&E) and the Planning Assessment Commission (PAC).

## 1.5 Study Team

This Project has been undertaken by the following experts who have been chosen due to their level of expertise and experience in the relevant specialist areas:

- Dr Steve Perrrens (Advisian) Specialist in surface water impacts from longwall mining and surface water modelling;
- Gareth Swarbrick (PSM) Specialist in longwall mining-induced subsidence effects;
- John Ross Specialist in sedimentary basin hydrogeology, groundwater impacts from longwall mining and groundwater modelling;
- Dr Barbara Mactaggart (Mactaggart Natural Resource Management) Specialist in ecological impacts from longwall mining-induced subsidence effects;
- Grant Sutton (Grant Sutton & Associates) Specialist risk assessment expertise in line with AS/NZS ISO 31000:2009;
- Peter Doyle (Advisian) Specialist in underground coal mining operations and management.

The peer reviewer for the Project is Emeritus Professor Jim Galvin of Galvin & Associates.



## 2 Statutory Context

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### 2.1 Legislation

Proposals for development in the Special Areas are regulated under a variety of legislation. The size, scale and nature of the development determine which regulating authorities are the decision-makers for each development and which are involved in the approvals process. Various pieces of legislation apply, from the federal *Environment Protection and Biodiversity Conservation Act 1999* to state statutes and planning policies. The legislation outlined below covers all key aspects of the regulatory regime covering the Special Areas as well as those that particularly regulate and empower WaterNSW such as the *Water NSW Act 2014*.

#### 2.1.1 Commonwealth Legislation

The *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) gives the Commonwealth jurisdiction over development proposals affecting water resources related to large coal mining development. Thus the Commonwealth Environment Minister can consider and impose conditions relating to the water resource in question. EPBC Act assessment and approvals are being devolved to the States. NSW has entered into a bilateral agreement with the Commonwealth that provides for assessments to be undertaken by NSW – a draft agreement has been prepared for approvals but has not yet been finalised – consequently decisions are made by the Commonwealth Minister for the Environment. However, any large coal mining development-related developments must still be referred to the Commonwealth Independent Expert Scientific Committee (IESC) on Coal Seam Gas and Large Coal Mining Development. States are also required to consider the cumulative impact of development proposals in undertaking EPBC Act assessments.

#### 2.1.2 Environmental Planning and Assessment Act 1979

The *Environmental Planning and Assessment Act 1979* (EP&A Act) governs the assessment and approval of development in NSW. The Act and its regulations require the preparation of environmental impact statements for 'designated developments'. These are developments that may have significant adverse impacts on the environment because of their nature, scale or location near sensitive environmental areas.

A development consent under the *Environmental Planning and Assessment Act 1979* (EP&A Act) must be in place before a mining lease under the *Mining Act 1992* can be granted (refer Section 2.1.6 below). All new coal mines, mineral sand mines, other large mines and any mines in environmentally sensitive areas of State significance are classified as State Significant Development under the EP&A Act. Development consent for mining projects of State significance is given by the Minister for Planning. Decisions on most major mining projects are made by the Planning Assessment Commission (PAC) under delegation from the Minister for Planning.

The EP&A Act includes requirements for those regulatory authorities that may issue licences under other acts, such as the *Mining Act 1992*, to take into account all matters likely to affect the environment.

For designated and State Significant Developments, an Environmental Impact Statement (EIS) must be prepared in accordance with the *Environmental Planning and Assessment Regulation 2000*. The EIS must follow the Secretary of the Department of Planning and Environment's Environmental Assessment Requirements (SEARs) in relation to its form, content and public availability. These



requirements are set by the Department via consultation with relevant government agencies and the community and may differ depending on the project (NSW Department of Planning and Environment, 2014).

### 2.1.2.1 Performance Measures for Natural Features in Mining Approvals

The planning regulator (DPE or the PAC) generally sets Subsidence Impact Performance Measures for key natural features like watercourses, water resources/storages and upland swamps when it approves major mining projects. These Performance Measures are reflected and sometimes extended within subsequent Subsidence Management Plan/ Extraction Plan approvals.

The Performance Measures seek to define the desired environmental outcomes or unacceptable environmental consequences, and their associated thresholds are typically classified as negligible, minor or significant. The terms 'negligible' and 'minor' are defined respectively in the approvals as 'small and unimportant, such as to be not worth considering' and 'small in quantity, size and degree given the relative context'.

Some examples from approvals granted for coal mines within the Special Areas are provided in Table 2.1.

**Table 2.1: Example Performance Measures for Coal Mines in the Special Areas**

Examples from Mine Approvals	Performance Measures
<b>Metropolitan Mine</b>	
Catchment yield to the Woronora Reservoir	<ul style="list-style-type: none"> <li>▪ Negligible reduction in the quality or quantity of water resources reaching the Woronora Reservoir</li> <li>▪ No connective cracking between the surface and the mine</li> </ul>
Woronora Reservoir	<ul style="list-style-type: none"> <li>▪ Negligible leakage from the Woronora Reservoir</li> <li>▪ Negligible reduction in the water quality of Woronora Reservoir</li> </ul>
<b>Dendrobium Mine</b>	
<ul style="list-style-type: none"> <li>▪ Swamps 1a, 1b, 5, 8,11, 14 and 23, and</li> <li>▪ Swamps 3, 4, 10, 13, 35a and 35b</li> </ul>	<ul style="list-style-type: none"> <li>▪ Minor environmental consequences including: <ul style="list-style-type: none"> <li>- negligible erosion of the surface of the swamps;</li> <li>- minor changes in the size of the swamps;</li> <li>- minor changes in the ecosystem functionality of the swamp;</li> <li>- no significant change to the composition or distribution of species within the swamp; and</li> <li>- maintenance or restoration of the structural integrity of the bedrock base of any significant permanent pool or controlling rockbar within the swamp.</li> </ul> </li> <li>▪ No significant environmental consequences beyond predictions in the Subsidence Management Plan</li> </ul>
Watercourses:	<ul style="list-style-type: none"> <li>▪ Minor environmental consequences including: <ul style="list-style-type: none"> <li>- minor fracturing, gas release and iron staining</li> <li>- minor impacts on water flows, water levels and water quality.</li> </ul> </li> </ul>
<ul style="list-style-type: none"> <li>▪ Wongawilli Creek</li> <li>▪ Donalds Castle Creek</li> </ul>	

These performance measures are then used by the mining companies to define performance indicators, triggers, and response actions in environmental monitoring and Trigger Action Response Plans (TARPs), against which ongoing environmental impact monitoring results are progressively assessed and periodically reported by the company. There has been considerable discussion in recent times among government agencies on the need to improve upon the definition of these performance measures particularly in relation to upland swamps where the change in swamp shallow groundwater regime needs to be considered.



## 2.1.3 Water NSW Act 2014

WaterNSW and the NSW NPWS jointly manage the Special Areas in accordance with the Special Areas Strategic Plan of Management. The Special Areas are the protected catchment lands surrounding the water storages, and are critical controls in the supply of quality water to Greater Sydney. Under section 47 of the *WaterNSW Act 2014*, such areas cannot be declared Special Areas unless the Minister is satisfied that the making of the declaration is necessary for either or both of the following purposes:

- protecting the quality of stored waters, whether intended for use for drinking or other purposes;
- maintaining the ecological integrity of an area of land to be declared to be a special area in a manner that is consistent with WaterNSW's objectives.

## 2.1.4 NSW Water Management Act 2000

The aim of the *Water Management Act 2000* is to provide for the sustainable and integrated management of the water sources of NSW for the benefit of both present and future generations. The *Water Act 1912* and the *Water Management Act 2000* contain provisions for the licensing of water capture and use. If any dams are proposed as part of mining projects, consideration must be given to whether the dams need to be licensed. A controlled activity approval under the *Water Management Act 2000* is typically not required for surface mining activities approved as State Significant Developments.

## 2.1.5 Dams Safety Act 1978 and Dam Safety Act 2015

The *Dam Safety Act 2015* establishes the role of Dams Safety NSW (replacing NSW Dams Safety Committee (DSC) that was established under the *Dam Safety Act 1978*) to achieve objectives relating to the safety of dams, including ensuring that any risks that may arise in relation to dams (such as any risks to public safety and to environmental and economic assets) are of a level that is acceptable to the community. Dams Safety NSW can declare a dam or proposed dam to be a 'declared dam' under the *Dams Safety Act 2015*.

One of the functions of Dams Safety NSW is to make recommendations on the development, implementation and modification of the dam safety standards, to keep owners of declared dams informed about the dam safety standards, and to regulate compliance with those standards. Determination of whether a dam is a declared dam is based on an assessment of its consequence category, which considers potential downstream impacts of dam failure.

Under the *Dam Safety Act 2015*, a 'notification area' can be declared covering an area around the dam structure and the impoundment. Any proposal to mine within the notification area requires consultation with Dam Safety NSW. Dam Safety notification areas are defined around all dams and reservoirs within the Metropolitan and Woronora Special areas which are the focus of this study.

## 2.1.6 Mining Act 1992

In NSW, mining leases are granted under the provisions of the *Mining Act 1992*, which is administered by the DPI (Resources and Energy). A mining lease gives the holder the exclusive right to mine for minerals over a specific area of land. To be granted a mining lease, applicants must demonstrate that there is an economically mineable mineral deposit within the area of the proposed lease and that they have the financial and technical resources to carry out mining in a responsible manner. A mining lease can only be granted over land for which there is an



appropriate development consent in place under section 65 of the *Environmental Planning and Assessment Act 1979*.

A key responsibility of the DPI (Resources and Energy) is to ensure compliance with the *Mining Act 1992* and associated *Mining Regulation 2016*. This includes:

- reviewing environmental impact assessments for proposed exploration and mining activities;
- promoting compliance through site inspections, audits (both mandatory and voluntary) and regular reporting;
- regulating rehabilitation and supervising mine closures;
- investigating complaints and incidents;
- taking appropriate enforcement action for non-compliance;
- coordinating with other relevant government departments and agencies to respond to non-compliances; and
- reviewing environmental performance prior to the granting of an authorisation (permit or licence).

Reports provided under the *Mining Regulations 2016* are confidential for the period of the authority (i.e. permit or licence), but can be shared with particular agencies including WaterNSW.

DPI (Resources and Energy) has a wide range of powers under the *Mining Act 1992* for regulating rehabilitation including:

- environmental management and rehabilitation conditions on mining titles;
- rehabilitation security bonds for all mining and exploration titles; and
- clear enforcement powers to ensure titleholders comply with their obligations.

The *Mining Act 1992* gives the DSC (now known as Dam Safety NSW) responsibility for advising on any mining proposals that would impact on Dam Safety Notification Areas.

## 2.2 Policies and Plans

### 2.2.1 State Environmental Planning Policies

State Environmental Planning Policies (SEPPs) are instruments created under the EP&A Act that regulate land use and development. Examples of relevant SEPPs include *SEPP (Mining, Petroleum Production and Extractive Industries) 2007*, *SEPP (Sydney Drinking Water Catchment) 2011* and *State Environmental Planning Policy (State and Regional Development) 2011*. SEPPs designate the consent authority for the activities they regulate, what development is permissible with and without consent and what development is prohibited. They also describe what the consent authority must consider when determining whether to give approval to a development (usually including advice from the Secretary of Planning), and set out non-discretionary development standards.

The *Sydney Drinking Water Catchment SEPP* includes a requirement that consent authorities (councils) and the Minister must determine that a development will have a neutral or beneficial effect on water quality in order to approve it. This is required to be assessed according to the Guideline prepared by the WaterNSW and using the assessment tool developed for that purpose. The SEPP also requires that all developments and activities incorporate the WaterNSW's recommended practices and standards. Further, Water Quality Information Requirements set out what information and modelling proponents must include in their development applications.



The *Mining SEPP Amendment 2013* gives effect to measures introduced under other policies, such as the *Strategic Regional Land Use Policy and the Aquifer Interference Policy* through changes to the *SEPP (Mining, Petroleum Production and Extractive Industries) 2007*.

## 2.2.2 State and Regional Development SEPP

State Significant Developments (SSDs), as defined by the State and Regional Development SEPP, require assessment by the Department of Planning and Environment. Consent can be given either by senior department personnel, the Planning Assessment Commission (PAC) or the Minister for Planning. Included in SSDs are all coal mining activities, some petroleum exploration activities and all petroleum production proposals. For all development proposals from private developers, the Minister has delegated decision-making powers to either the department (for proposals with fewer than 25 objections lodged) or to the PAC.

In assessing development proposals for SSDs, the Department of Planning and Environment may seek advice from the relevant NSW Government agencies, including WaterNSW, the Dam Safety NSW, the Environment Protection Authority (EPA), the Office of Environment & Heritage (OEH), the Department of Primary Industries (DPI) (Water) and the Department of Industry (DoI) (Resources and Energy). Once approval to a proposal has been given, these agencies are not able to refuse authorisations such as an environmental protection licence or a mining lease where they are consistent with the approval. However, aquifer interference under the *Water Act 2000* must still be separately approved by DPI (Water).

## 2.2.3 Water Sharing Plans

Water Sharing Plans (WSP) are being progressively developed for rivers and groundwater systems across New South Wales following the introduction of the *Water Management Act 2000* (WMA 2000). These plans protect the health of rivers and groundwater while also providing water users with perpetual access licences, equitable conditions, and increased opportunities to trade water through separation of land and water. There are two operational WSPs (surface water and groundwater) that cover the Metropolitan and Woronora Special Areas.

### 2.2.3.1 Water Sharing Plan for the Greater Metropolitan Region Unregulated River Water Sources 2011

The *Water Sharing Plan for the Greater Metropolitan Region Unregulated River Water Sources 2011* applies to the unregulated surface water sources within the Study Area. The WSP is a legal document made under the *Water Management Act 2000*.

The WSP includes provisions to provide water for the river's environmental needs, its ecological processes and direct how water available for extraction is to be shared. The WSP also sets rules for the management of access licences, water allocation accounts, the trading of or dealings in licences and water allocations, the extraction of water, the operation of dams and water flow management.

All water extraction, other than for basic landholder rights (domestic and stock rights and native title rights), must be authorised by an access licence. WaterNSW currently has water licences under the *Water Management Act 2000* for water extraction from rivers and dams in the Metropolitan and Woronora Special Areas to meet the drinking water needs of Sydney and surrounding areas.

WaterNSW extracts water from the following water sources within the WSP:

- the **Upper Nepean and Upstream Warragamba Rivers Water Source** –includes the Cataract, Cordeaux, Avon and Nepean Dam catchments, as well as the catchments of Pheasants Nest Weir and Broughtons Pass Weir; and



- the **Southern Sydney Rivers Water Source** – all unregulated surface water in the hydrological catchments including the Woronora River including-g the Woronora Dam catchment.

WaterNSW’s licence entitlements (share components) and extraction limits for each water source are shown in Table 2.2 (DPI Water, 2016).

**Table 2.2: WaterNSW Entitlement Volumes and Extraction limits under the Greater Metropolitan WSP within the Study Area**

Extraction Management Unit	Management Zone	Share Component/ Entitlement (ML/year)	Extraction Limit (ML/year)	Notes
Upper Nepean and Upstream Warragamba	Upper Nepean River Tributaries Headwaters, Lake Burragorang, Pheasants Nest Weir to Nepean Dam, Mid Cataract River	620,000	581,000	Share component based on maximum historical extraction over last 10 years. Annual extraction limit is based on average historical transfers to Sydney Water and system yield modelling.
Southern Sydney Rivers	Upper Woronora River	32,000	13,000	Annual extraction limit based on average historical transfers to Sydney Water and system yield modelling.

Source: DPI Water, 2016

WaterNSW’s license also defines environmental flow releases from the dams and water resources.

### 2.2.3.2 Water Sharing Plan for the Greater Metropolitan Region Groundwater Sources 2011

The *Water Sharing Plan for the Greater Metropolitan Region Groundwater Sources 2011* applies to the groundwater sources within the Study Area. DPI Water administers and periodically reviews the WSP. The current plan covers 13 different groundwater sources and commenced on the 1 July 2011.

The WSP includes provisions for water to support the ecological processes and environmental needs of high priority groundwater dependent ecosystems (GDEs) and rivers, and directs how the remaining groundwater available for extraction is to be shared. The WSP also sets management rules for water access licences, water allocation accounts, dealings in licences and water allocations, water supply works approvals, and the extraction of water.

The water sources covered by the WSP within the study area comprise:

- the **Sydney Basin Central Groundwater Source** (Woronora Special Area occurs within this area); and
- the **Sydney Basin Nepean Groundwater Source** (Metropolitan, Warragamba and Wingecarribee Special Areas occur within this area).

There are two management zones within the Nepean Groundwater Source. The WSP pertains to all water occurring naturally below the surface of the ground, all water contained within alluvial sediments below the surface of the land, all water contained within any coastal sands and all water contained within any porous rock aquifers and fractured rock aquifers that occur within the plan area. The plan does not differentiate between superficial aquifers, regional aquifers and deeper groundwater systems.



WaterNSW does not currently hold any groundwater entitlement for borefield extraction, although initial applications were made for the Kangaloon borefield development in 2009. Depending on the outcomes of future Metropolitan Water Plan reviews, any further pilot testing programs, analysis of sustainability and associated planning approvals (NOW, 2011b), new entitlements may be granted.

Mining companies hold groundwater entitlements under the WSP for their groundwater take based on predicted and actual mine water inflows.

## 2.2.4 NSW Aquifer Interference Policy

The *NSW Aquifer Interference Policy* defines the regime for protecting and managing the impacts of aquifer interference activities on NSW's water resources and strikes a balance between the water needs of towns, farmers, industry and the environment. The *Aquifer Interference Policy* details how potential impacts on water resources will be assessed.

New developments need to be assessed under the policy's criteria to quantify impacts to groundwater. Minimal impact criteria are stated in the policy for highly productive and less productive groundwater systems.

Most mining or petroleum exploration activities taking place under the *Mining Act 1992* and the *Petroleum (Onshore) Act 1991* require proponents to prepare Groundwater Monitoring and Modelling Plans in consultation with the DPI Water. The plans are required to ensure proponents embarking upon exploration understand the requirements of the *Aquifer Interference Policy*.

## 2.3 Catchment Management

A number of NSW Government agencies have responsibilities for managing Sydney's drinking water catchments. Chief among these is WaterNSW with responsibilities for the Special Areas, but key responsibilities are also held by the National Parks and Wildlife Service (NPWS), Dam Safety NSW, the DPI (Water), the DoI (Resources and Energy), the OEH and the EPA. WaterNSW was established on 1 January 2015 under the *Water NSW Act 2014*.

WaterNSW operates as an owner, regulator and partner in the management of the declared Sydney Catchment Area. The following sections briefly summarise the legal framework in which WaterNSW responds to mining proposals and ongoing activities within the declared Sydney Catchment Area.

### 2.3.1 WaterNSW's Regulatory Functions

As discussed in Section 2.1.3, WaterNSW has specific objectives and functions under the *Water NSW Act 2014* in relation to the declared Sydney Catchment Area, covering the bulk of Sydney's water supply.

WaterNSW is responsible for maintenance and operation of all prescribed dams within the Special Areas and is also required to ensure the safety of prescribed dams it owns under the provisions of the *Dams Safety Act 1978* involving the commitment of considerable resources.



## 2.3.2 WaterNSW's Current Position on Mining in the Declared Sydney Catchment Area

To make its advice transparent and consistent, WaterNSW has developed a set of principles (accessible at <http://www.watarnsw.com.au/water-quality/catchment/mining/principles>) that underpin its decision-making in relation to mining and coal seam gas activities. The principles establish the outcomes that WaterNSW considers as essential to protect the drinking water supplies to the four and a half million people of Sydney, Illawarra, Blue Mountains, Southern Highlands and the Shoalhaven. The principles relate to:

- Protection of water quantity;
- Protection of water quality;
- Protection of water supply infrastructure;
- Protection of human health;
- Protection of ecological integrity;
- Sound and robust evidence regarding environmental impacts.

WaterNSW's response to mining matters also needs to consider its Board's position on longwall mining and coal seam gas detailed in the Mining Principles, which are that WaterNSW:

- opposes any coal mining within the Dams Safety Notification Area of Prescribed Dams owned and managed by WaterNSW in the declared Catchment Area, or elsewhere, where it is predicted to damage water supply infrastructure; and
- opposes all coal seam gas activities within the Special Areas.

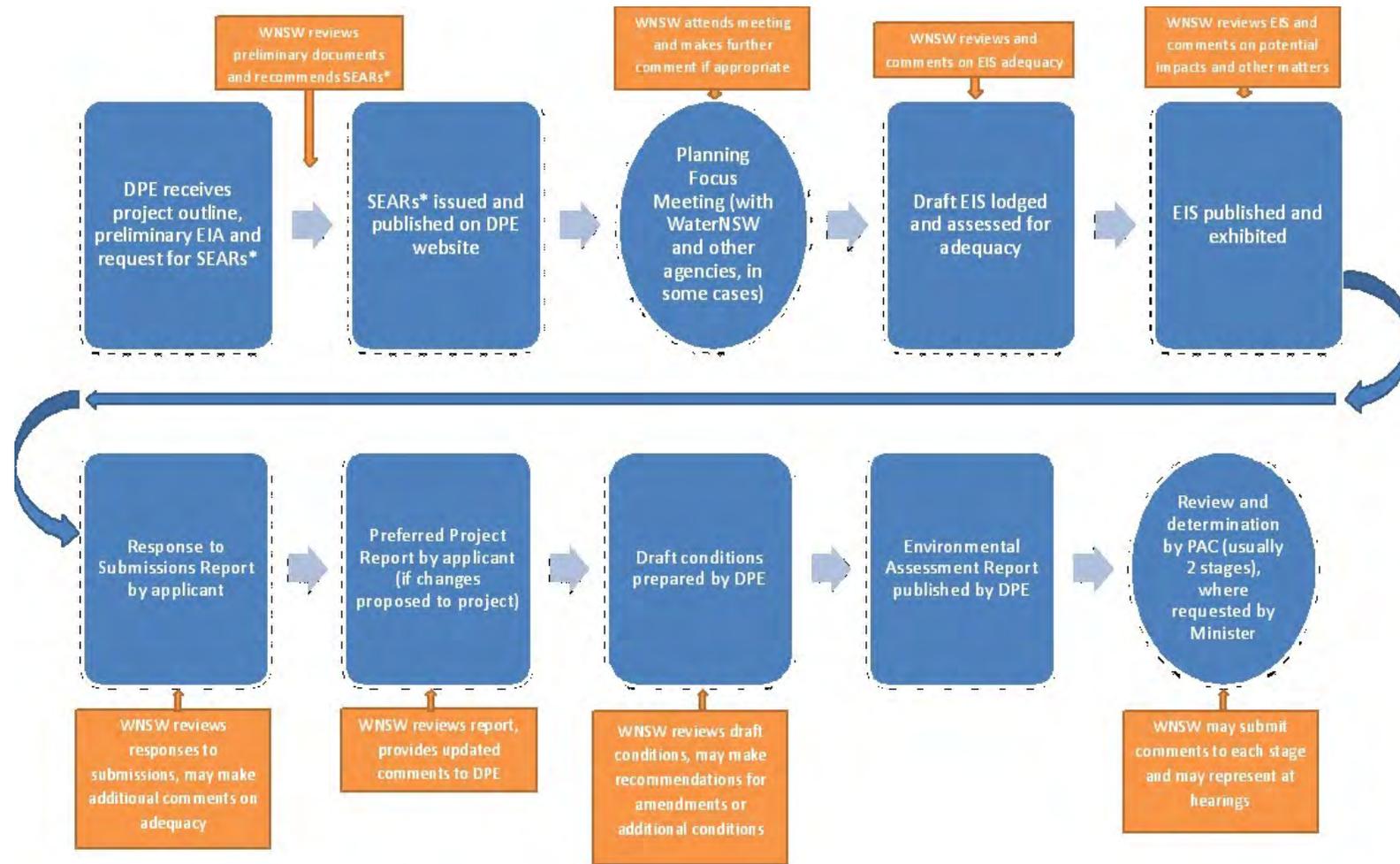
## 2.3.3 WaterNSW's Role in Mine Planning and Approvals Process

WaterNSW is aware that mining activities have in the past resulted in, and/or have the potential for future, adverse impacts upon:

- the quality of water in rivers, streams and storages;
- the quantity of water yielded by the catchment areas;
- the ecological integrity of the Special Area;
- the safety and integrity of catchment infrastructure works and other WaterNSW assets, and the security of stored waters, the cultural heritage value of catchment infrastructure works and other WaterNSW assets.

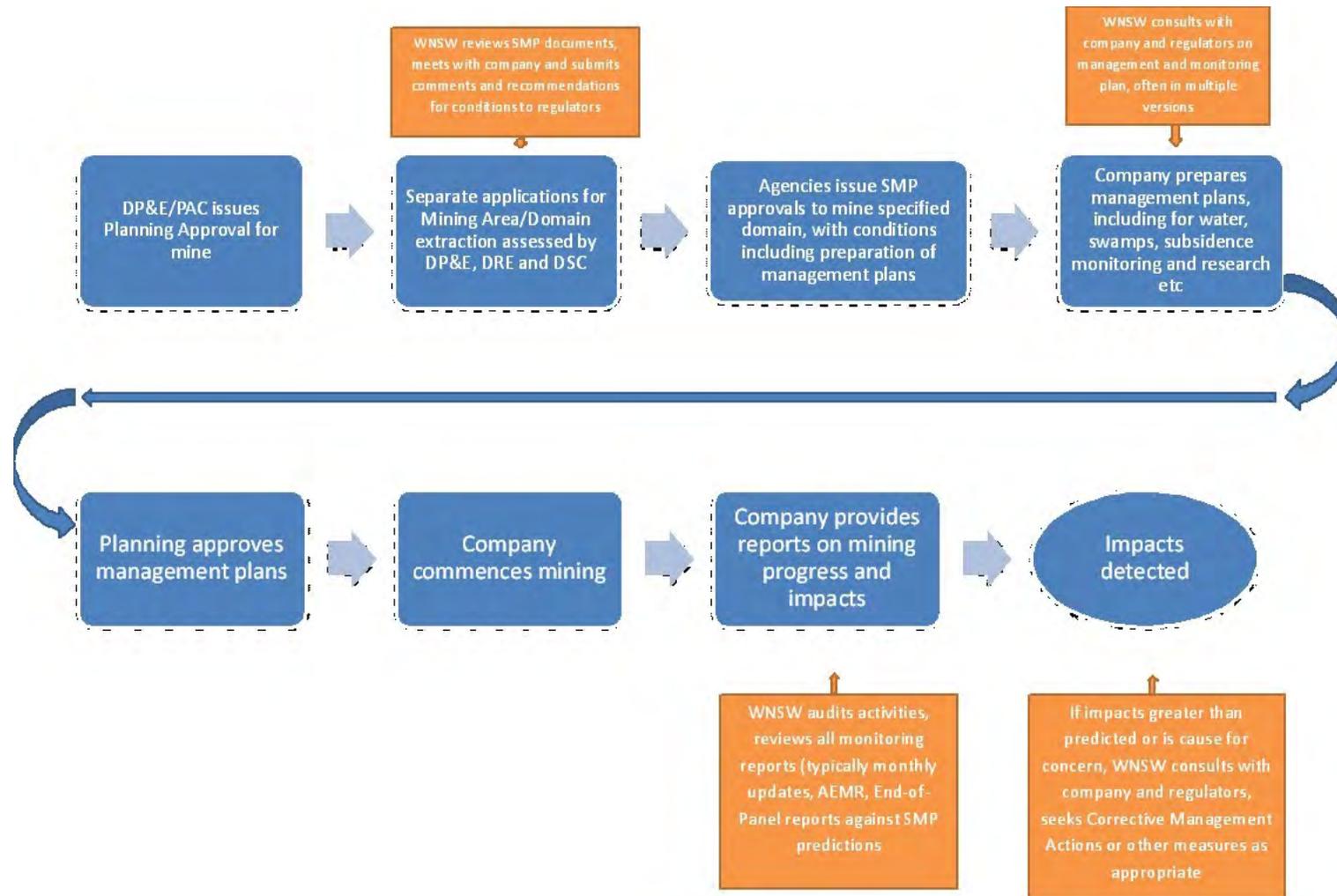
Apart from the legislative functions identified above and the limited powers endowed by the *Water NSW Act 2014* to control access to Special Areas, WaterNSW has no regulatory powers to approve or direct how mining within Sydney's drinking water catchment is planned or conducted. Instead, WaterNSW provides advice to the bodies that assess mining applications (DP&E, PAC and the DoI) on how those activities may affect stored water, water supply infrastructure and the drinking water catchment, and ecological integrity before a decision is made, and then works with those agencies and the mining companies to minimise the environmental consequences of mining if approval is given.

Figure 2.1 and Figure 2.2 and summarise the numerous points at which WaterNSW seeks to influence mining proposals in the planning process and in post-approval operations.



\* SEARs – Secretary’s Environmental Assessment Requirements

**Figure 2.1: Process for Preparation, Assessment and Determination of an application for an Underground Mining State Significant Development Project in the Special Areas**



**Figure 2.2: Process for Post-Approval Assessment and Management of Mining Projects in the Special Areas**



In addition to advice to regulatory authorities, WaterNSW also engages directly with the mining companies operating within the Sydney drinking water catchment. A governance framework has been agreed with all mining companies operating in the Special Areas and regular executive and technical working group meetings are held to ensure that WaterNSW and the companies are mutually aware of technical, operational and strategic aspects of mining operations and proposals within the Special Areas. WaterNSW continues to liaise regularly with the mining companies in accordance with the governance frameworks.



**Advisian**

WorleyParsons Group



### 3 Features of the Project Area

This section of the report ‘sets the scene’ for subsequent sections of the report. It outlines the features of the catchments within the Special Areas that are subject to potential impacts and consequences of mining induced subsidence, and provides a basis for consideration of local, national and international scientific literature applicable to the assessment of current and likely future impacts of longwall mining.

#### 3.1 Sydney Drinking Water Catchment and Special Areas

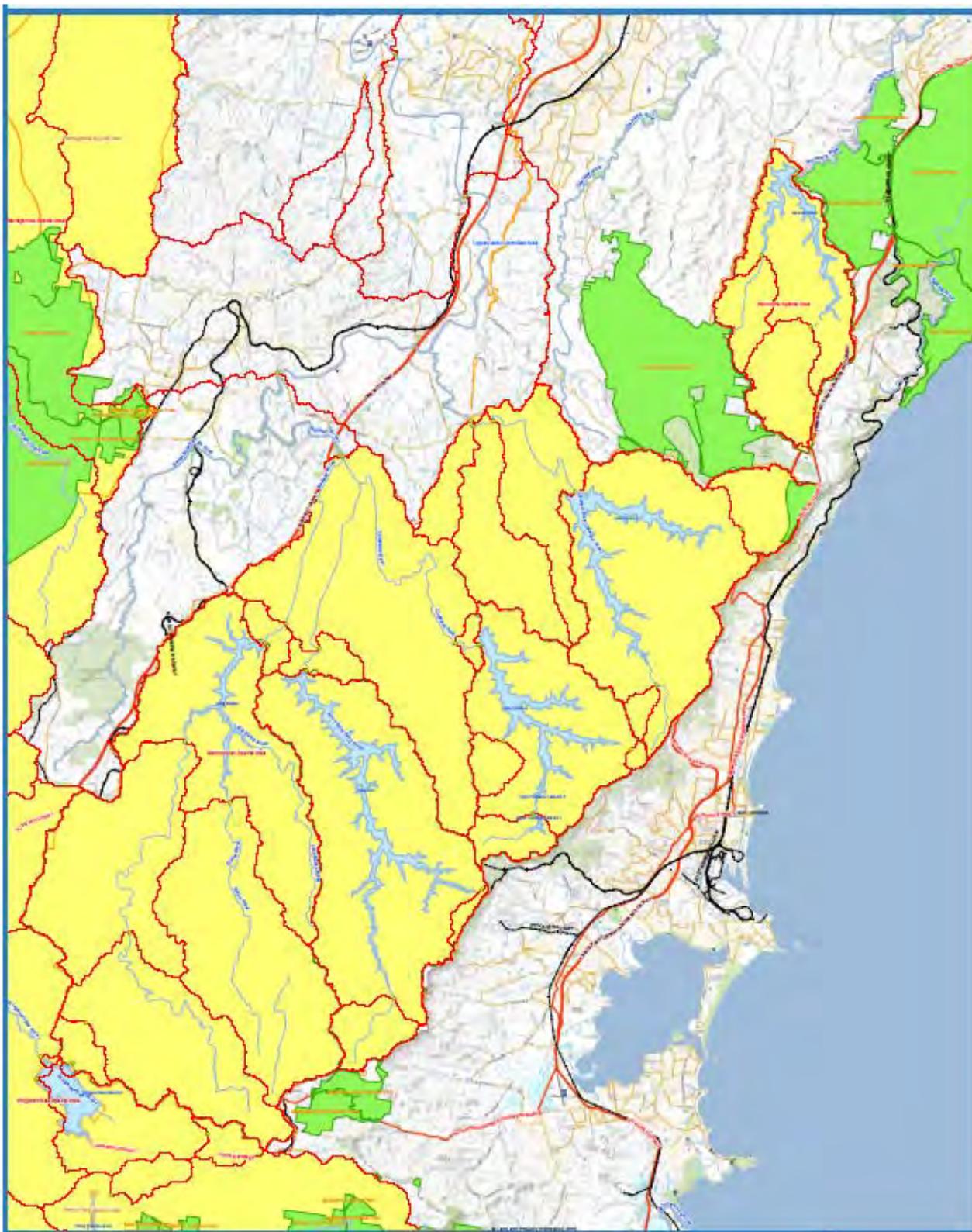
The Sydney Catchment consists of three main drainage basins within the Sydney Basin, a geological province that covers about 49,000 km<sup>2</sup>, the majority of which is onshore (44,000 km<sup>2</sup>). It extends from Batemans Bay to Newcastle and is bounded on the west by the Great Dividing Range. The three separate catchments are the Central Coast, the Hawkesbury-Nepean and the Sydney Metropolitan and Woronora, the latter two supplying most of greater Sydney’s drinking water.

WaterNSW is responsible for the management of 27 sub-catchments that drain into 11 major dams which store raw water. WaterNSW manages this water and its release into a range of distribution waterways including rivers, pipes and canals (GHD, 2013). Water from the catchment is provided by WaterNSW to customers including Sydney Water, councils and private customers. Sydney Water is responsible for managing nine water filtration plants and the water supply system that provides treated water to over four million customers.

Many of the major dams, reservoirs and canals used for drinking water supply are surrounded by ‘Special Areas’ established under the *Sydney Water Catchment Management Act 1998*, 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 protect Sydney’s drinking water. The Special Areas cover approximately 3,700 km<sup>2</sup> though the areas protected are discontinuous (SCA, 2014a), see Figure 3.1. This Project focusses 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 listed in Table 3.1. Collectively the reservoirs and weirs provide approximately 24% of the supply for the Sydney Water supply area.

**Table 3.1: Reservoirs within the Metropolitan and Woronora Special Areas**

Reservoir	Catchment Area (ha)	Total Operating Capacity (ML)	Water Surface Area at Full Supply (ha)
Woronora	7,225	71,790	380
Cataract	12,618	97,190	846
Cordeaux	8,684	93,640	783
Avon	14,256	146,700	1,055
Nepean	31,824	67,730	318
Broughtons Pass Weir	8,169	50	1.31
Pheasants Nest Weir	13,596	25	0.25



Source: WaterNSW, 2016

**Figure 3.1: Location of the Metropolitan, Woronora and Warragamba Special Areas**

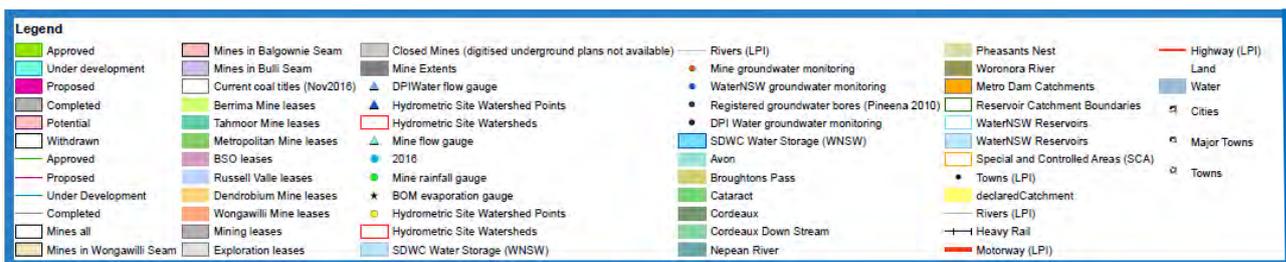


Figure 3.2: Figure 3.1 Legend

In addition to Special Areas there are also ‘Controlled Areas’ around water supply infrastructure, particularly the Warragamba pipelines and the Upper Canal, to which public access is prohibited. The Upper Canal is a critical piece of infrastructure which has been working since 1888 and provides between 20% and 40% of Sydney’s daily water demands.

A third restricted access category is the ‘Dam Safety Notification Area’, which surrounds the infrastructure of dams and their storages, due to the risks that dam failure can pose to life and property. The size of a Notification Area depends on the nature of the storage, the local geology, and the potential mining operations possible. Notification areas are established by Dams Safety NSW under Section 369 of the *Mining Act 1992*.

### 3.2 History of Water Supply and Mining Activities in the Special Areas

Table 3.2 below, adapted from NSW Chief Scientist & Engineer (2014), summarises the history of mining and water supply activities in the Metropolitan and Woronora Special Areas.

Table 3.2: History of Water Supply and Mining Activities in the Special Areas

<b>Pre-1800</b>	<ul style="list-style-type: none"> <li>Aboriginal occupation of area - Dharawal, Wadi Wadi and Gundurngurra people estimated to go back at least 15,000 years</li> <li>1788 First European settlement in the Sydney area</li> </ul>
	<ul style="list-style-type: none"> <li>1800s Hand-got longwall mining on the advance in use in Australia</li> <li>1857 Commercial quantities of coal produced at Kemira Colliery</li> <li>1850-1988 Kemira/Mt Keira</li> <li>1878-1991 Coal Cliff Colliery (bord and pillar) operated</li> <li>1861-1955 Mt Pleasant Colliery</li> <li>1861 – 2004 Russell Vale mine commenced, reopened in 1886 as the South Bulli (Bellambi) Colliery</li> <li>1865-1970? Mt Kembla Colliery</li> <li>1878 - 1991 Coal Cliff (bord and pillar) operated</li> <li>1880 Metropolitan Special Area declared to protect Upper Nepean catchment</li> <li>1888 Metropolitan Colliery opened at Helensburgh</li> <li>1888 Prospect Reservoir, Broughton's Pass Weir, Pheasants Nest Weir and the Upper Canal completed</li> <li>1892-1983 South Clifton Colliery</li> </ul>
<b>1800s</b>	
<b>1900 - 1950</b>	<ul style="list-style-type: none"> <li>1900-1962 Excelsior No. 1 and No.2</li> <li>1907 Construction of Cataract Dam complete</li> <li>1910-1983 Avondale Colliery</li> <li>1916-1993 Wongawilli Colliery</li> <li>1926 Cordeaux Dam completed</li> <li>1927 Avon Dam completed</li> <li>1930-1980 Old Wollondilly Coal Mine (Warragamba Special Area)</li> <li>1935 Completion of Nepean Dam</li> <li>1935-1973 Wollondilly Extended Coal Mine (Warragamba Special Area)</li> </ul>



<b>1900 – 1950 (ctd)</b>	<ul style="list-style-type: none"> <li>▪ 1941 Woronora Dam completed; Woronora Special Area declared</li> <li>▪ 1942-1973 North Bulli Colliery</li> <li>▪ 1946-1989 Huntley Colliery</li> <li>▪ 1946-1993 Nebo Colliery</li> <li>▪ 1947-1985 Corrimal Colliery</li> </ul>
<b>1950 - 2000</b>	<ul style="list-style-type: none"> <li>▪ 1955-1996 Oakdale Colliery (Warragamba Special Areas)</li> <li>▪ 1957-1982 Valley No. 1 (Warragamba Special Areas)</li> <li>▪ 1961 Mechanised longwall mining on the retreat introduced</li> <li>▪ 1971-1999 Avon Colliery</li> <li>▪ 1971-1991 Darkes Forest Colliery</li> <li>▪ 1972-1981 Bulli Colliery</li> <li>▪ 1976-1986 Nattai North Colliery (Warragamba Special Areas)</li> <li>▪ 1968-1981 Brimstone Colliery (Warragamba Special Areas)</li> <li>▪ 1980-2001 Cordeaux Colliery</li> <li>▪ 1988-1991 Kemira Colliery (longwall in Wongawilli Seam)</li> <li>▪ 1993-2007 Wongawilli Colliery consolidated with Kemira and Nebo mines to become Elouera Colliery</li> <li>▪ 1999 Sydney Catchment Authority become operational</li> </ul>
<b>2000- present</b>	<ul style="list-style-type: none"> <li>▪ 2004 South Bulli (also known as Bellambi, Belpac No.1) becomes known as Gujarat NRE Colliery, currently known as Russell Vale</li> <li>▪ 2005 Longwall mining commences at Dendrobium Coal Mine</li> <li>▪ 2007 Elouera Mine sold and renamed NRE Wongawilli Mine</li> <li>▪ 2015 WaterNSW becomes operational (replaces Sydney Catchment Authority)</li> </ul>

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

## 3.3 Coal Mining Operations

The first mines to exploit the Illawarra Coalfield were located near Mount Keira, now within the Metropolitan Special Area, which began operations in 1848 with commercial quantities first produced in 1857. The Metropolitan Colliery, located near Helensburgh, opened in 1888.

A large number of coal mines, active and inactive, are scattered through the area, including within the Special Areas. Three mines are extracting coal from under the Special Areas as at December 2016 (SCA, 2014b). The locations of existing mining leases in the study area are shown on Figure 3.3.

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 from which the coal has been extracted, which tend to fill with collapsed rock and overburden material as the longwall progresses. Subsidence rates tend to be substantially greater over longwall mines. Both mining processes are further described below.

### 3.3.1 Bord and Pillar Mining

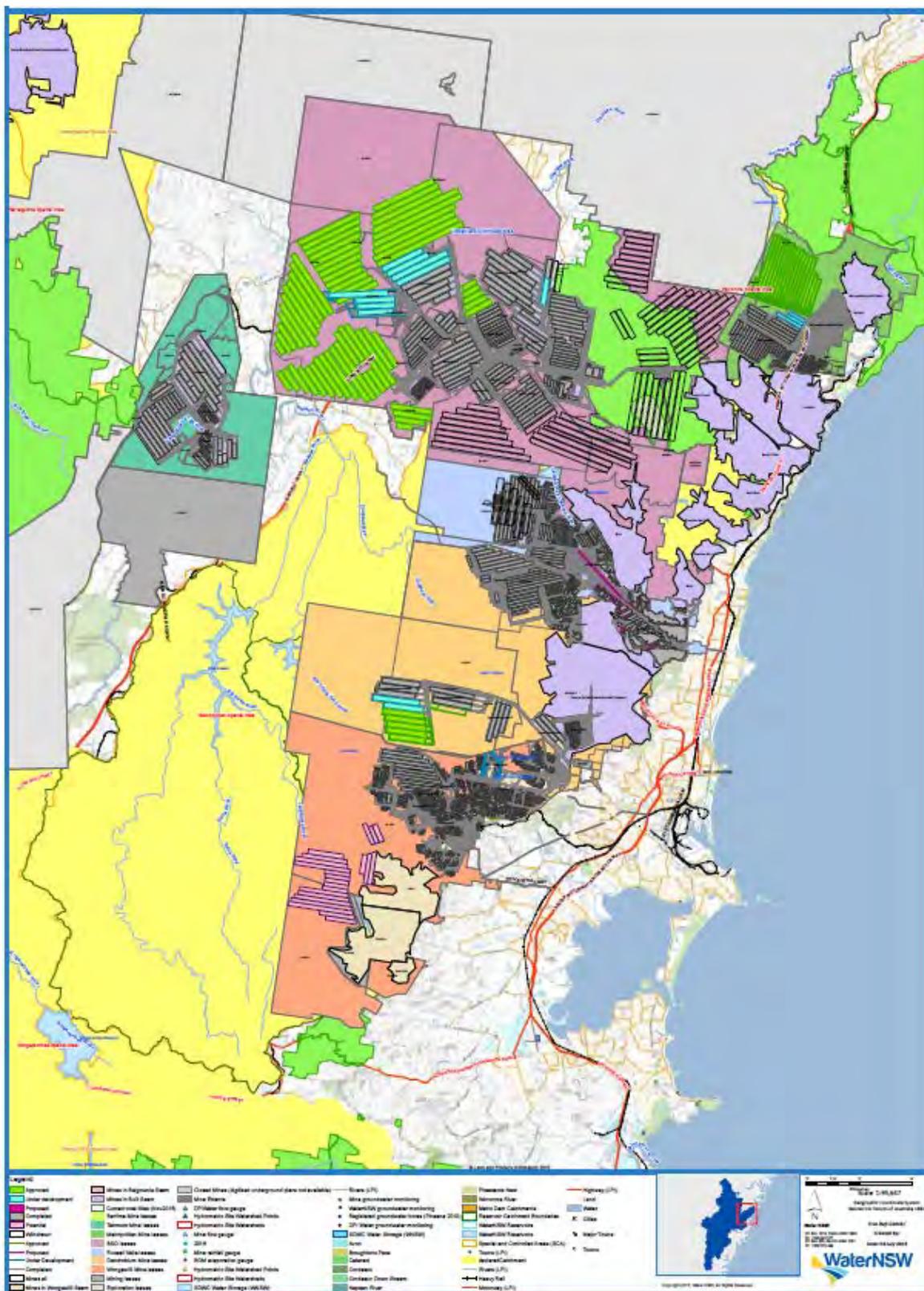
Bord and pillar mining, also called 'room and pillar' is an older method of mining coal seams. This was used from the 19<sup>th</sup> Century through to the 1960s when longwall mining became more prevalent. Bord and pillar mining cuts a grid of tunnels ('roads' or 'bords') through the coal seam, leaving pillars of coal remaining to support the overburden strata above these 'first workings'. The sizes of pillars and bords are restricted by legislation. In NSW pillars must be a minimum of one tenth the depth of cover, or 10 m and bords may only be 5.5 m wide except where special exemptions have been sought (NSW Chief Scientist & Engineer, 2014).



In many cases, these pillars are then extracted, during 'second workings', through a range of methods including: traditional and modern split and lift methods; traditional and modern Wongawilli method; and other methods. Partial pillar extraction involves the removal of a portion of the pillars during second working, however pillars are left behind to maintain support and decrease the extent of roof/overburden collapse into the mine void.

Even with partial pillar extraction, bord and pillar mining is less efficient than longwall mining due to the coal left behind in the supporting pillars. As a rough rule of thumb, first workings remove 10-20% of the seam areal extent, partial pillar extraction may remove 50-60% of the area and longwall methods up to 80-90% (McNally & Evans, 2007).

Mining under the Metropolitan and Woronora Special Areas was initially undertaken using hand bord and pillar mining until pillar extraction became possible with improvements in mining techniques and the arrival of mechanised mining. Minimal or no subsidence monitoring occurred during this period. Old bord and pillar mines occur under the Special Areas. Bord and pillar method mining is still used in modern longwall mines to drive the roadways and access through to and around the longwall panels (NSW Chief Scientist & Engineer, 2014).



Source: WaterNSW, 2016

**Figure 3.3: Existing Coal Titles and Mining Leases in the Study Area**

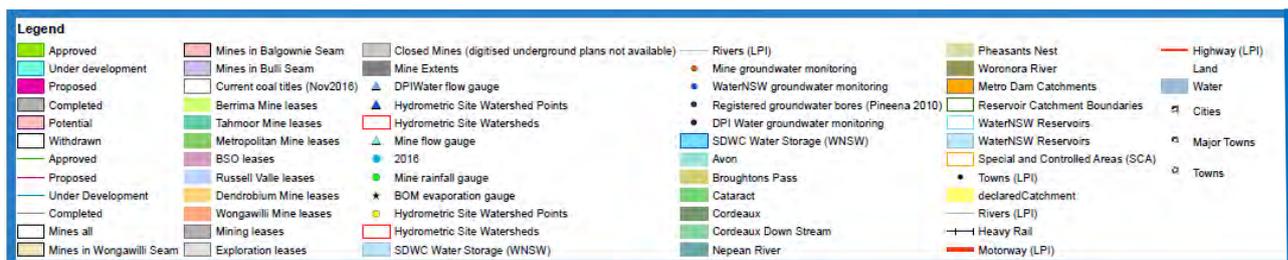


Figure 3.4: Figure 3.3 Legend

### 3.3.2 Longwall Mining

Hand-got longwall mining was in use in Australia in the 1800s. Longwall mining was introduced on a wider scale in the 1960s, expanded rapidly in the 1970s, and is now the principal extraction method for underground coal mining in Australia. It involves using hydraulic supports to support the overburden strata while the coal seam is cut out in full – as the mine moves along the coal seam, the supports are moved, allowing the overburden material to cave into the resulting void. This method generally leads to more subsidence than the bord and pillar method, due to the larger scale removal of coal. It is considered more efficient than bord and pillar mining as it removes more of the coal seam. A longwall ‘panel’ is the block of the coal seam that is being mined – typically, these are up to 4 km long and up to 400 m wide and are developed in sets to exploit large areas of coal seams (DSC, 2013).

The three mines operating in the Special Areas as at December 2016 are the Metropolitan, Wongawilli and Dendrobium Mines. Completed mining in the area has undermined approximately 8% of the Special Areas, with a further 1% approved and another 2% planned. Within the Metropolitan and Woronora Special Areas, 25% of the land area is currently undermined (GHD, 2013). The 2% of the Special Areas currently planned to be undermined does not include areas 5 and 6 at Dendrobium Mine or areas under the original Bulli Seam Operations Project which may be undermined by Illawarra Coal at some stage in the future. The extent of these areas is not known at this stage.

### 3.3.3 Historic and Current Mining

The current (as at December 2016) and historic underground mines located under the catchments of WaterNSW’s storages are listed in Table 3.3 and shown on Figure 3.3.

Table 3.3: Mines Located under WaterNSW Storage Catchments

Storage	In Operation as at December 2016 <sup>1</sup>	Care & Maintenance <sup>2</sup>	Proposed <sup>3</sup>	Historic <sup>4</sup>
Nepean	-	-	-	-
Avon	Dendrobium Area 3B Wongawilli	-	-	Avon Avondale Huntley Wongawilli Elouera



Storage	In Operation as at December 2016 <sup>1</sup>	Care & Maintenance <sup>2</sup>	Proposed <sup>3</sup>	Historic <sup>4</sup>
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	-	-	Darke Forest Coalcliff

Sources:

<sup>1</sup> Australian Government (2016) Figure 8 Mines and infrastructure in the Sydney Basin bioregion, as at 18 January 2016

<sup>2</sup> Australian Government (2016) Figure 10 Coal resource development proposals in the Sydney Basin bioregion as at January 2016 NB. Australian Government (2016) is Confidential

<sup>3</sup> WaterNSW Map - Mining in Metropolitan Catchment August 2015

## 3.4 Regional Geology

### 3.4.1 Stratigraphy

The Metropolitan, Woronora and Warragamba Special Areas lie within in a gently deformed sequence of Triassic sandstones and shales that form the upper sequence of the Sydney Basin. The *Southern Coalfield 1:100,000 Geological Series Sheet* and accompanying notes (Moffitt, 2000) indicate that the surface geological unit exposed across most of the area is the mid-Triassic Hawkesbury Sandstone. Most of the overlying Wianamatta Group rocks have been eroded away with only thin shale caps present in elevated portions of the southern Metropolitan Special Areas. In the base of deep valleys, such as those of the Nepean, Avon, Cordeaux and Cataract Rivers, there is exposure of the underlying Newport and Garie Formations and the Bald Hill Claystone; the uppermost formations of the Narrabeen Group. Beneath each of the dams and lakes in the Metropolitan Special Area, older Narrabeen Group rocks (mostly the Bulgo Sandstone and a succession of sandstones and claystones) crop out.

In the deep valleys that drain the Woronora Special Area, and beneath Lake Woronora and the dam wall, only Hawkesbury Sandstone is exposed. The drainage system associated with the Warragamba Special Area is more incised, and as well as Narrabeen Group rocks being exposed in the deep valleys, older Permian Illawarra Coal Measures are also exposed in all the valleys that drain to Lake Burrangang.

Thin Quaternary deposits (mostly sandy alluvium and colluvium) occur adjacent to some of the main drainage lines in the upper catchments away from the incised valleys. On the main plateau area, colluvial deposits (mostly sand, silt and peat deposits) are common and occur as headwater and valley fill swamps.

A large number of igneous intrusions and flows which vary in age, form, lithology, and stratigraphic emplacement, occur across the Southern Coalfield. These range from late Permian to late Tertiary in age. The form of the intrusions and flows varies from plugs, sills, dyke swarms, and lopoliths to extensive flows. Most of the near surface igneous features within the Special Areas are Cretaceous



or Tertiary in age. Most of these features have been intruded along structural weaknesses in the basin. Where volcanic intrusions are within, or adjacent to, individual seams within the Illawarra Coal Measures, the coal quality is affected.

Ridges and higher hills in the Kangaloon – Robertson area (in the Upper Avon, Nepean and Wingecarribee catchments) are capped by flood basalts, which are of late Tertiary age. Beneath the areas of basalt cap, there are known to be Tertiary alluvial sediments.

A summary of all the Southern Coalfield stratigraphic units is presented in Table 3.4 with an expansion of the Illawarra Coal Measures stratigraphy in Table 3.5.

All of the economic coal measures of the Southern Coalfield are located within the Illawarra Coal Measures and the Sydney Sub Group formations. The primary coal seams that are mined or potentially exploited for gas are the Bulli, Balgownie and Wongawilli Coal Seams.

**Table 3.4: Summary Stratigraphy of the Southern Coalfield**

Age	Group	Sub-Group	Symbol	Formation	Rock Types		
Quaternary			Qa		Alluvium		
			Qs		Colluvium – Swamp deposits		
			Qt		Colluvium – Talus		
			Qp		Peat		
Tertiary			T-Rb	Robertson Basalt *	Alkali olivine basalt		
			T-Ct	Cordeaux Teschenite	Crinalite		
Cretaceous			Ktc	(Mount Cotopaxi)	Trachytic intrusion		
Jurassic			Jt		Microsyenite, trachytic intrusions		
			Jes		Syenite, microsyenite		
			Jv		Basalt, dolerite and volcanic breccia		
Triassic	Wianamatta Group		Rw	Bringelly Shale *	Undifferentiated shale, laminite and sandstone		
				Minchinbury Sandstone *			
				Ashfield Shale *			
	Narrabeen Group	Clifton Sub-group		Rnc	Rm	Mittagong Formation *	Shale, laminite, sandstone
					Rh	Hawkesbury Sandstone	Quartzose sandstone, minor conglomerate and shale
					Rnz	Newport Formation	Undifferentiated quartz-lithic sandstone, siltstone and claystone
Garie Formation							
Bald Hill Claystone					Dominantly red-brown claystone and shale		
Bulgo Sandstone	Quartz-lithic sandstone, shale and claystone						
Stanwell Park Claystone	Red-green-grey shale and quartz sandstone						
Scarborough Sandstone	Quartz-lithic sandstone, pebbly in part						
Wombarra Claystone	Grey shale and minor quartz-lithic sandstone						
Coal Cliff Sandstone	Quartz-lithic sandstone						
Permian	Illawarra Coal Measures	Sydney Sub-group	Pi	Various Formations (see Table 3.5)	Sandstone, siltstone, claystone and coal		
		Cumberland Sub-group		Various Formations			
	Shoalhaven Group		Ps	Various Formations	Sandstone, shale, siltstone and minor conglomerate		



Source: After Moffitt, 2000

\* - These formations mostly absent from the Metropolitan and Woronora Special Areas

**Table 3.5: Stratigraphy of the (Eastern) Illawarra Coal Measures**

Age	Group	Sub-Group	Symbol	Formation	Rock Types
Permian	Illawarra Coal Measures	Sydney Sub-group	Pi	Bulli Coal	Coal
				Loddon Sandstone	Quartz-lithic sandstone with minor siltstone and claystone. Contains Balmain Coal Member.
				Balgownie Coal	Coal
				Lawrence Sandstone/ Burraborang Claystone	Lithic sandstone with minor claystone and siltstone Claystone
				Eckersley Formation	Interbedded claystone, siltstone, coal and minor sandstone. Contains several coal members
				Wongawilli Coal	Coal
				Kembla Sandstone	Lithic sandstone with interbedded claystone and siltstone
				Allans Creek Formation	Coal, sandstone, siltstone and claystone. Contains American Creek coal member
				Darkes Forest Sandstone	Lithic sandstone with minor siltstone and claystone
				Bargo Claystone	Claystone and siltstone
				Tongarra Coal	Coal, siltstone and claystone
				Wilton Formation	Claystone, siltstone and interbedded sandstone
				Marrangaroo Conglomerate	Conglomerate, sandstone
			Cumberland Sub-group		Various Formations
	Shoalhaven Group		Ps	Various Formations	Sandstone, shale, siltstone and minor conglomerate

Source: After Moffitt, 2000

### 3.4.2 Geological Structure

The rock strata in the Special Areas are essentially flat lying, with a regional dip of 1° to 2° to the north-east, north or north-west depending on the specific location. However, there are variations in dip, indicating a degree of structural deformation. Moderate deformation has occurred producing a series of gentle folds and warps. Regional geological structures across the Special Areas shown on the 1:100,000 Southern Coalfield map include the Mount Murray Monocline, the Alpine Monocline, the Nepean Monocline, and the Woronora Anticline. Towards the coastal escarpment, there are numerous smaller anticline, syncline and fault features that have been mapped as the result of more than 150 years of coal mining and geological investigations. Throughout the Metropolitan Special Area there are several dome features which are interpreted to be surface disturbance of sedimentary strata caused by sub-surface igneous intrusions.



At the southern edge of the Metropolitan Special Area there is more complex structural deformation and faulting, reflected in a northwest trending horst and graben structure termed the Mittagong Horst-Graben Complex (Lee, 2000).

The predominant orientation of major faults and monoclines across the Metropolitan Special Area is east-south-east to west-north-west.

Immediately to the east of the Warragamba Special Area, the southern portion of the north-south Lapstone Structural Feature (generally known as the Nepean Fault system) occurs. The Lapstone Structural Complex is described as a number of north south related faults and folds, which plunge to the south. The escarpment is east facing, and is commonly referred to as a monocline, but in reality changes from north to south between a monocline and a series of en-echelon faults (Parsons Brinckerhoff, 2008c).

Regional uplift and faulting associated with both these major structural features (that are still considered tectonically active) has significantly increased the degree of fracturing and faulting, and enhanced the groundwater resource potential of the regional aquifers across these areas (Ross, 2014).

Regionally, the role of fracturing and faulting in interconnecting shallow and deep groundwater systems is less certain, although it is widely regarded that there is negligible vertical flow through deep seated faults in areas that have not been mined. Tonkin and Timms (2015) concluded there is a lack of evidence for direct vertical flow paths via geological structures from the ground surface through overburden strata to coal seams in the Southern Coalfield. Also AGL (2013) has confirmed that there is no apparent connectivity between the Hawkesbury Sandstone aquifers and the deeper water bearing zones in the Narrabeen Group and the Illawarra Coal Measures across the Camden Gas Project area to the north. This provides further evidence that faults in non-mined areas are not natural conduits and claystones are effective confining layers for groundwater flow.

In mined areas, the presence of both small scale and larger extensional faults and any associated movement along these defects in the rock mass, is suspected to increase the risk of vertical flow from shallow groundwater systems to deep mining voids.

### 3.5 Hydrogeology

This section describes the hydrogeological processes and natural groundwater systems across the Special Areas that have not been impacted by anthropogenic activities, particularly mining activities.

Extraction and use from all groundwater systems is managed by DPI Water under the *Water Sharing Plan for the Greater Metropolitan Region Groundwater Sources*. The plan does not differentiate between (high value) groundwater resources located in the shallow fractured and porous rock aquifers and the (low value) groundwater found in the deeper groundwater systems of the Southern Coalfield. Mine water abstractions are licensed via water access licences (WALs) under this WSP.

There are two groundwater sources that cover the Metropolitan and Woronora Special Areas:

- Sydney Basin Nepean; and
- Sydney Basin Central.

The whole of the Metropolitan Special Area occurs within the Sydney Basin Nepean Groundwater Source while the Woronora Special Area occurs within the Sydney Basin Central Groundwater Source. Background information on the spatial extent of the plan and the water management



criteria for each of the groundwater sources is provided in the background report to the WSP (NOW, 2011b).

### 3.5.1 Groundwater Systems

The groundwater systems underlying the Metropolitan, Woronora and Warragamba Special Areas are features of the natural environment and are important components of the catchment water cycle. Groundwater provides a small (but important) component of the overall water balance for catchments across the Special Areas. Groundwater from superficial and regional bedrock aquifers sustains baseflows to streams, and within the riparian corridors, supports (or partially supports) a variety of ecosystems.

All water within the catchments is derived from rainfall with surface water runoff and evapotranspiration processes dominating. Rainfall declines from east to west and recharge contributions vary from area to area but in naturally vegetated areas, the relative contributions are likely to be of the order of <5% to groundwater, <50% to surface water and >50% to evaporation/transpiration.

The primary focus of WaterNSW's function is to protect surface water quantity and quality, particularly surface water flows and supporting hydrological processes across the Metropolitan and Woronora Special Areas. However protecting the sizeable groundwater resources and its contribution to stream baseflows and terrestrial/riverine ecosystems is also an important consideration.

Two regional aquifers (Robertson Basalt and Hawkesbury Sandstone) are large enough in areal extent, and saturated to reasonable depths to be useful water supply resources across the region. The extent of the Robertson Basalt is south of, and largely absent from, the mined parts of the Metropolitan Special Area.

Most beneficial aquifers in this region are located less than 200 metres below ground level (mbgl). The Hawkesbury Sandstone located in the southern portion of the Metropolitan Special Area is a significant (high yield/low salinity) groundwater resource that was investigated for emergency drinking water supply for the greater Sydney metropolitan area in the 2000s (Ross, 2014). Across the northern Metropolitan and all of the Woronora Special Areas, the groundwater resource potential is much lower with the regional sandstone aquifer categorised as a low yield/low salinity resource.

The groundwater systems of the Southern Coalfield were previously classified by the Department of Planning (NSW Government, 2008) as either:

- Shallow unconsolidated sediments, or
- Consolidated rocks.

More detailed conceptual models (such as Minchin et al, 2016) suggest three distinct groundwater systems:

- Deep groundwater system;
- Shallow groundwater system; and
- Perched groundwater system (associated with shallow sandstone and swamps).

Both these groupings are too generic for consideration in this Review so the following (top down) groundwater system classification is proposed:



- Superficial aquifers:
  - Quaternary alluvium;
  - Quaternary colluvium.
- Regional aquifers:
  - Tertiary volcanics;
  - Triassic Hawkesbury Sandstone and Gosford Sub-Group rocks.
- Deeper groundwater systems (comprising minor aquifers and aquitards):
  - Triassic Narrabeen Group rocks (below the Gosford Sub-Group);
  - Permian Illawarra Coal Measures;
  - Permian Shoalhaven Group rocks.

## 3.5.2 Groundwater Recharge, Discharge and Flow

### 3.5.2.1 Processes

At a regional scale, the following natural hydrological and hydrogeological processes occur:

- Rainfall provides (major) runoff to the regional drainage system and provides (minor) recharge to unconsolidated sediments (superficial aquifers), and to underlying consolidated (fractured and porous) basalt/sandstone strata;
- Recharge to the surficial groundwater systems (i.e. the superficial and regional aquifers) is governed by rainfall intensity, the prevailing permeability and porosity of materials, and other processes including evaporation and evapotranspiration;
- Runoff is impeded in upland areas where swamps are prevalent, or in areas where a regolith profile is well developed and rainwater can infiltrate and recharge groundwater. These areas act as temporary water stores and where large swamps exist, provide a baseflow component to stream flow;
- Runoff is more rapid in areas where rock outcrop occurs or where the regolith is thin. Groundwater recharge is generally low in rocky plateau areas (especially where there are shale cap rocks) and incised river valleys. Where there is substantial secondary permeability and porosity in sandstone sub-crop, recharge rates can be moderate to high;
- Discharge from the regional aquifer systems is via springs (mostly in the basalt landscape), exposed fractures or direct baseflows to streams in topographically lower areas, and to terrestrial vegetation where water tables are close to surface;
- Beneath each of the dam storages, the hydrological processes are assumed to have changed over the last century due to the presence of stored waters, including some leakage into the adjacent and underlying groundwater systems.

All groundwater systems are ultimately recharged by rainfall. Residence times for superficial aquifers are generally weeks, months or years while for regional aquifers can be hundreds to tens of thousands of years. For the deeper groundwater systems, groundwater ages can be hundreds of thousands of years. Long term regional monitoring of aquifer and deeper groundwater systems in the Southern Coalfield is sparse and downward flow rates between aquifer and aquitard units are difficult to estimate. Short-term monitoring indicates that the shallower groundwater systems respond to rainfall events and climatic trends more rapidly than the deeper systems.



### 3.5.2.2 Superficial Aquifers

Superficial aquifers have localised water tables that are sometimes in direct connection with regional aquifers and streams (such as the Quaternary alluvium and occasionally the colluvium) and are sometimes perched (such as most of the Quaternary colluvium). The superficial aquifers are all unconfined.

The perched water tables associated with upland swamps (except the larger headwater swamps) are usually ephemeral. Some unsaturated vertical flow occurs beneath upland swamps to recharge the sandstone aquifers after heavy rain, however a larger proportion of the superficial groundwater is thought to be removed through evaporation, transpiration and baseflows to adjacent streams (see Appendix F for further discussion). Hillside swamps may be a reflection of where there is a degree of connection between superficial aquifers and regional groundwater. Even minor seeps of regional groundwater through fractures and porous zones can assist in the development and maintenance of the shallow superficial aquifer associated with these swamps.

### 3.5.2.3 Regional Aquifers

The regional water table occurs within either the Tertiary volcanics (where present) or the Triassic Hawkesbury Sandstone. The regional aquifers within the Hawkesbury Sandstone are unconfined near surface and semi-confined at depth.

Groundwater recharge to the regional aquifers occurs everywhere across the Special Areas (except in the incised river valleys and along the escarpments where the aquifers are discharging to surface drainage lines). Most recharge occurs in the more elevated portions of catchments where there is higher rainfall and more fractured rocks are exposed near surface. Within the Hawkesbury Sandstone there is a downward component of flow however most groundwater flow is inferred to be sub-horizontal. Although 'perching' on bedding planes, shale lenses or ironstone bands is common in similar sandstone terrains in Newnes Plateau and the Blue Mountains, there is limited evidence of it within the regional sandstone aquifer in the Southern Coalfield.

Groundwater flow for the regional aquifers generally follows the topography but some inter-catchment flow is possible in upper catchment areas (URS, 2009a and URS, 2009b). The sandstone plateau is heavily dissected in the northern Metropolitan Special Area near the water storages and consequently Narrabeen Group rocks are exposed in the base of the gorges. As a full section of Hawkesbury Sandstone is exposed in these gorges, the regional aquifer discharges as either baseflow to streams, hillside springs, or seepage contributions to terrestrial vegetation. Across the whole of the sandstone landscape, baseflow discharges to streams dominate over hillside springs and seeps. In the Woronora Special Area, only a partial section of Hawkesbury Sandstone is exposed in the gorges so there is some regional groundwater flow beyond the dam and water storage into the Georges River catchment. Groundwater levels in the regional sandstone aquifer are above the full supply levels (FSL) of all the Metropolitan dams and all groundwater discharges to the reservoirs.

### 3.5.2.4 Deeper Groundwater Systems

The deeper groundwater systems comprise the groundwater found in the geological strata immediately above, within and below the Illawarra Coal Measures. These deeper rocks form a succession of minor aquifers, low permeability water bearing zones and aquitards. The minor aquifers are generally confined unless exposed along escarpments and along the floors of incised valleys.



Limited direct rainfall recharge to the uppermost Triassic Narrabeen Group rocks (predominantly the Bulgo Sandstone) occurs in the eastern portion of the Metropolitan Special Area where this unit is exposed and receives rainfall recharge. The Bulgo Sandstone is considered a minor aquifer due to its relatively low permeability. There is no known (direct rainfall) groundwater recharge to the deeper groundwater systems found in the lower Triassic and Permian sedimentary rocks across the Special Areas.

A number of lines of evidence (e.g. laboratory and field permeability tests, vertical gradients in piezometers well removed from longwalls, environmental isotopes, radiogenic isotopic age dating (Ross, 2014, KBR, 2008, David et al, 2015) suggest that natural groundwater flow from surface recharge into and through the Narrabeen Group rocks and deeper sequences is very slow, typically in the order of thousands to tens of thousands of years (or longer).

Within individual sandstone units and between the various sedimentary rocks overlying the Illawarra Coal Measures there is potential for vertical flow as groundwater pressure levels generally decrease with depth. The widespread claystone units within the Clifton Sub-Group of the Narrabeen Group (Bald Hill, Stanwell Park and Wombarra Claystones) are generally effective aquitards (AGL, 2013). The anisotropically low permeability of the claystone units within the Narrabeen Group rocks restricts vertical groundwater flow between units. Most natural groundwater flow is consequently inferred to be sub-horizontal within each geological formation.

For the Metropolitan Special Area, natural groundwater flow is to the north and west following the dip of the strata. For the Warragamba Special Area, the groundwater flow direction is less certain but is probably to the north and east. Some groundwater would discharge into the gorge areas where Triassic Narrabeen Group rocks and Permian rock types are exposed however deeper groundwater would continue to flow beneath catchments to ultimately discharge in the centre of the Sydney Basin or below the Illawarra escarpment.

Beneath each of the water storages, the natural flow processes will have changed over the last century with recharge to (rather than discharge from) the Narrabeen Group rocks that have been inundated by the water storage lakes.

### 3.5.2.5 Baseflow Contributions

For this study it is the baseflow contributions to streams that WaterNSW is particularly concerned about as it seeks to ensure that catchment yield (both quantity and quality) is not compromised by mining.

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 (refer Section 1.3), 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.

Across the wider catchment, and in order of expected volumetric contributions, the baseflow sources contributing to persistent surface flow in the Special Areas are considered to be:

- Groundwater discharges from the regional Hawkesbury Sandstone aquifer;
- Groundwater discharges from superficial aquifers within upland swamps;



- Spring discharges from regional aquifers across the basalt landscape to the south that sustain some tributary flows in the upper Nepean, Burke, and Little Burke Rivers, and parts of the Avon catchments;
- Bank storage and interflow in the mid catchment areas (i.e. water that recharges soil/weathered rock and shallow groundwater during high rainfall/flow events that immediately drains once high stream flows recede).

All of these groundwater baseflow contributions are small in comparison to evapotranspiration and surface water runoff components, and are difficult to measure, particularly when rainfall runoff is still occurring. Flow components (baseflow and quick-flow) may be measured at flow gauges and distinguished by baseflow separation analysis, but the accuracy of low-flow measurements at many gauges in the WaterNSW catchments is not high and there remains significant differences of opinion as to how baseflow separation is best analysed (see Section 3.7.5).

In the groundwater literature and groundwater numerical modelling studies, baseflow volumes are generally only the deeper (and longer term) groundwater discharge contributions to stream flow. Contributions from superficial aquifers, interflow and bank storage are short term and not able to be effectively modelled in 'longer time step' groundwater models.

It is important that baseflows derived from different studies are not directly compared without an understanding of the components and methodology used to derive the volume, percentage of streamflow or percentage of long term average rainfall.

For example, Minchin and Brown (2016) provide a comparison of rainfall recharge and baseflow estimates from various field and modelling studies across the Southern Highlands and Metropolitan Special Areas. However the methodologies used to derive these estimates (or any underlying assumptions) are not discussed.

**Table 3.6: Summary of Recharge and Baseflow Estimates**

Process		Hydro Simulations, 2016c	Crosbie, 2015	Coffey, 2012a,b	NOW, 2011a	Pells, 2013	WaterNSW, 2016
Recharge	% LTA <sup>1</sup> rain	6.5%	3 - 8.5%	2.7 or 6%	6%	5%	no estimate
	mm/year	65	40-100	-	-	50	no estimate
Baseflow	BFI <sup>2</sup> %	10-15%	no estimate	8%	no estimate	no estimate	20-40%
	mm/year	4-7	no estimate	-	no estimate	no estimate	80-160
	% LTA rain	0.5-1%	no estimate	0.5-3%	no estimate	no estimate	8-16%

<sup>1</sup> LTA = long term average

\* Source: Adapted from Minchin and Brown (2016)

<sup>2</sup> BFI = ratio of groundwater discharge to total river flow (%)

Groundwater recharge estimates are considered to be that proportion of long term average rainfall that reports to the regional water table (although each of the individual references has not been checked). Long intense rainfall events are known to provide greater recharge than short duration rainfall events, with antecedent soil moisture also an important factor.

The groundwater baseflow estimates in Table 3.6 are based on different estimation methods and hence slightly different results are not unexpected (this literature review has not assessed the relative merits of each method or queried the accuracy of the baseflow estimates). The quoted



baseflow estimates in Table 3.6 mostly relate to the regional sandstone aquifer contribution (i.e. not all the sub-surface contributions) and to pre-mining conditions.

Rainfall recharge and baseflow discharge rates are intuitively expected to be lower pre-mining compared to post-mining due to the broad-scale surface cracking that occurs in subsided catchments (Section 4.1).

In addition to the quoted studies, Coffey Geotechnics (2008) regional groundwater model for the Kangaloon borefield evaluated recharge and baseflow contributions for the Nepean and Avon River catchments (to each of the dams) during extreme drought periods. Groundwater recharge estimates were 0.3% of LTA rainfall while baseflow estimates equated to 0.5% of LTA rainfall.

WaterNSW's estimates of baseflow contributions being 20 to 40% of reservoir inflows are based on the application of a digital filter to modelled daily flows and cannot be directly compared to the groundwater study estimates. Even allowing for superficial aquifer, interflow and bank storage contributions, these estimates appear unrealistically high (see Section 3.7.5 for further discussion).

### **Superficial Aquifer Baseflows**

WaterNSW estimates that there is 3,599 ha (Table 3.9) of upland swamps across the catchments located within the Metropolitan and Woronora Special Areas. This area makes up almost 5% of the total catchment area.

It is known that these swamps retain rainfall and then release a proportion as baseflows to headwater streams immediately after rain. Most baseflow is generated within 4 to 6 weeks of a large rainfall event, and during extended dry periods, there are negligible baseflow contributions from these superficial aquifers. The swamp hydrology and baseflow contributions will differ between swamps but assuming an average 1,300 mm of rainfall per annum across all swamps and a 20% of LTA rainfall baseflow contribution, this equates to around 0.5 ML of baseflow per annum.

### **Basalt Aquifer Baseflows**

The basalt aquifers provide substantial spring flow in the uppermost portions of the Avon, Nepean and Wingecarribee catchments, however none of these areas are located within the parts of the Special Areas where coal mining activities have or are likely to occur. Coffey (2007) confirms that these inflow volumes are small and just the inflows to the Wingecarribee Special Area in a relatively dry period were estimated to be 25 litres per second (L/s) (of the order of two ML/d).

In the uppermost Avon and Nepean River catchments, similar spring contributions are likely given similar exposures of basalt. Assuming a rough estimate of 3-4 ML/d for spring discharges (based on a longer length of contact with the underlying Wianamatta Group shales), the annual baseflow contribution (after agricultural use in the upper Avon and Nepean catchments) is likely to be less than 1,000 ML.

### **Hawkesbury Sandstone Aquifer Baseflows**

There is general agreement in the literature that rainfall recharge to the sandstone landscape is between 0.5 and 8.5% (with most recharge events with rainfall in excess of 20 mm in the range of 3 to 5%). As this regional aquifer is full and overflowing (and with no groundwater abstractions), baseflow contributions must be less than 8.5% (the uppermost estimate of rainfall recharge). Baseflows in the order of 1-2% of LTA rainfall are considered most likely from the regional sandstone aquifer across the Metropolitan and Woronora Special Areas.

Assuming that the sandstone terrain is approximately 60,000 ha (derived from Table 3.8 less the area of upland swamps, shale and volcanic areas), baseflows would not exceed 2% of LTA rainfall



and, for average rainfall of 1,300 mm per annum, the annual baseflow contribution is likely to be of the order of 10,000 to 15,000 ML.

### **Bank Storage and Interflow**

Bank storage generally refers to water held in weathered rock and sediments along the banks of streams after flood events while interflow is water that is able to flow in the unsaturated zone generally at the interface between soil and weathered rock (again generally after high rainfall events). No estimates of the contribution to baseflow by bank storage and interflow across the Special Areas have been found, but volumes are expected to be small.

This water is usually included in the surface water runoff hydrograph as water contributes to streamflow within days and at most a few weeks of high rainfall/high flow events.

## **3.5.3 Groundwater Attributes**

This section describes the main physical attributes of each of the groundwater systems with a focus on natural permeability, storage, flow, and water quality in the natural (i.e. not under-mined) groundwater systems. It is noted that there is a general paucity of (pre-mining) baseline studies and information for the different groundwater systems across the Special Areas.

### **3.5.3.1 Superficial Aquifers**

#### **Quaternary Alluvium**

Very minor alluvial deposits occur along the base of some of the gullies, creeks and rivers in the upper catchments on the Woronora Plateau. These are predominantly sand and sandy clay sediments that contain groundwater that is recharged by rainfall. These sediments contain thin unconfined aquifers that have very small storage volumes and low salinity water. This groundwater provides baseflow to the adjacent streams immediately after rain but volumes diminish during dry periods.

#### **Quaternary Colluvium**

Minor colluvial deposits occur across the Woronora Plateau. They are mostly associated with headwater swamps and valley infill swamps. Perched aquifers in colluvium are recharged by rainfall and runoff from contributing catchments (where present). Storage volumes are very small (except for some of the larger headwater swamps) and the water quality is low salinity. This groundwater supports a large diversity of flora and fauna species within the swamps, and for the larger swamps, can provide baseflow to streams for several weeks after large rainfall events.

### **3.5.3.2 Regional Aquifers**

#### **Tertiary Volcanics**

These volcanic rocks are mostly fractured basalt flows located at topographically high locations but can also exist as plugs and intrusions with associated dyke swarms and sills. Groundwater recharge rates are high, storage is moderate, flow paths are short, and discharge rates are high through spring discharge and terrestrial vegetation transpiration. Water quality is mostly low salinity. This groundwater system is generally absent within the Special Areas, but has been found to be full and overflowing in the area immediately south of the Metropolitan Special Area.

The groundwater discharges as springs which then either flow overland or discharge to the nearby streams in the uppermost parts of the Avon, Nepean and Wingecarribee catchments outside the Special Areas. Spring flows decrease during drought periods.



## **Triassic Hawkesbury Sandstone and Gosford Sub-Group Rocks**

These sandstone rocks form the main regional aquifer across the whole of the Special Areas. The aquifer is a dual permeability aquifer given there is both porous and fractured flow. In areas located away from structural features, groundwater flow in porous layers dominates with only minor fracture flow. In other areas where there is faulting and folding, groundwater flow in joints, fractures and fault zones dominates over flow in porous zones.

A good appreciation of the hydrogeology of these sandstone formations across the whole of the Sydney Basin is provided in Russell et al (2009).

Groundwater recharge occurs everywhere but is most pronounced in the upper portions of catchments. Groundwater recharge rates are low-moderate, storage is very large, flow paths are long, and discharge rates are low through stream baseflows, occasional hillside springs and terrestrial vegetation transpiration. Groundwater recharge varies from less than 0.5% of LTA rainfall in non-fractured plateau areas to more than 3-5% in areas with enhanced secondary permeability (Coffey, 2008 and Pritchard et al, 2004). Groundwater flow is mostly in the more fractured zones (although there are some porous zones) and flow is mostly sub-horizontal. Vertical flow is constrained by the Bald Hill Claystone aquitard at the base of these Triassic sandstones.

Groundwater discharge mostly occurs lower in the landscape to contribute to stream baseflow. In non-fractured areas, these contributions are small and mostly via natural joints and fractures. Natural groundwater discharge seeps are easily identified by run-of-river surveys and assessing geochemical attributes. Groundwater discharge areas typically exhibit iron oxide staining, and the water is slightly lower in pH and dissolved oxygen, and slightly higher in salinity (for example SCA, 2007 and SCA, 2008).

Water quality is mostly low salinity (EC less than 500  $\mu\text{S}/\text{cm}$ ) across the Special Areas especially near the primary recharge areas. At Kangaloon, age dating suggests that groundwater is between 2,000 and 6,000 years before present (BP) within 5 km of the primary recharge areas with slightly older ages (up to 10,000 years BP) at downgradient locations (Parsons Brinckerhoff, 2008a and 2008b). Beneath the Illawarra Escarpment, the water quality is also low salinity (EC generally less than 300  $\mu\text{S}/\text{cm}$ ) (HydroSimulations, 2015) however there is no known reliable age dating data. At Warragamba-Wallacia, the water quality in the sandstone aquifers is slightly poorer due to the overlying Wianamatta Group shales. Groundwater in this area has been dated at around 15,000 years BP at a distance of 5 to 7 km downgradient of the recharge areas (Parsons Brinckerhoff, 2009b). Further to the north at Camden, groundwater in the Hawkesbury Sandstone has been dated at 40,000 to 100,000 years BP (Parsons Brinckerhoff, 2014).

### **3.5.3.3 Deeper Groundwater Systems**

The deeper sedimentary rocks beneath the Woronora Plateau also contain significant groundwater volumes however the rock permeabilities are lower and the rocks are commonly described as containing minor aquifers and aquitards. These rocks have little or no productive groundwater resource potential across the Special Areas.

Natural groundwater attributes for the deeper groundwater systems are not well known across the Special Areas, however a general appreciation is provided in AGL (2013) (of the area immediately to the north of the Metropolitan and Warragamba Special Areas).



## **Triassic Narrabeen Group Rocks (below the Gosford Sub-Group)**

The Triassic Narrabeen Group groundwater system is important because it contains large groundwater volumes in multiple sandstone units. These units are separated by claystone aquitards that restrict vertical movement and most (natural) groundwater flow is inferred to be horizontal within each of the units. This groundwater system is located between the regional aquifers in the Hawkesbury Sandstone and the water bearing zones in the deeper Illawarra Coal Measures.

These sedimentary rocks (except for some sandstones) are rarely aquifers but rather a succession of low permeability water bearing zones (in the sandier units) and aquitards (in the shaley units) (McNally and Evans, 2007). Groundwater storage volumes are large and water quality is generally brackish to slightly saline. Groundwater attributes of both the sandstone units and the claystone aquitards are generally poorly known, although on a local scale, there have been some detailed studies on permeability, connectivity and water quality of units (such as Parsons Brinckerhoff, 2013b).

An understanding of the groundwater attributes of these rocks (pre-mining) is important because, should this strata be severely compromised by mining, water will be lost to underlying coal mines from this groundwater system and through this system from shallow groundwater systems.

## **Permian Illawarra Coal Measures**

The coal seams within the Illawarra Coal Measures have higher permeabilities compared to the interbedded sandstone, siltstone and claystone that comprise this sequence. The seams can form minor aquifers where the strata are located within 150 m of surface. At greater depths away from the Illawarra Escarpment, the coal measures are low permeability water bearing zones.

Groundwater storage volumes are low and mine water quality in the eastern Metropolitan Special Area is brackish (but the data set is poor). At Dendrobium, mine water EC from the Wongawilli Seam is known to be up to 3,000  $\mu\text{S}/\text{cm}$  (Ziegler and Middleton, 2011 and Minchin et al, 2016). Further to the north (along the groundwater flowpath), similar salinities are known in mine water at West Cliff colliery at Appin, but salinities are much higher south of Camden. Groundwater from deep gas wells that are part of the Camden Gas Project and tap the Bulli and Balgownie seams is moderately saline (with EC up to 18,200  $\mu\text{S}/\text{cm}$ ) and is dated between 375,000 and 650,000 years BP (Parsons Brinckerhoff, 2014).

## **Permian Shoalhaven Group Rocks**

These rock types (located below the coal measures) are predominantly low permeability sandstone and siltstone. They are unaffected by coal mining activities and are not discussed further in this project report.

### **3.5.4 Surface Water and Groundwater Interaction**

The following groundwater systems (in order of likely baseflow volume contributions) are considered the most important for sustaining baseflow contributions to the drinking water catchments:

- Hawkesbury Sandstone regional aquifers;
- Superficial aquifers in the colluvium;
- Regional aquifers in the basalts;
- Superficial aquifers in the alluvium.



As basalts are outside of the main Special Areas affected by mining activities, they are not discussed further. The behaviour and interaction between the two shallow groundwater systems (alluvium/colluvium and Hawkesbury Sandstone) are described below under superficial and regional aquifers.

### 3.5.4.1 Superficial Aquifers

The alluvial and colluvial formations and associated aquifers are temporary water stores that support ecosystems and baseflows to adjacent streams. Groundwater levels are generally higher than the regional water table in the Hawkesbury Sandstone.

Monitored alluvial systems (Nepean River alluvium at Kangaloon) have been known to decline when pumping has occurred in the underlying sandstone (URS, 2007b). These small alluvial systems are therefore considered connected aquifers.

The shallow groundwater systems in upland swamps are mostly perched and are not known to decline when pumping has occurred in the underlying sandstone (URS, 2007b and URS, 2008b). However in some hillside swamp instances, spring discharges from the regional sandstone aquifer to the colluvium are suspected to contribute to the hydrology of these swamps (HydroSimulations, 2016). These colluvial systems are mostly considered disconnected aquifers.

These superficial aquifers (particularly those associated with the headwater swamps) provide baseflow contributions to streams in the weeks after large rainfall events. Flows rarely persist for more than two months. The collective baseflow contribution from these swamps across the Special Areas and the temporal variability of flows is not well known but an indication is provided in the baseflow discussion in Section 3.5.2.5.

### 3.5.4.2 Regional Aquifers

Most of the streams in the Metropolitan and Woronora Special Areas are incised into the Hawkesbury Sandstone and are naturally losing streams in the uppermost portion of their catchments but for the most part are naturally gaining streams i.e. they receive baseflow contributions from adjacent and underlying groundwater systems. Groundwater flow contours for the Hawkesbury Sandstone aquifer show that regional groundwater flow in the Upper Nepean and Upper Avon catchments is towards the more incised streams in the middle and lower catchment areas (URS, 2009a). This pattern of groundwater flow from the rainfall recharge areas located higher in the catchment to the discharge areas in the incised and gorge areas is considered typical of natural groundwater flow patterns for this sandstone aquifer across the Special Areas.

For the substantial water storages located behind each of the dam walls, the reverse situation is likely to occur i.e. each of the reservoirs is likely to be losing water into the adjacent and underlying (deep) groundwater systems. Also increased groundwater discharge would also be expected back into the river systems immediately downstream of each of the dam walls because of the steep hydraulic gradients. These storage losses have not been quantified but are considered very small compared to the surface water inflows and outflows, and evaporation losses from each of the storages.

There are no known streams in the Special Areas that are considered losing streams along their full length, however those located in areas of longwall mining where there has been riverbed cracking (such as Waratah Rivulet in the Woronora Catchment) can become losing streams. The degree to which streams lose flow into the underlying groundwater systems (i.e. the length of stream and the loss volumes) is still the subject of much investigation. Further discussion is provided in Chapter 4.



## 3.6 Surface Water Catchments and Drainage Systems

The hydrologic characteristics of a catchment are a function of its physical features (topography, geology and soils), climate (rainfall, evapotranspiration and seasonality) and vegetation. The sections below outline some of the key features of the landscape within the Metropolitan and Woronora Special Areas which contain a complex pattern of landform, vegetation and drainage systems. The sections below provide an overview of the characteristics of the catchments and drainage systems with details of some systems provided to illustrate the complexity of the landscape.

### 3.6.1 Topography

The Metropolitan and Woronora Special Areas are located within the Woronora Plateau, which is a deeply dissected sandstone plateau with Wianamatta Group shales occurring as thin lenses. Upland swamps are a common feature of the Special Areas towards the Illawarra Escarpment that marks the eastern edges of the Woronora Plateau. The escarpment consists of cliff faces below which lies a large continuous talus mantle on steep slopes of bedrock (Hazelton & Tille, 1990).

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 surface elevations range from approximately 180 m to 365 m AHD (Australian Height Datum), with ridgelines typically rising between 50 and 100 m above the drainage floor (Merrick, 2008a). The topography broadly coincides with Hawkesbury Sandstone dip slopes falling to the north-west. The southern slopes tend to be more rugged, consisting of joint controlled escarpments of Hawkesbury Sandstone (Merrick, 2008a).

### 3.6.2 Soils and Land Characteristics

The *Soil Landscapes of the Wollongong-Port Hacking 1:100,000 Sheet* (Hazelton & Tille 1990) describes the main soil landscape groupings found on the Woronora Plateau as:

- **Hawkesbury (ha) - Colluvial:** The Hawkesbury soil landscape is located adjacent to the main water storages. This soil landscape is located on rugged, rolling to very steep hills on Hawkesbury sandstone, with local relief of 100-200 m, slopes >25% and surface rock >50%. Vegetation comprises mostly uncleared eucalypt woodland, open forest and tall open forest. Soils are shallow (<50 cm) discontinuous Lithosols/Siliceous sands associated with rock outcrop; Earthy sands; Yellow earths; and locally deep sands on inside of benches and along joints and fractures. This soil landscape is subject to extreme soil erosion hazard, mass movement (rock fall) hazard, steep slopes, rock outcrop, shallow, stony, highly permeable soil and very low soil fertility.
- **Gynea (gy) – Erosional:** A few small areas of the Gynea soil landscape group lie adjacent to the main water storages. This soil landscape consists of undulating to rolling rises and low hills on Hawkesbury sandstone with local relief of 20-80 m, slopes 10-25% and rock outcrops <25%. Vegetation comprises extensively cleared open forest with eucalypt woodland. Soils are shallow to moderately deep (30-100 cm) with Yellow Earths and Earthy Sands on crests and insides of benches; shallow (<20%) Siliceous Sands on leading edges of benches; localised Gleyed Podzolic soils and Yellow Podzolic soils on shale lenses; and shallow to moderately deep (<100 cm) Siliceous Sands and Leached Sands along drainage lines. This soil landscape contains localised steep slopes and is subject to high soil erosion hazard, rock outcrop, shallow highly permeable soil and very low soil fertility.



- **Lucas Heights (lu) – (Residual):** areas of this soil landscape group are located on the ridge lines between the water storages. This soil landscape consists of gently undulating crests, ridges and plateau surfaces of the Mittagong formation. Local relief is 10-50 m, slopes are <10% and there is an absence of rock outcrops. Vegetation comprises extensively to completely cleared dry low open forest and low woodland. Soils are moderately deep (50-150 m) and hard setting. Yellow Podzolic Soils and Yellow Soloths exist on ridges and plateau surfaces; Lateritic Soils on crests; Yellow Earths on shoulders of plateaux and ridges and Earthy Sands in valley flats. This soil landscape is subject to stoniness, hard-setting surfaces and low soil fertility.
- **Bundeena (bu) – Residual:** The Bundeena soil landscape is located in various locations with the Plateau between the water storages. This soil landscape group is located on very low rolling rises on exposed Hawkesbury Sandstone coastal headlands with local relief of up to 80 m and slope gradients <20%. Ridges and crests are broad up to 200 m wide, with gently inclined slopes with occasional benches up to 50 m wide. Small swamps and seepage areas are common on benches and along drainage lines, rock outcrop occurs over 30-50% of the land surface of this group. Soils comprise Silicious Sands and Earthy Sands occurring on benches; Yellow Earths on midslope; Gleyed Podzolic soils on lower slopes and Acid peats in areas of poor drainage. This soil landscape is subject to high erosion hazard, highly permeable soil, very low soil fertility and seasonally high water tables.
- **Maddens Plains (md) – Residual:** exists in various areas along the plateau with a landscape of moderate to gently undulating rises dominated by dells (hanging swamps) on Hawkesbury Sandstone plateau surfaces. Local relief is <40 m, slopes <10%. Very broad drainage depressions with scattered rock outcrops <15%. Vegetation comprises sedgelands, wet heath and dry heath with isolated stands of open woodland and scrubland. Soils comprise acid peats in swamps, Gleyed Podzolic soils in drainage lines; Silicious Sands and Podzols on lower slopes and Yellow Earths on crests. This soil landscape is subject to seasonal and permanent waterlogging, low fertility and high erosion hazard.

In general, vegetation on the Woronora Plateau region is diverse but mainly comprises woodland, open-forests and heaths (Hazelton & Tille, 1990). Further detail on terrestrial vegetation is provided in Section 3.8.3 below.

### 3.6.3 Streams

The Woronora Plateau has a relatively high drainage density, due primarily to the weathering resistance of the sandstone formations and its relative weakness along joints and other discontinuities. The high drainage density in the Woronora Plateau also reflects the erodibility of the soils, hydrologic character of the system, and the size and quantity of sediment load moved from the basin (Schumm, 1977).

The main drainage lines on the plateau are the Woronora, Cataract, Cordeaux and Avon Rivers and O'Hares Creek (lying between the Metropolitan and Woronora Special Areas). These major streams flow to the northwest down the elevation gradient:

- The Nepean River rises to over 700 m about one km north-east of Robertson and flows into Lake Nepean, created by Nepean Dam.
- The Cordeaux River enters the Nepean River approximately 10 km below Nepean Dam and immediately above Pheasants Nest Weir.
- The Avon River is a significant tributary to the Cordeaux River, entering the river 11.5 km below Avon Dam and 20 km below Cordeaux Dam.



- The Cataract River enters the Nepean River about 21 km below the confluence of the Cordeaux and Nepean Rivers and 17 km below Cataract Dam.

The Nepean, Avon, Cordeaux and Cataract rivers above and below the dams comprise significant gorge reaches. The gorges are near intact above the dams. The Woronora River rises to 360 m 6 km north-west of Darkes Forest and falls north and east for 36 km to where it meets Georges River at Como. Woronora Dam is located on Woronora River 11 km downstream of its headwaters (DPI, 2016).

### 3.6.3.1 Stream Order

The significance of streams is conventionally assessed using the Strahler system of stream classification. Based on this system, examples of third order and higher streams potentially impacted by mining in the Southern Coalfield are provided in Table 3.7.

**Table 3.7: Examples of Third and Higher Order Streams Potentially Impacted by Mining in the Southern Coalfield**

Strahler Stream Order	Stream
3	Wongawilli Creek, Waratah Rivulet (above Flat Rock Creek), Brennans Creek, Elladale Creek, Simpsons Creek, Flying Fox Creek (Nos 1, 2 and 3), Kembla Creek, Sandy Creek, Native Dog Creek, Rocky Ponds Creek, Ousedale Creek, Foot Onslow Creek, Mallaty Creek, Harris Creek, Navigation Creek
4	Georges River, Cordeaux River (above Kembla Creek), Waratah Rivulet, Stokes Creek
5	Bargo River, Avon River, Cataract River (above Lizard Creek), Cordeaux River (below Kembla Creek)
6	Cataract River (below Lizard Creek), Cordeaux River (below Avon River)
7	Nepean River

Source: NSW Government, 2008

### 3.6.3.2 Geomorphology

As documented in the *Southern Coalfield Strategic Review* (NSW Government, 2008) the essential landscape feature which has determined the valley forms and cliff lines is the Hawkesbury Sandstone, which is highly resistant to weathering. This has meant that weathering and erosion caused by moving water has been concentrated along the networks of faults and joints which occur naturally in this rock as the result of stresses imposed during geologic time.

The drainage systems are highly diverse in morphology and have been shaped by the underlying geology, relief and climate, which are expressed differently across the Special Areas. They range from headwater swamps and wooded or forested valleys, where sediment has accumulated over millennia to form un-channelised valley fills, to the lowland rivers that are characterised as broad, deep and supplied with sediment from the upper reaches. In between these headwater and lowlands, the streams in the elevated catchments tend to be bedrock (sandstone) lined, with rock bars and channel beds often comprising small boulders and cobbles with much of the sediment being transferred downstream due to steeper longitudinal gradients and higher stream power in the upper reaches of the catchments.

Erosion along this system of faults and joints (predominantly oriented northwest-southeast and northeast-southwest) has led to the development of a system of deeply incised river gorges which drain the Plateau. The river valleys, particularly the downstream sections as they approach the Hawkesbury River Valley, are often narrow with steep sides and stream beds largely composed of the sandstone bed rock, with rock bars and boulder-strewn channels. These steep-sided valleys, particularly the downstream sections, may take the form of a gorge, with imposing sandstone cliffs



on one or both sides of the river. River gorges in the Southern Coalfield include the Cataract River Gorge and the Nepean River Gorge. The cliff faces within these gorges may vary between 10 and 50 m in height.

At the upstream end of most catchments, although the rivers are less incised and their valleys are broader and more open in form, the sandstone bedrock remains the key geomorphological determinant. Stream beds are still generally composed of exposed sandstone bedrock, with rock bars and channels strewn with smaller boulders and cobbles. The sandstone bedrock becomes a drainage surface (either at the base of swampy vegetation draping the landscape or below the regolith) which sheds groundwater towards the streams. The groundwater (from surrounding ridges) provides baseflow for the streams and supports the generally perennial character of the larger streams and rivers (NSW Govt, 2008). The diversity of stream geomorphology is illustrated by the following material summarised from various reports prepared for the mining companies.

### **Dendrobium Mine**

The *Watercourse Impact, Monitoring, Management and Contingency Plan for Area Dendrobium Area 3B* (Dendrobium, 2015) describes the geomorphology of Area 3B, the area currently being undermined by Dendrobium longwalls. The eastern part of the area is broadly sited on a plateau dissected by a number of relatively shallow sub-catchments draining either into Cordeaux River via Wongawilli Creek, Donalds Castle Creek or five un-named 1<sup>st</sup> and 2<sup>nd</sup> order streams draining directly to the southern end of Lake Avon. The headwaters of Wongawilli Creek are located along a drainage divide separating runoff and shallow groundwater outflow from Native Dog Creek and Lake Avon to the west. Donalds Castle Creek and its tributaries drain through a weakly incised plateau. The geomorphology of sub-catchments in Area 3B is typically characterised by upland plateau and a series of 'benches' comprised of catenary hill-slopes and swamps enclosed in roughly crescent-shaped cliff lines.

### **Proposed Russell Vale Expansion Project**

Annexure O of the NRE Expansion Project (Russell Vale) (GeoTerra, 2012) provides a *Stream Assessment*, including geomorphology, for the proposed Wonga East and Wonga West mining domains, which lie approximately 13 km northeast of Dendrobium Mine.

In the Wonga West streams, four channel types and four pool types are present. The channel types comprise:

- Valley fill upland swamps with an indistinct channel.
- Narrow indistinct overgrown channels associated with a low sedge/heath and a relatively thick sandy riparian soil with a streambed consisting of weathered bedrock and/or sandy material.
- Rock platforms of variable width which are usually smooth except for minor depressions on joint planes and occasional potholes. These platforms normally grade into a thinly vegetated sandy soil on either bank and can exhibit deposition or hydrated iron oxide observed as orange to black discolouration of the rock surface.
- Incised channels in sandstone which exhibit rough riffle like surfaces, usually with accumulations of boulders and other sediments. These channels are usually bound by solid rock outcrop.

The pool types include:

- Shallow linear small pools located in depressions formed by joint systems or cross-bedding and sometimes associated with potholes. Accumulated water is usually less saline than in surrounding pools and has minor to no interaction with the local groundwater system.



- Linear pools associated with narrow erosion channels in sandy soil. The soil is usually vegetated with heath like species, while the downstream end is constrained by a rockbar or outcrop.
- Larger pools constrained by a downstream rockbar which can be undercut by erosion and exhibit signs of chemical weathering.
- Larger pools constrained by downstream sediments. The sediments may extend for a considerable distance downstream.

Cataract Creek, Cataract River and Bellambi Creek catchment are located upstream of Cataract Reservoir. Cataract Creek, located within the Wonga East area, is relatively steep, particularly in its headwaters, with a reducing gradient with distance downstream, and flows through a series of short pools, sandy reaches, rock bars and boulder fields. Table 3.8 below provides the gradients between monitoring points on Cataract Creek (designated CC2 to CC10).

**Table 3.8: Cataract Creek Stream Gradients**

Stream Reach	Vertical Fall (m)	Distance (m)	Gradient (m/m)
Headwater to CC2	87	865	0.101
CC2 to CC3	8	535	0.015
CC3 to CC5	1	110	0.009
CC5 to CC6	4	635	0.006
CC6 to CC9	5	1,250	0.004
CC9 to CC10	4	435	0.009
CC10 to Cataract Dam	1	375	0.003

Source: *GeoTerra, 2012*

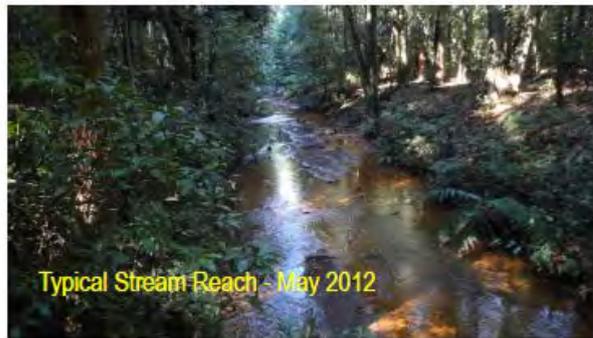
The steep headwater tributaries of Cataract Creek have eroded through the Hawkesbury Sandstone and, in the deeper eroded areas, through to the Bald Hill Claystone and the underlying Bulgo Sandstone.

Between sites CC5 and CC9 a series of long elongated pools that are concentrated by low (<0.5 m high) shallow rockbars, which predominate in the upper to mid-section, along with occasional gravel sized riffle sections that also predominate in the upper to mid-section of the creek.

Significant reaches of sandy based substrate dominate between CC7 and CC9, which has developed in an eroded interspersed shale and sandstone sequence compared to the Hawkesbury Sandstone. A limited number of rock bar constrained pools are present between CC7 and CC9. Two moderate sized <1 – 2 m deep pools have developed at significant bends at rock bars within this section of the creek.

The stream bed and banks of the plateau streams are well vegetated and do not show significant erosion or bank instability.

The photographs shown in Figure 3.5 below (reproduced from GeoTerra 2012) indicate the typical nature of the rock bars and riffles and pools in the reach of Cataract Creek between CC5 and CC9.



Source: GeoTerra, 2012

**Figure 3.5: Typical Cataract Creek Rock Bars, Riffles and Stream Reach**

### **Metropolitan Colliery**

Appendices 1, 2, 3 and 4 of the *Metropolitan Coal Water Management Plan for Longwalls 23 – 27* (Peabody Energy, 2014) contain Mapping and Photographic Records for Waratah Rivulet, Eastern Tributary, Tributary A and Tributary B. Records are provided for both pools and rock bars. A sample of the mapping summary (for Pool G1 on Waratah Rivulet, located upstream of LW 20) is provided in Figure 3.6 below.



## POOL G1 - STREAM MAPPING SUMMARY



G1-1 Upstream end of Pool G1 looking downstream



G1-2 Downstream end of Pool G1 looking upstream

G1-3 Cracking across pool and deposits

G1-4 Cracking in rockbar



G1-7 On rockbar G1 looking upstream



G1-16 Displaced Sandstone

G1-8 On rockbar G1 looking downstream



G1-5 Cracking in rockbar



G1-6 Cracking in rockbar



G1-9 South East bank



G1-10 Iron Staining



G1-11 North West bank



G1-14 Displaced Sandstone



G1-12 Displaced Sandstone



G1-13 Crack



G1-17 Displaced Sandstone

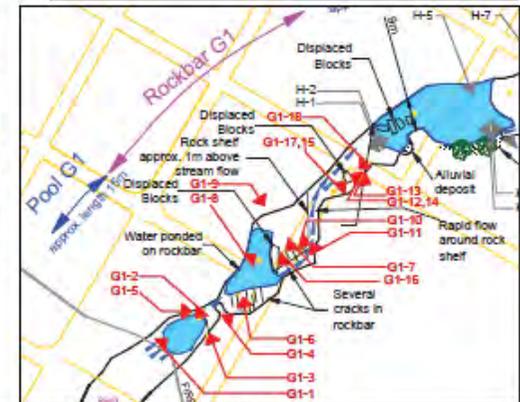


G1-18 Displaced Sandstone



G1-15 Displaced Sandstone

- Pool G1 and Rockbar G1 notes (as at 27 Jun 2011)**
- Pool length is approximately 15m. Width varies from approximately 6m to 10m. Average depth is approximately 0.4m with a maximum of approximately 0.7m
  - Some widening of cracks
  - Displaced sandstone from previous heavy flow at location of previously observed cracks (see photos)
  - Base of the pool is sandstone covered in stained sediment. Minor alluvial deposits on north side of pool
  - Pool flows out onto rockbar. Narrow turbulent flow over rockbar and some ponding. Rock shelf both sides of flow to approximately 1m maximum above water level
  - Cross bedding present
  - Rockbar approximately 24m wide u/s end and 32m wide at d/s end
  - Flow has increased significantly from previous mapping in Dec 2008



**Photo Details**

Photo ID	Easting	Northing	Bearing
G1-1	309573	6214194	45
G1-2	309586	6214204	226
G1-3	309588	6214196	335
G1-4	309595	6214202	46
G1-5	309685	6214202	95
G1-6	309698	6214210	345
G1-7	309717	6214226	232
G1-8	309703	6214222	52
G1-9	309705	6214242	140
G1-10	309719	6214227	104
G1-11	309723	6214225	332
G1-12	309739	6214248	350
G1-13	309739	6214248	170
G1-14	309739	6214248	290
G1-15	309739	6214248	130
G1-16	309705	6214221	225
G1-17	309730	6214244	130
G1-18	309739	6214249	226

**Figure 3.6: Stream Mapping Summary – Pool G1 on Waratah Rivulet**



### 3.6.4 Upland Swamps

As noted in Section 3.6.1, upland swamps are a significant feature of the catchments within the Metropolitan and Woronora Special Areas. These swamps are highly diverse in character, reflecting the area's geologic, topographic and climatic variation. Many attempts have been made to categorise the upland swamps into types, variously based around geomorphology, hydrology, vegetation and nutrient characteristics. This is not just a local issue, with many problems with swamp nomenclature arising globally (Mactaggart, *et al.* 2008).

Attributing swamps to a particular 'type' has implications for understanding system processes, drawing comparisons between and within swamps, predicting impacts and consequences and for on-going management and restoration practices. In addition, the naming and description of upland swamps has legal ramifications as upland swamps are recognised as a Coastal Upland Swamps of the Sydney Basin Endangered Ecological Community, listed under the *Threatened Species Conservation Act 1995* (TSC Act).

The upland swamps of the Woronora Plateau have been collectively referred to in the past as dells (Young, 1982) and have been variously categorised over the years by researchers, government agencies and consultants. Terms are used synonymously and interchangeably within the Southern Coalfield and Western Coalfields. There are also elements and system processes within an upland swamp (e.g. peat formation, valley cut and fill processes, vegetation successional change) that have contemporaneous processes in other swamp landform systems.

The literature pertaining to the Woronora Plateau tends to categorise upland swamps into two, or sometimes three, types. The most common two types are **headwater swamps** and **valley floor swamps**. Related terms for headwater swamps include 'valley-side swamps', 'headwater-drainage divide swamps', 'low slope headwater valley swamps'. Related terms for valley floor swamps include 'valley bottom swamps', 'valley filling swamps', 'valley fill swamps', 'valley in-fill swamps' and 'in-valley swamps'. The less commonly referenced type, hanging swamps, warrants its own category in some of the literature, though it tends to be disregarded in the work of fluvial geomorphologists.

While headwater swamps and valley-in-fill swamps have some universality in their definitions or characterisations within the landscape, the valley-side swamps and hanging swamps are outliers and are not readily pigeon-holed. Valley-side swamps have been delineated as a separate type, for example in (Metropolitan Coal, 2015c), they are also included in the definition of headwater swamps in (Commonwealth of Australia, 2014a). To further muddy the waters, in the Western Coalfield the term hanging swamps is often used synonymously with valley-side swamps.

It is unlikely there will ever be a consensus with terminology. Therefore for the purpose of this Southern Coalfield-centric review, four terms have been adopted based on a composite of descriptions derived from various sources including (e.g. Young, 1982, Tomkins and Humphreys, 2006, Merrick 2008b, Commonwealth of Australia, 2014a and Metropolitan Coal, 2015c ). The four swamp types are described as follows:

- **Headwater swamps**
  - This upland swamp type occurs in the headwaters or elevated sections of the Woronora Plateau, where they usually occupy broad, shallow, trough-shaped valleys on first-order and sometimes second-order drainage lines. They can also extend up the valley sides and drainage lines to straddle catchment divides in areas of shallow, impervious substrate formed by either the bedrock sandstone or clay horizons. Characteristically they have gentle slopes with the majority being less than 10°.



- Excess rainfall produces a perched water table within the sediments that is independent of the natural regional water table and these water levels tend to fluctuate seasonally with climatic conditions. In some headwater swamps there could be minor groundwater seepage from the outcropping sandstone at the edges of the swamp. These swamps sit on a relatively impermeable, low gradient sandstone base with dispersed seepage flows that encourage the growth of hydrophytic<sup>1</sup> vegetation that in turn traps sediment, thereby increasing the water holding capacity of the system. These swamps usually terminate at points where the watercourse suddenly steepens or drops away at a 'terminal step'. Terminal steps often occur at constrictions in the landscape where two ridges converge, causing a narrowing of the swamp and a concentration of water flows into a central channel.
- Contained surface water and groundwater storage from the larger swamps contributes to baseflow but contributions from some of the smaller swamps may be limited and seasonally variable. Direct connectivity between swamps and underlying groundwater systems appears to depend on location.
- Headwater swamps comprise the majority of upland swamps and are often large or are represented by clusters of swamps. The Department of Environment & Climate Change (DECC) has recognised four large clusters on the plateau areas which it considers to have particular significance in providing large contiguous areas of related habitat. These swamp clusters comprise Maddens Plains (O'Hares and Cataract catchments), Wallandoola Creek (Cataract catchment), North Pole (southern Avon catchment) and Stockyard (southern Avon catchment). The swamp clusters were identified following a vegetation survey of the catchments of Nepean, Avon, Cordeaux, Cataract and Woronora Rivers and O'Hares Creek by the NPWS and SCA during 2003 (NPWS, 2003). A total of 6,444 ha of upland swamp was mapped by this project within the 105,039 ha of its study area.
- **Valley-side swamps**
  - Valley side swamps 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. At localised seeps, peat accumulation can occur, sustaining hydrophytic vegetation. These swamps tend to terminate either on a horizontal step in the bedrock, or where broken rock, scree or deeper soil occurs at the base of the outcropping rock;
  - Valley-side swamps can be disconnected vegetatively from headwater swamps – occurring as pockets on the sides of valleys surrounded by terrestrial vegetation; and
  - Examples of valley-side swamps above Metropolitan Colliery include Swamps 19, 23, 26, 27, 28, and 30 -36.
- **Valley infill swamps**
  - These swamp types are less common than headwater swamps and occur on relatively flat sections of more deeply incised second and third order watercourses. They also tend to be elongated downstream. They are thought to be formed by deposition of sediments behind obstructions in the watercourse, such as fallen rocks or log jams that result in a slowing of the water flow and deposition of sediments. They may also terminate at 'steps' in the underlying substrate where the gradient suddenly becomes steeper. Once initiated,

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<sup>1</sup> A plant that is adapted to living in waterlogged soil or wholly or partially submerged in water.



the swamps are probably self-reinforcing, trapping more sediment, raising the water table and fostering the growth of vegetation and formation of peat.

- Valley infill swamps have multiple sources of water including stream flow along distinct channels, rainfall infiltration and seepage from the deeper regional water table in the Hawkesbury Sandstone. Because of their relatively large catchment areas these swamps and their direct connection to flowing streams tend to be wetter than many headwater and valley-side swamps;
  - Contained groundwater within the valley infill swamps has a higher likelihood of direct connection to surrounding groundwater in rock strata as a result of the incised host topography. As an example, monitoring of Swamp 18 (Elouera Colliery) by Illawarra Coal included installation of a number of piezometers both within the swamp and beyond the swamp in hardrock ridge line areas. Groundwater levels measured in these piezometers indicate the potential exchange of groundwater between the swamp and the hardrock. Levels beyond the swamp were found to be generally higher than levels within the swamp at the downstream end.
  - Examples of this upland swamp type include Flatrock Swamp on Waratah Rivulet and Swamp 20 above Metropolitan Colliery, Swamps 18 and 19 on Native Dog Creek above Elouera Colliery and Martins Swamp above the closed Nebo Colliery.
- **Hanging swamps**
- This swamp type occurs mainly in the Blue Mountains and Newnes Plateau, but have also been identified in the Bargo and Cataract gorges on the Woronora Plateau.
  - There are very few hanging swamps in the Special Areas due to the low incidence of cliff lines and the relative scarcity of siltstone beds and iron-stone bands in the Hawkesbury Sandstone.
  - These swamps are fed by seepage through the sandstone (via the joints and bedding planes that break that sandstone into large blocks), which then emerges on the cliff face of the valley side when it reaches much less permeable underlying claystone. Hanging swamps occur on quite steep, sometimes near-vertical, slopes. They have only shallow or minimal sediment and are essentially a thick mat of shrub and fern vegetation.

Although these swamp types may occur discretely in the landscape, they can also occur in the same connected swamp system. For example, large headwater swamps may transition into valley infill swamps at their downstream end. Similarly, valley-side swamps may grade into the steeper margins of some headwater swamps.

There over 1,400 swamps located in the Woronora and Metropolitan Special Area water storage catchments. Characteristics of these swamps are summarised in Table 3.9 and their locations are shown on Figure 3.7. As shown in Table 3.9, swamps make up approximately 5% of the combined reservoir catchment areas.



**Table 3.9: Areas of Upland Swamps within the Special Areas**

Catchment	Catchment Area (ha)	Number of Swamps in Catchment	Total Area of Swamps in Catchment (ha)	Swamp Areas as Proportion of Catchment Area (%)
Avon	14,256	178	829	5.8%
Cataract	12,618	223	1,203	9.5%
Cordeaux	8,684	126	592	6.8%
Nepean	31,824	751	526	1.7%
Woronora	7,225	151	449	6.2%
<b>Totals</b>	<b>74,607</b>	<b>1,429</b>	<b>3,599</b>	<b>4.8%</b>

Source: WaterNSW email dated 23/9/2016

It is interesting to note that the Cataract catchment has swamps covering a significantly larger proportion of the catchment (9.5%) than the Avon, Cordeaux and Woronora catchments (5.8% - 6.8%), a high proportion of which are located on the catchment to the north of Loddon River arm of the reservoir (see Figure 3.7). Conversely, the swamps within the Nepean catchment cover only 1.7% of the catchment area. To the extent that swamps may help sustain 'baseflow' in the creeks, the northern section of the Cataract catchment can be expected to be more sensitive to any impacts from underground mining than other sections of the catchments.

### 3.7 Regional Climate and Hydrology

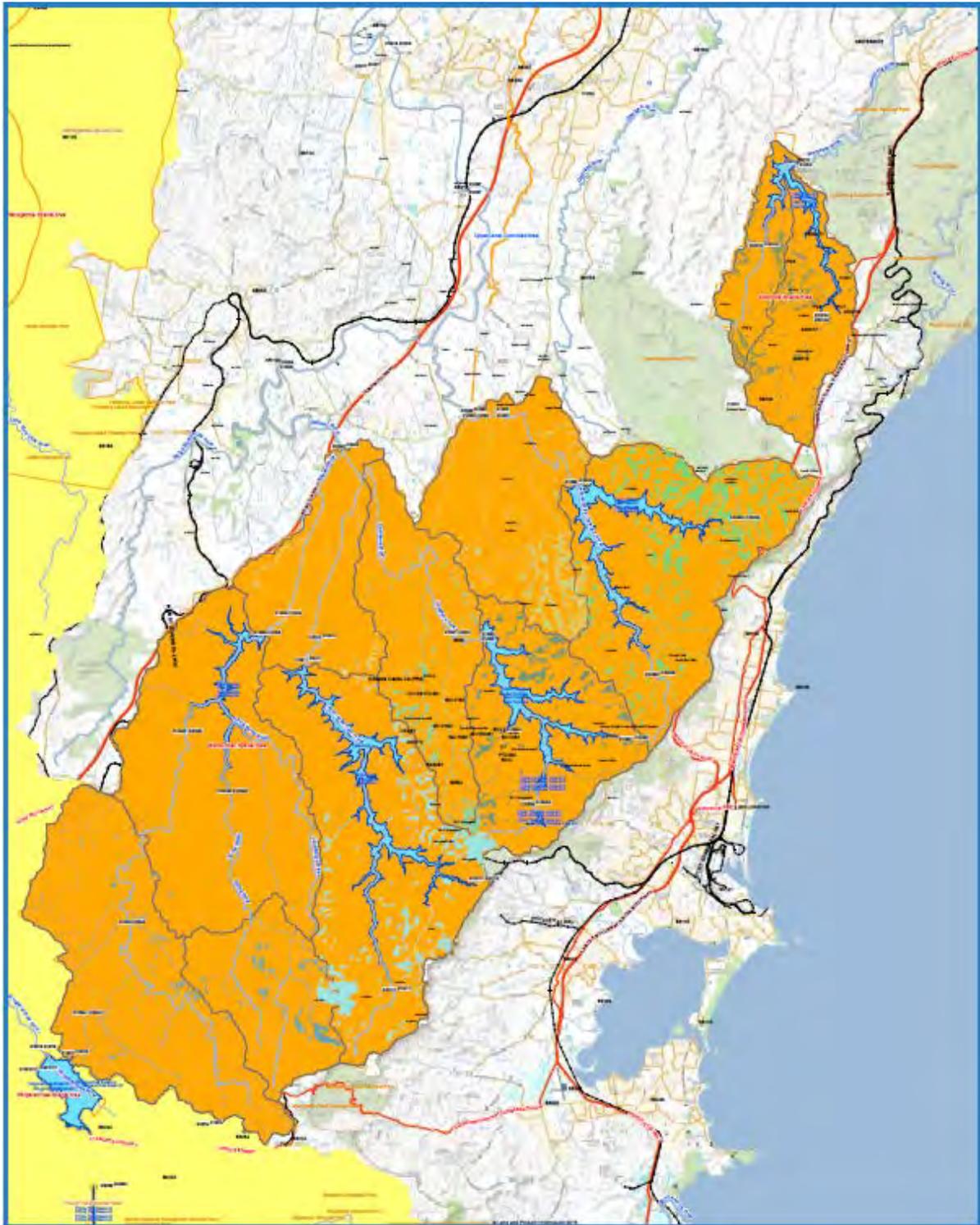
#### 3.7.1 Climate

The climate of the Southern Coalfield region is warm to mild temperate (Climate Zone Maps for NSW and the ACT <https://www.abcb.gov.au/Resources/Tools-Calculators/Climate-Zone-Map-NSW-and-ACT>).

There are a number of Bureau of Meteorology (BoM) rainfall gauges in the study area, as well as mine operated rainfall and evaporation gauges, as shown on Figure 3.7. A summary of a number of representative stations is provided in Table 3.10.

**Table 3.10: Representative Rainfall Stations in the Study Area**

Stn No	Station Name	Latitude °S	Longitude °E	Elevation (m AHD)	Ave Annual Rainfall (mm)	Period of Record
68002	Avon Dam MWSDB	34.35	150.63	55	961	1919 - 1967
68016	Cataract Dam	34.26	150.81	340	1,064	1904 - 2013
68018	Cordeaux No.1 Dam	34.33	150.73	341	1,119	1909 - 1967
68020	Cordeaux Quarters	34.33	150.75	330	1,147	1932 - 1967
68024	Darkes Forest (Kintyre)	34.23	150.91	370	1,429	1894 - Open
68028	Helensburgh	34.19	150.97	238	1,444	1889 - 2007
68047	Nepean Dam	34.33	150.60	560	953	1926 - 1970
68070	Woronora Dam	34.12	150.93	177	1,122	1927 - Open
68108	Woonona Popes Road	34.34	150.9	45	1,277	1886 - Open
68148	Cataract Reservoir (Letterbox)	34.27	150.88	426	1,431	1907 - 1948



**Figure 3.7: Location of Rainfall Stations, Stream Gauges and Swamps in the Study Area**

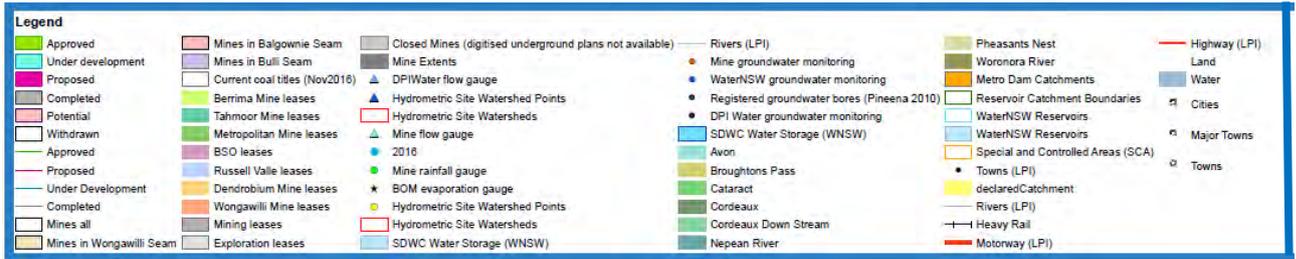


Figure 3.8: Figure 3.7 Legend

Average monthly rainfall data obtained from the BoM for a number of representative stations within the study area is provided in Table 3.11 below, together with average monthly pan evaporation data for Woronora Dam.

Table 3.11: Average Monthly Rainfall and Evaporation in the Study Area

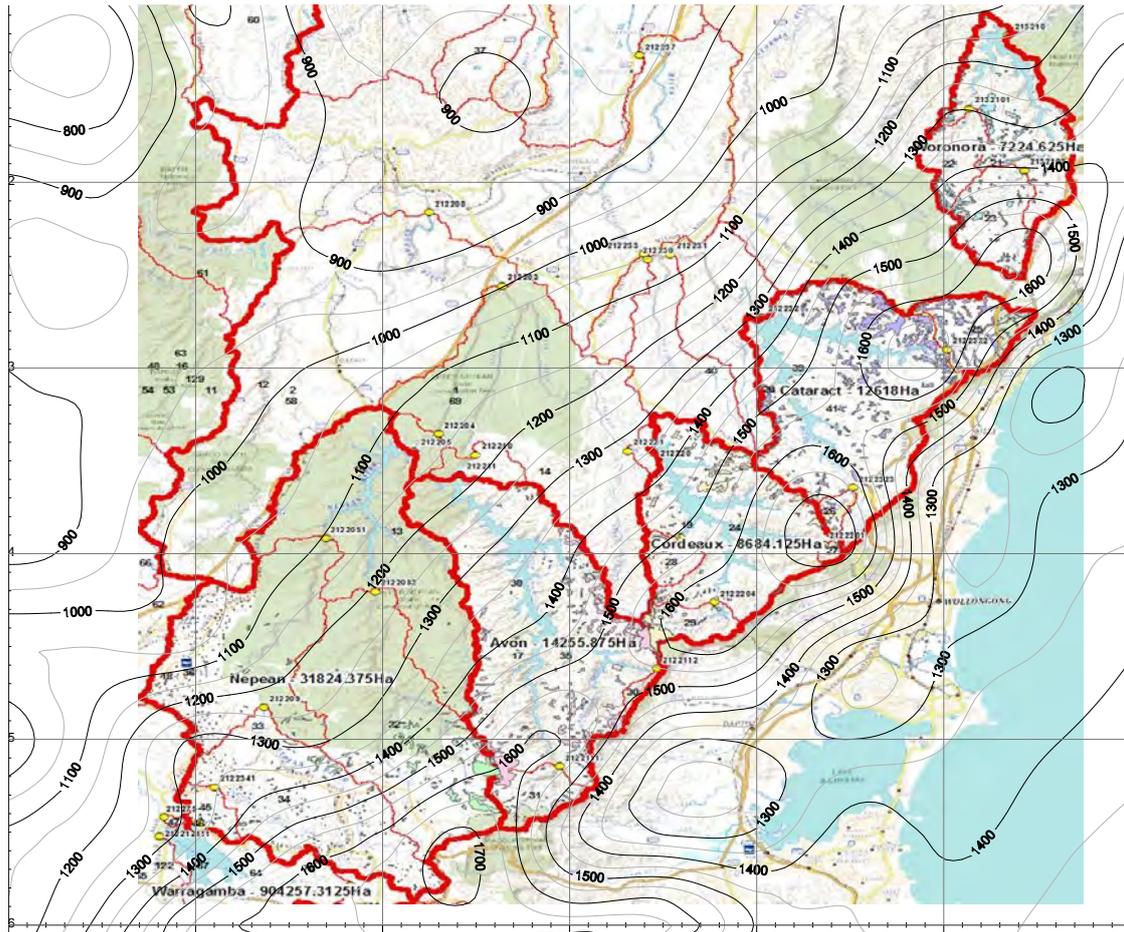
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
<b>Rainfall (mm)</b>													
Cataract Dam*	94	116	109	99	96	113	76	70	55	78	79	78	1,064
Woronora Dam	104	123	104	96	98	133	67	74	60	77	83	80	1,122
Darkes Forest	134	161	152	128	131	147	98	91	78	92	106	105	1,429
<b>Pan Evaporation (mm)</b>													
Woronora Dam	158	126	106	72	64	43	46	66	90	124	135	168	1,198

Source (rainfall data): BOM website <http://www.bom.gov.au/climate/data/> Accessed on 22/9/2016

Source (evaporation data): Resource Strategies (2008) Metropolitan Coal Project, Section 4, Environmental Assessment.

Based on the data in Table 3.11, peak average monthly rainfall for Woronora Dam occurs in June and in February for Darkes Forest and Cataract Dam. Rainfall is generally higher between January and June and lower in July to December.

Figure 3.9 shows isohyets of average annual rainfall across the study area, based on gridded data provided by BoM for the period 1961 to 1990. The figure shows the spatial variability of rainfall, with rainfall decreasing significantly across the study area from east to west.



Source: BoM gridded data (1961-90) Grid resolution 0.05°/5 km

**Figure 3.9: Average Annual Rainfall Isohyets across the Study Area**

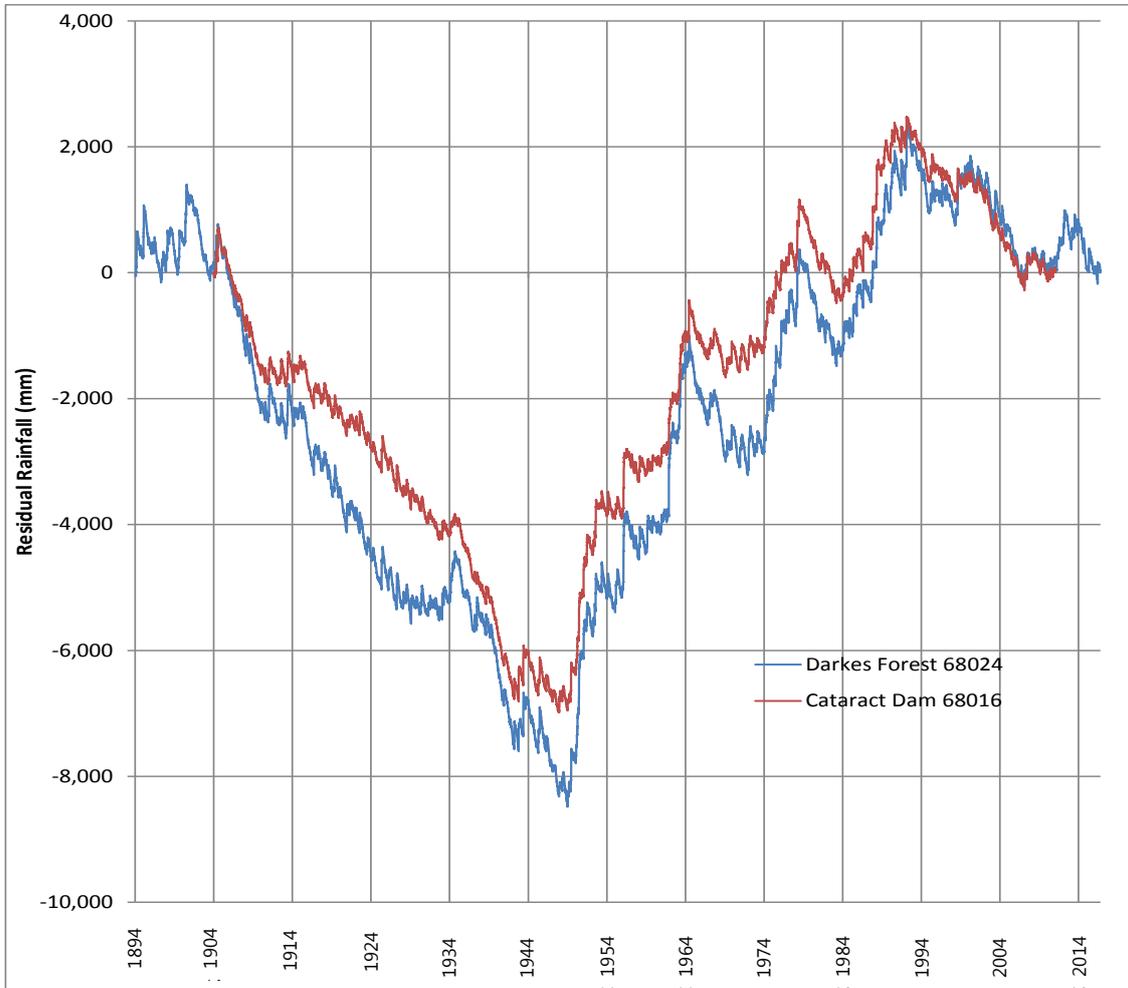
Table 3.12 summarises the area weighted average rainfall for each catchment based on the rainfall isohyetal data in Figure 3.9. The table and the figure show that there is a marked decreasing rainfall gradient from east to west. As a weighted average across the catchment, the Woronora and Nepean catchments receive less annual rainfall than the other catchments.

**Table 3.12: Area Weighted Average Annual Rainfall**

Catchment	Catchment Area (ha)	Area Weighted Average Annual Rainfall (mm)
Woronora	7,225	1,375
Cataract	12,618	1,555
Cordeaux	8,684	1,530
Avon	14,256	1,425
Nepean	31,824	1,275



Historically, rainfall has varied significantly with periods of drought and flood that are characteristic of the Australian climate. Figure 3.10 shows a plot of rainfall residual at Darkes Forest (1894 to 2016) and Cataract Dam (1904 to 2013). The rainfall residual shows departures from the long-term average. Upward sloping lines indicate relatively wet periods, and downward sloping lines indicate relatively dry periods.

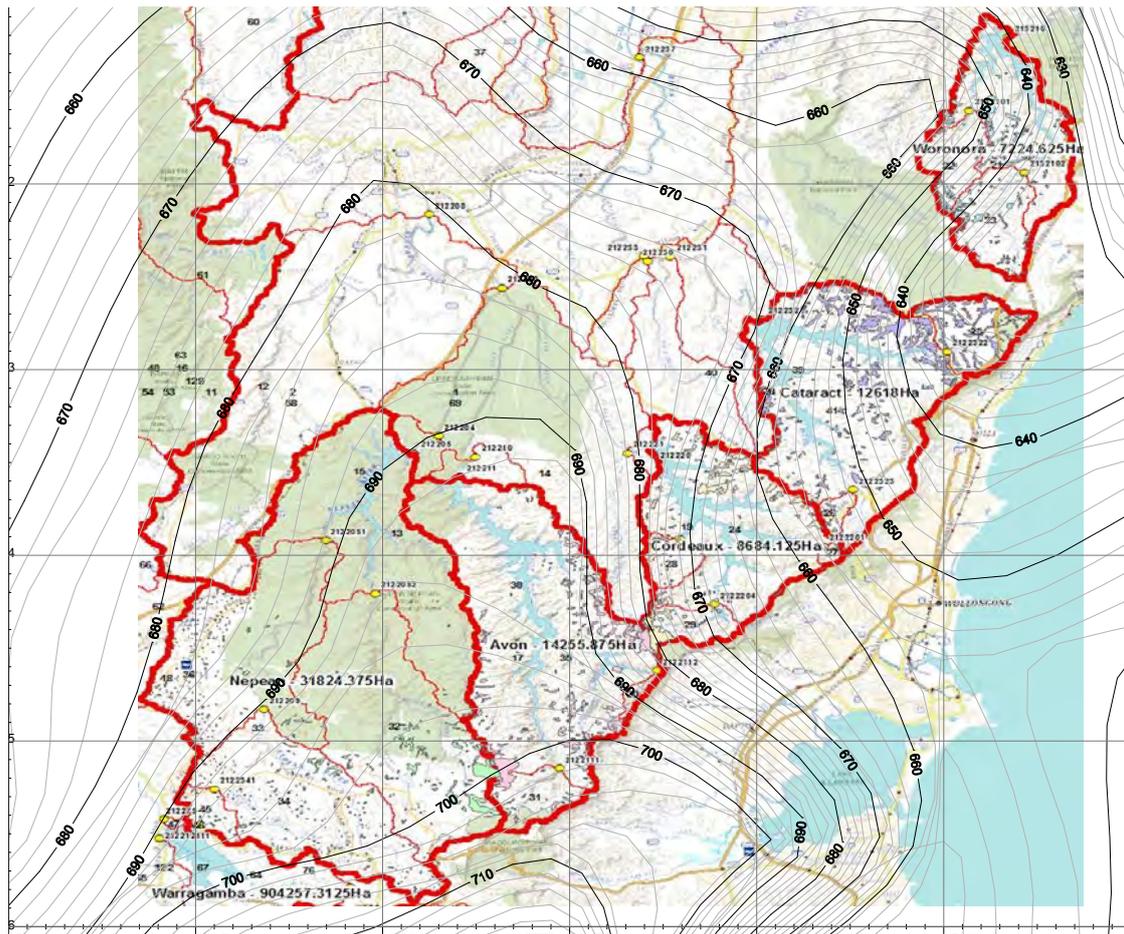


**Figure 3.10: Residual Rainfall**

The figure shows that the period between 1905 and 1948 and the period since 1992 were relatively dry. The period between 1950 and 1992 was relatively wet (with the exception of the late 1960s and the early 1980s).

Figure 3.11 shows the areal 'actual' average annual evapotranspiration based on gridded data provided by BoM. The 'actual' evapotranspiration is the evapotranspiration that would actually occur after taking account of the available soil moisture. This contrasts with the 'potential' evapotranspiration that reflects the evapotranspiration that would occur where water supply was not limited (such as under full irrigation).

The analysis underlying this mapping was undertaken by the BoM in collaboration with the Cooperative Research Centre for Catchment Hydrology at the University of Melbourne. The methodology is based on Morton's (1983) complementary relationship areal evapotranspiration model. The application of the model and the verification of the model to Australian conditions are outlined in BoM (2001).



Source: BoM gridded data (1961-90) Grid resolution 0.1°/10 km

**Figure 3.11: Areal Actual Average Annual Evapotranspiration across the Study Area**

Figure 3.11 shows that the areal actual average annual evapotranspiration generally decreases from south to north.

### 3.7.1.1 Climate Change

In 2009, the Sydney Catchment Authority prepared the report *Climate Change and its impact on Sydney's Water Supply*. The report assessed the impacts of climate change on the capacity of Sydney's water supply system, based on predictions of impacts on rainfall, evaporation and the streamflow into Sydney's reservoirs. The modelling undertaken for that study predicted that both average annual rainfall and evaporation for the Metropolitan Dams would increase for both the near (2030) and far (2070) future. Under these conditions streamflow to the Metropolitan Dams was also predicted to increase slightly in both the near and far future.

More recently, high spatial resolution climate projections have been provided in *Climate Change in Australia - Projections for Australia's Natural Resource Management (NRM) Regions* (CSIRO, 2015). These reports present projections of future climate for various NRM regions which are grouped into 'clusters', one of which is the East Coast cluster (East Coast south sub-cluster), which includes the Study Area. A summary of the relevant predictions for the East Coast sub-cluster are provided below:

- Natural climate variability will remain the major driver of rainfall changes in the next few decades;



- A decrease in rainfall is projected for winter and a range of changes are projected in the other seasons, with a tendency for increase in summer;
- The intensity of heavy rainfall events is predicted to increase;
- Potential evapotranspiration is predicted to increase in all seasons by late in the 21<sup>st</sup> century;
- Both soil moisture and runoff are predicted to decrease overall by late in the 21<sup>st</sup> century, influenced by changes in rainfall and the increase in potential evapotranspiration;
- Harsher fire-weather climate is predicted.

The *State of the Climate 2016* (BoM & CSIRO, 2016) further confirms the following future climate effects that would affect the study area:

- Extreme rainfall events are likely to increase in intensity by the end of the century across most of Australia;
- Winter and spring rainfall is projected to decrease across southern continental Australia, with more time spent in drought;
- A projected increase in the number of days with weather conducive to fire in southern and eastern Australia.

In summary, the current projected overall decrease in rainfall and increase in potential evapotranspiration due to climate change is predicted to result in decreases in soil moisture and runoff, which in turn is likely to result in a reduction in yield of WaterNSW's water supply storages. However, the CSIRO highlight the need to consider the risk of both a drier and wetter climate in impact assessment in the East Coast sub-cluster.

### 3.7.2 Catchments and Water Storages

As shown on Figure 3.1, the Metropolitan Special Area is approximately 900 km<sup>2</sup> in area and encompasses the catchments of the Nepean, Bourke, Avon and Cataract Rivers. The Woronora Special Area is approximately 77 km<sup>2</sup> in area and encompasses the upper catchments of the Woronora River and Waratah Rivulet.

Flow in the Special Areas is regulated by five major water storages whose characteristics are summarised in Table 3.13.

**Table 3.13: WaterNSW Storages in the Metropolitan and Woronora Special Areas**

Storage	Contributing Rivers & Creeks	Total Operating Capacity (ML) <sup>a</sup>	Water Storage Area at Full Supply (km <sup>2</sup> ) <sup>a</sup>	Catchment Area (ha) <sup>b</sup>	Approximate Elevation (m AHD) <sup>c</sup>
Woronora	Woronora River Waratah Rivulet	71,790	4.0	7,225	180
Cataract	Cataract River Loddon Creek Belambi Creek	97,190	8.5	12,618	280
Cordeaux	Cordeaux River Goodarin Creek Kembla Creek	93,640	7.8	8,684	320
Avon	Avon River Gallaghers Creek Native Dog Creek	146,700	10.5	14,256	330
Nepean	Nepean River Bourke River	67,730	3.3	31,824	320



Sources:

- <sup>a</sup> WaterNSW website <http://www.watarnsw.com.au/> Accessed 1/9/2016
- <sup>b</sup> WaterNSW Email to Advisian dated 23/9/2016
- <sup>c</sup> NSW Topographic Maps 2006, 1:100,000 series for Wollongong, Kiama, Burragorang and Moss Vale

### 3.7.3 Flow Regime

A number of stream flow gauges are located on the watercourses within the study area, as shown on Figure 3.7. Table 3.14 provides details of the gauged catchment areas draining to each reservoir and summarises the flow records for the major catchments draining to each reservoir. (For simplicity, the table omits details of two small gauged catchments in the Cordeaux catchment and one in Avon catchment.) The data shows that, apart from the Nepean catchment, less than half of the catchment area is gauged. Accordingly, estimates of yield are reliant on rainfall-runoff or statistical models (see Section 3.7.5). It is interesting to note that the data 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 generally correspond to the areas of higher rainfall.

**Table 3.14: Streamflow Gauges within the Special Areas**

Reservoir	Woronora		Cataract		Cordeaux	Avon	Nepean		
<b>Gauged Catchment Areas</b>									
Total Catchment (km <sup>2</sup> )	72.93		124.91		81.16	138.8	313.47		
Gauged Catch't (km <sup>2</sup> )	32.64		26.1		17.4	16.51	229.83		
Gauged (%)	45%		21%		21%	12%	73%		
<b>Catchment Details</b>									
River	Woronora River	Waratah Rivulet	Cataract River	Loddon River	Cordeaux River	Avon River	Nepean River	Nepean River	Bourke River
Gauge Location	Fire Rd 9F	Fire Rd 95	Corrimal No 1	Bulli Appin Road	Cordeaux Dam	Summit Tank	Maguires Crossing	Nepean Dam Inflow	
Gauge Number	2132101	2132102	2122323	2122322	2122204	2122111	212209	2122051	2122052
Catchment Area (km <sup>2</sup> )	12.15	20.49	9.18	16.92	9.36	14.47	69.56	142.01	87.82
<b>Flow Record Length</b>									
Start Date	11/01/2008	21/02/2007	3/06/1990	9/03/1990	20/02/2007	29/03/1990	1/01/1990	15/02/1990	17/02/1990
End Date	22/08/2016	22/08/2016	13/09/2016	12/09/2016	19/09/2016	5/09/2016	30/08/2016	6/09/2016	9/09/2016
Calendar Years	8.6	9.5	26.3	26.5	9.6	26.4	26.7	26.6	26.6
Data Years	7.3	9.5	11.6	25.5	9.2	13.0	25.3	25.2	25.7
Percent Missing	15.2%	0.5%	56.0%	4.0%	4.0%	50.7%	5.1%	5.1%	3.2%
<b>Flow Statistics</b>									
Average Annual Flow (ML/year)	2,971	6,840	6,046	14,115	4,785	6,874	39,155	46,514	21,913
Average Annual Flow (ML/ha/year)	2.45	3.34	6.59	8.34	5.11	4.75	5.63	3.28	2.50



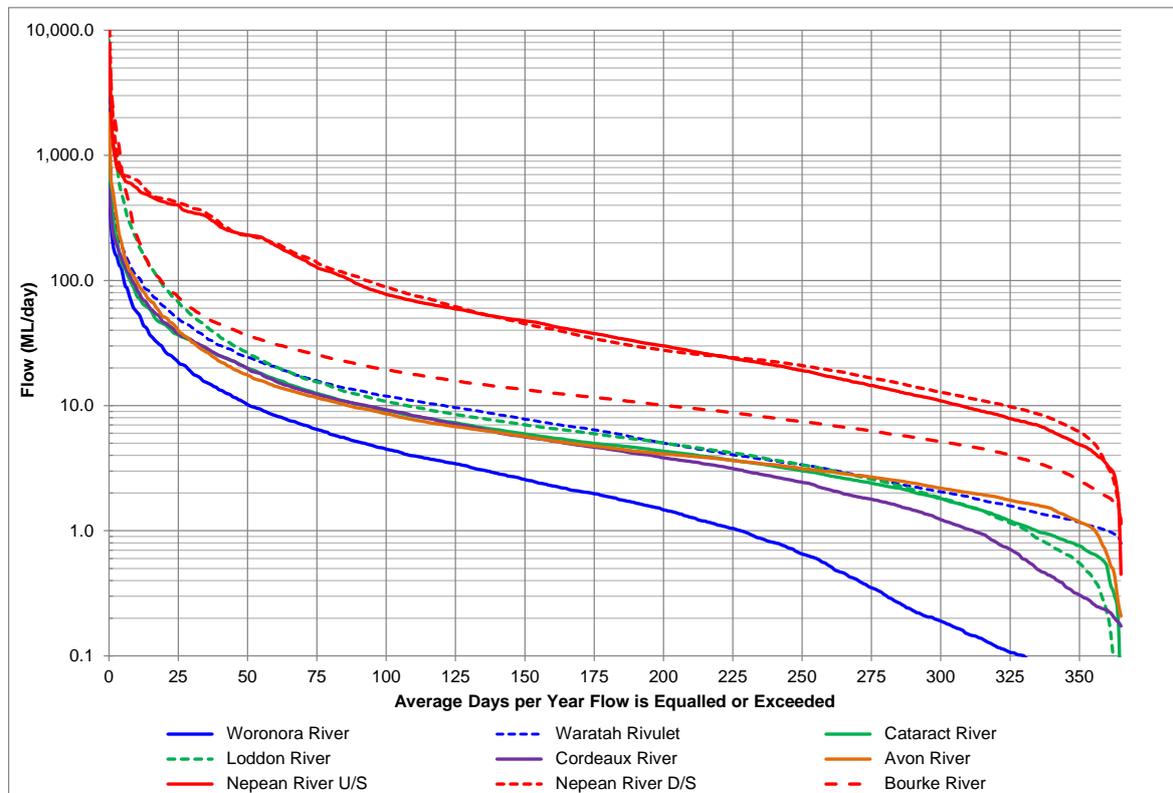
Further details of the flow characteristics of the catchments listed in Table 3.14 are presented in the following figures:

- Figure 3.12 is a flow duration graph for the gauging stations listed in Table 3.14.
- Figure 3.13 is the same data as Figure 3.12 converted into the flow expressed as mm/day in order to provide common basis for comparison of the runoff characteristic of each catchment;
- Figure 3.14 is a graph showing the cumulative percentage of flow for the gauging stations listed in Table 3.14.

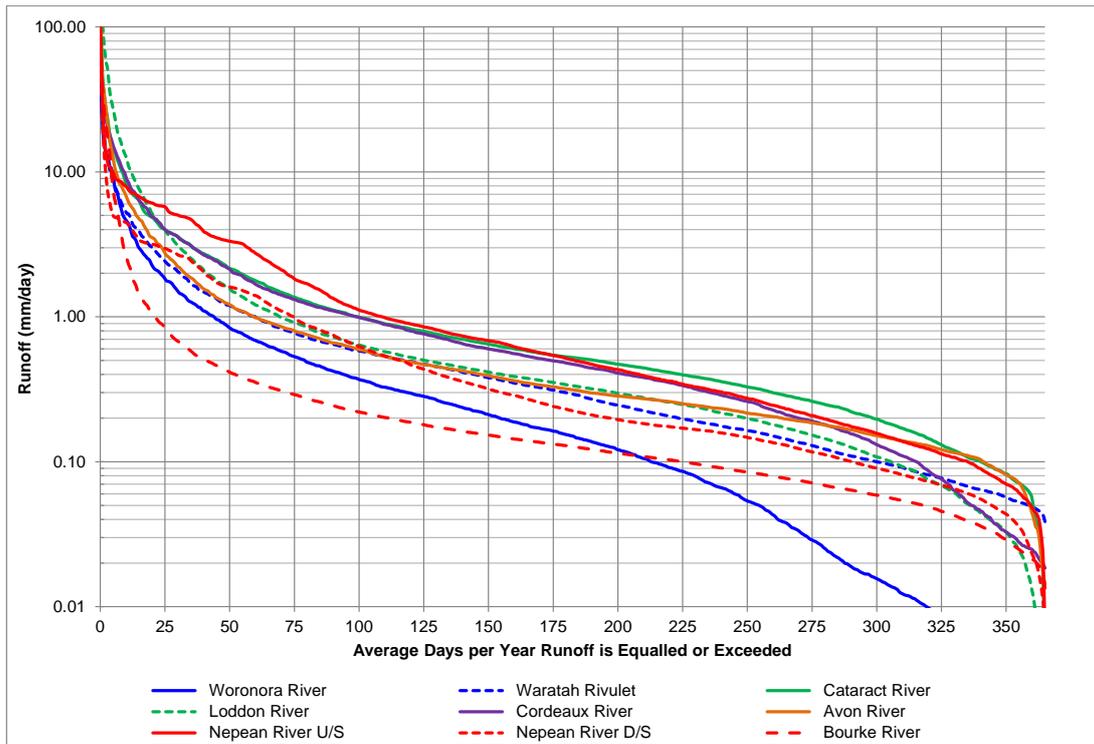
For all graphs, common colours listed below are used for rivers draining to each reservoir, with the different line types for each of the different rivers draining to a particular reservoir:

- Woronora —
- Cataract —
- Cordeaux —
- Avon —
- Nepean —

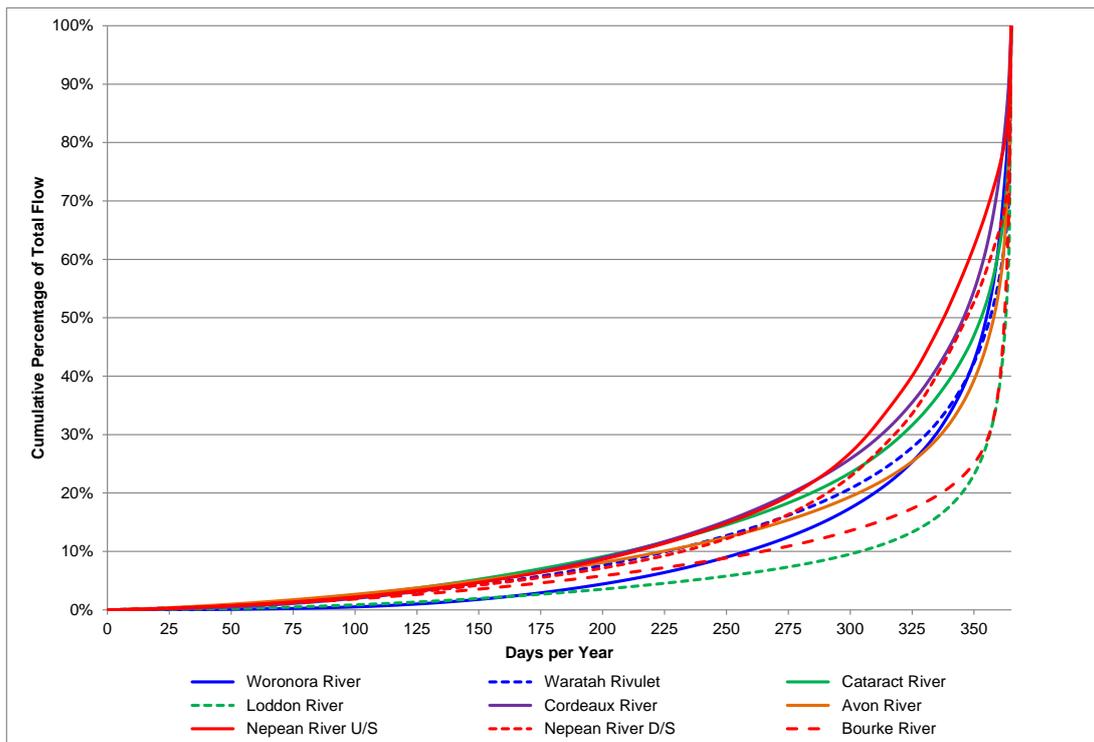
For purposes of maintaining simplicity in the legend of each graph, the Nepean River at of Maguires Crossing is referred to as 'Nepean River U/S (upstream)' and the Nepean River at Nepean Dam Inflow is referred to as 'Nepean River D/S (downstream)'.



**Figure 3.12: Flow Duration Graphs (ML/d) for Catchments within the Metropolitan and Woronora Special Areas**



**Figure 3.13: Flow Duration Graphs (mm/day) for Catchments within the Metropolitan and Woronora Special Areas**



**Figure 3.14: Cumulative Flow Graphs for Catchments within the Metropolitan and Woronora Special Areas**



Key features of the flow regime of the various rivers shown in Figure 3.12 to Figure 3.14 are:

- The differences in the flow duration curves for each river in Figure 3.12 are largely attributable to the contributing catchment area and rainfall. However, the curves for Woronora River and Cordeaux River both exhibit a slightly different shape to the others and indicate a more gradual decline in the low flow regime compared to the others which reduce rapidly after about 225 days per year. The reasons for this are not immediately apparent, but warrant consideration when potential mining impacts are considered.
- Figure 3.13 provides common basis for comparison of the runoff characteristic of each catchment with the runoff expressed as the depth of water (mm) over the contributing catchment area. The graph shows that runoff from all catchments except the Woronora River and Bourke River all follow a similar trend and form a relatively narrow band – indicating similar runoff characteristics. As with Figure 3.12, the runoff characteristics of the Woronora River differ significantly from the others. The Cordeaux River fits within the band of the other rivers but maintains the more gradual drop off of flow shown in Figure 3.12. Apart from the Woronora River, the Bourke River exhibits distinctly lower runoff than the other catchments.
- Figure 3.14 is intended to provide an indication of the duration of flows that contribute most to the total annual flow from the catchments. The graph shows that for most catchments, 20% of the average annual flow occurs between 275 and 310 days per year depending on the particular catchment. The corollary is that 80% of the flow occurs between 55 and 90 days per year. The two exceptions are Loddon River and Bourke River in which 80% of the average annual runoff occurs over 20 and 30 days respectively. This indicates that these two catchments have less persistent low flows than the other catchment. In the case of the Loddon River this may be a function of the relatively small catchment size (9.18 km<sup>2</sup>) but contrasts with the Cordeaux River of a similar catchment area (9.36 km<sup>2</sup>). The differences illustrate the differences in runoff characteristics across the Special Area.

### 3.7.4 Water Supply

The Water Supply System Model and Yield Review 2009/10 (SKM, 2011) reviewed historic inflow estimates and synthetic inflow series for the dams in the Sydney Catchment Area. The report also provides details of a number of operating scenarios including a table of average annual inflows and releases from each dam for a scenario designated R24. Relevant data for dams and weirs in the study area is presented in Table 3.15 below. Table 3.15 also includes data for the “reliability yield” and a “security yield” (WaterNSW, pers comm, 2016) which are significantly less than the average.



**Table 3.15: Water Supply System Model Data**

Storage	Avg Inflow (GL/year)	Avg Env'al Flow (GL/year)	Avg Water Supply (GL/year)	Avg Evap (GL/year)	Avg Spill (GL/year)	Reliability Yield <sup>4</sup> (GL/year)	Security Yield <sup>5</sup> (GL/year)		
Woronora	31	7	15	3		11.5	10.5		
Cataract	82	20	164	25		21	14		
Cordeaux	55	12					16	13	
Avon	73	16					20.5	17	
Nepean	107	27					19.5	13.5	
Pheasants Nest Weir	28 <sup>1</sup>	8 <sup>2</sup>					81 <sup>3</sup>	N/A	N/A
Broughtons Pass Weir	20 <sup>1</sup>	5 <sup>2</sup>					23 <sup>3</sup>	N/A	N/A
<b>Totals</b>	<b>396</b>	<b>95</b>			<b>179</b>	<b>28</b>	<b>104</b>	<b>87.5</b>	<b>68</b>

<sup>1</sup> Inflow from catchment below dam

<sup>2</sup> Environmental flow in addition to flow from dams

<sup>3</sup> Includes spills from upstream dams

<sup>4</sup> Reliability yield for which, after accounting for environmental flows, the storage can only go below 50% of full storage capacity for three months

<sup>5</sup> Security yield for which, after accounting for environmental flows, the storage can only go below 50% of full storage capacity for less than 1 in every 100,000 months (8,333 years)

Notwithstanding the fact that the modelled outflows and losses (environmental flow, water supply, evaporation and spill) exceed the inflows, the data in Table 3.15 indicates the following key aspects of the storages and weirs in the Special Areas:

- water supply accounts for <15% of inflow;
- environmental flows account for 24% of inflow;
- evaporation losses account for 7% of inflow.

### 3.7.5 Baseflow

From a WaterNSW perspective (refer Section 1.3), 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.

From a surface water perspective, the term 'baseflow' is ill defined and there remains considerable debate amongst hydrologists regarding an appropriate definition and any physical processes that can be attributed to baseflow derived from analysis of flow records alone. Typically, baseflow is considered to comprise a number of components such those outlined in Section 3.5.2.5. The issue regarding the definition of 'baseflow' is further compounded by the use of the term 'baseflow index' (BFI) which has different meanings:

- From a groundwater perspective, BFI is often expressed as the ratio of groundwater discharge to total river flow expressed as a percentage (see Table 3.6);
- For rainfall-runoff modelling using the Australian Water Balance Model (AWBM), BFI is one of the parameters in the model derived from calibration (see further discussion below).



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.

It is often contended that upland swamps are important contributors to baseflow. Evans & Peck (2014) noted that the fact that only one of the headwater swamps, out of six, monitored in the Russell Vale Expansion project area exhibited behaviour consistent with the hypothesised significant contribution to baseflow from upland swamps in general. This suggests that the dominant contribution to baseflow may be from valley-fill swamps rather than headwater swamps and not upland swamps in general as is commonly supposed. This observation is supported by the fact that in Dendrobium Area 3 only the hydrograph for Piezometer 7 in Swamp 15a (see Appendix F) exhibits a recession curve that indicates drainage to a surface drainage outlet. These observations reflect the findings of Western et al (2008) who studied the hydrology of several high altitude bogs in Victoria and concluded that the strong baseflows of peat catchment streams reflect storage in the underlying regolith, not releases from the peatland itself.

### 3.7.5.1 Analysis of Baseflow from Streamflow Data

The question of how to assess baseflow has been the subject of significant research and debate over several decades, much of it in Australia. An early review of various methods of separation of baseflow using digital (Grayson et al 1996) commented that methods such as those proposed by Chapman & Maxwell (1996) and Boughton (1993) provide a better theoretical basis than digital filters such as that of Lyne and Hollic (1979). In relation to the use of digital filters, the state of knowledge at that time was summarised as:

*"It must be stressed that the resulting 'quickflow' and 'base flow' from any of the methods should not be regarded as true amounts of surface and subsurface flow from the catchment. The methods are simply consistent, robust and expeditious techniques for numerically separating data in rapid and slow response. Only when additional information is available such as from tracer studies can physical interpretations be put on the filtered responses"*

A similar view was expressed in a joint study by SKM and CSIRO (2012) which noted in relation to the Lyne and Hollick filter method:

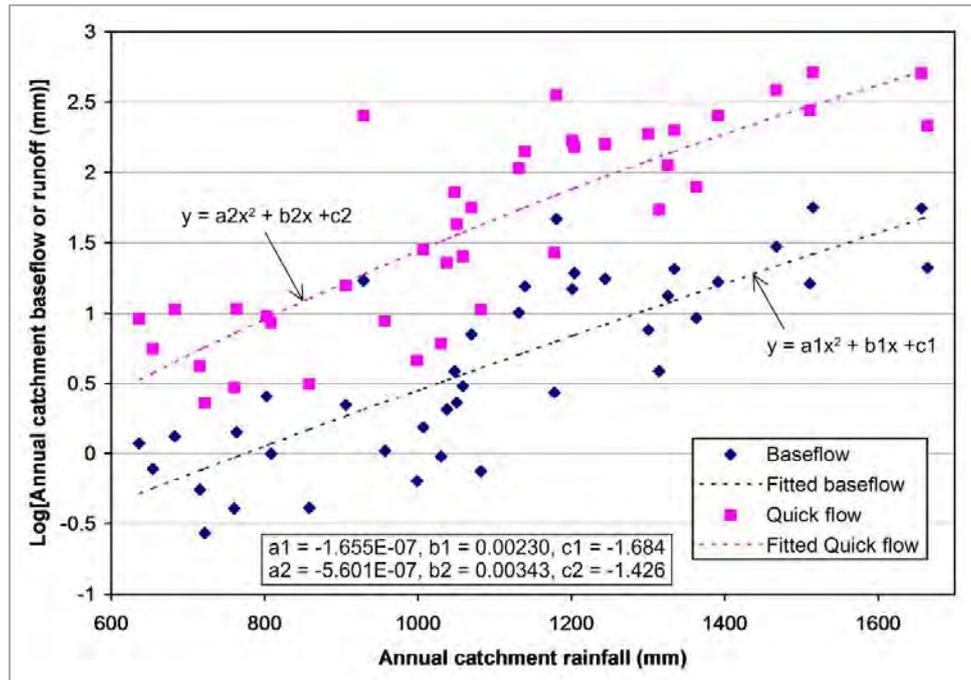
*"Hence the baseflow estimates from this method must be considered as a conservative estimate and in practice, almost always over estimate baseflow compared to the more accurate Tracer method."*

The study by SKM and CSIRO concluded that tracer method was the most accurate and low cost approach for estimating groundwater discharge (baseflow) to rivers and recommended that continuous salinity measurement be made at established river gauging sites. The study also concluded that the Lyne and Hollick filter method could be used to support the tracer method.

A recent study by Coffey (2016) examined methods of baseflow separation using the flow data from Maldon Weir on the Nepean River downstream of Cordeaux, Avon and Nepean Dams. The objectives of the study included undertaking an assessment of baseflow contributions and the quantity of reductions in 'natural;' flows which may be attributable to the effects of mining in the catchment. Coffey reviewed a variety of numerical filtering techniques and adopted the local minimum method for analysing the minima in the streamflow time series for comparison with numerical filtering. The local minimum method indicated that as a proportion of rainfall 'quick flow' and 'baseflow' were 10.3% and 1% respectively. In other words, baseflow comprises about 9% of total flow. Further analysis was undertaken using digital filters constrained to give the total baseflow equivalent to that from the local minimum method. The resulting relationships are



shown in Figure 3.15. The equations in Figure 3.15 indicate that for catchment average rainfall between 1,275 and 1,555 mm/year (see Table 3.12) baseflow would average 1-2% of rainfall and about 8% of total runoff.



Source, Coffey (2016), Figure 4.3

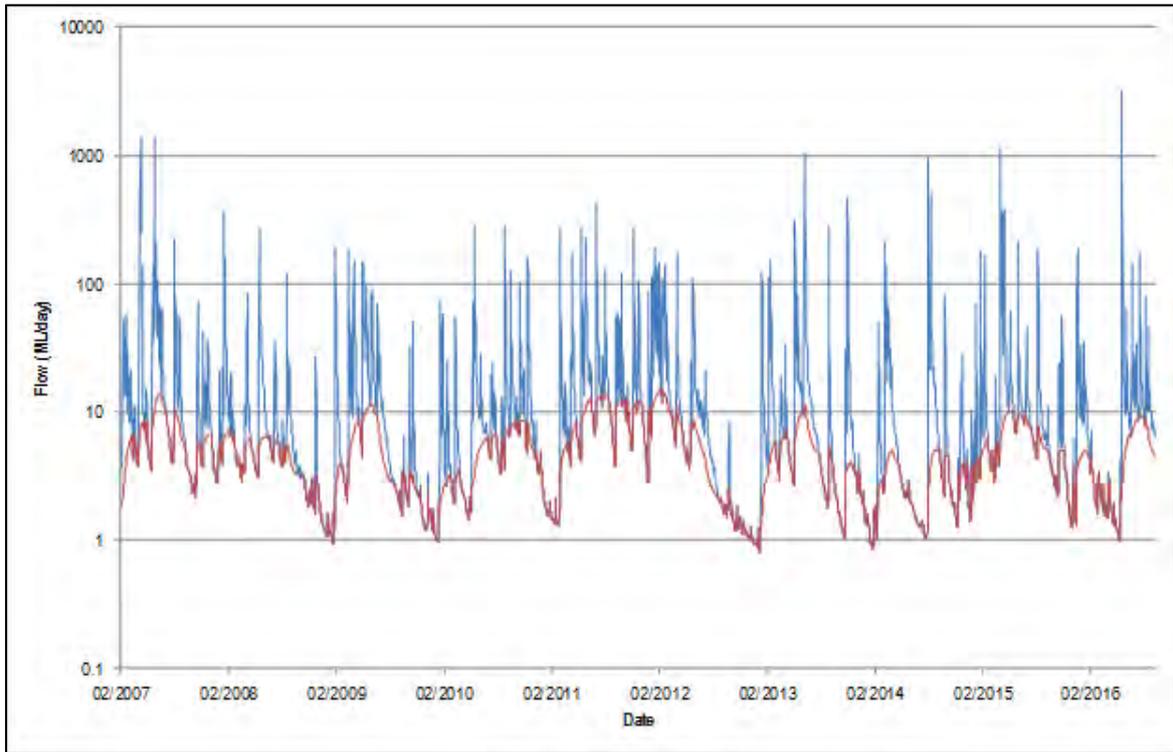
**Figure 3.15: Fitted Relationship between Baseflow and Quick Flow vs Rainfall**

Coffey noted a number of limitations:

- Because there no direct measurements of baseflow, "baseflow analysis for these systems is not able to be regressed against observation, and baseflow is, from a technical/experimental viewpoint, completely unknown."
- The presence of storages upstream of the selected gauging site leads to large attenuation of natural flows;
- Evaporation from the upstream storages is a significant loss (estimated to be 22% of the measured flow at the gauging site) distorts the analysis. The basis of the estimate of 22% is not explained and seems excessive compared to the 7% derived from the system yield review by SKM (2011) – see Section 3.7.4.

### 3.7.5.2 Baseflow Representation in Rainfall-Runoff Models

WaterNSW has undertaken an analysis of baseflow as a proportion of total flow into a number of the dams in the project area. This analysis involved a number of steps to develop and calibrate a rainfall-runoff model (using the Sacramento conceptual model), development of an extended climate dataset and the use of this dataset to develop a synthetic flow record. Although the structure of the Sacramento model includes a component that generates baseflow which is added to the surface runoff component, WaterNSW reported (pers. comm.) that a separate series of modelled baseflows could not be extracted. Instead the full synthetic record was analysed using digital filter method proposed by Lyne and Hollic (1979) to derive estimates of the baseflow component of the synthetic flow record as shown in the example in Figure 3.16.



Source: WaterNSW (Dec, 2016)

**Figure 3.16: Example of Recorded Total Flow and Separated Baseflow for Waratah Rivulet**

This analysis provided estimates of the baseflow component as a percentage of total flow into the various dams set out on Table 3.16 below.

**Table 3.16: Baseflow Estimates Derived by WaterNSW**

Catchment	Estimated Baseflow (% of Total Flow)
Woronora	26%
Cataract	26%
Avon	33%
Nepean	24%

As shown in Figure 3.16, the filter analysis gives rise to situations in which the assessed baseflow is greater than 100 ML/day associated with major flow events. However, for purposes of assessing potential impacts of mining on baseflow, the flow regime of interest is likely to be in those sections of the flow hydrograph where there is no, or minimal, surface flow component (red line on the recession following a major flow event with no blue line above it in Figure 3.16). In the case of the modelled hydrograph in Figure 3.16, if the baseflow component of interest for assessing potential impacts of mining is assumed to be at times when 'baseflow' is greater than 75% of the total, the baseflow would comprise 11% of the total.

The AWBM rainfall-runoff has been adopted for a number of studies of the streamflow characteristics in catchments currently, or potentially, affected by mining (eg WRM, 2015; Gilbert & Associates, 2015 and HydroSimulations, 2016a). Although not specifically stated, it appears that the studies by WRM and HydroSimulations calibrated the AWBM catchment models using the standard calibration procedure for AWBM (Boughton, 2010) which involves the following steps using recorded runoff, recorded catchment rainfall and estimated evaporation:



- Initially, the average storage capacity is scaled so that the calculated runoff volume equals the recorded runoff;
- The parameters that affect the temporal distribution of runoff (BFI, Kbase and Ksurf) are then calibrated against the pattern of runoff.

The quoted BFI parameters for the models developed by WRM (for Bellambi Creek) and HydroSimulations (for sub-catchments of Donalds Castle Creek, Wongawilli Creek and an unnamed catchment draining to Lake Avon) are set out in Table 3.17.

**Table 3.17: Catchment Areas and BFI Values Documented by WRM and Hydrosimulations**

Catchment	Monitoring Site	Catchment Area (ha)	Record Prior to Mining (years) <sup>1</sup>	BFI
Bellambi Creek	South Bulli No 1	932	4.3	0.317
	DC2	108	1.0	0.32
Donalds Castle Creek	DC13	164	na	0.34
	DCU	622	5.1	0.32
Wongawilli Creek	WC15	119	3.5	0.32
	WC21	243	1.2	0.42
	WWL	2,008	2.1	0.32
Lake Avon Tributaries	LA4	82	2.3	0.32

Sources: WRM (2015) and HydroSimulations (2016a)

Key issues relating to the calibrated BFI parameters listed in Table 3.17 are the small catchment area for many of the sites, the short length of record prior to mining and the techniques used to develop and verify a satisfactory calibration. In addition, the adopted evapotranspiration is not specified.

In relation to the model calibration for Bellambi Creek, WRM (2015) note:

*"It was not possible to perfectly replicate all streamflow features of interest (e.g. annual flow, flow frequency, monthly flow, daily flow, hydrograph shape, and baseflow) at all temporal scales. The calibration parameters were selected to achieve a compromise between matching the above parameters."*

HydroSimulations (2016a) describe the calibration procedure as follows:

*Calibration was carried out manually, focussing on 'history matching' of observed and modelled flows during the pre-mining period at each monitoring site. Model calibration was carried out with the focus on simulating recession and low flow periods.*

Neither of these methods of calibration conform to current practice for calibration of rainfall-runoff models which involves the use of the 'leave one out cross validation' (LOOCV) procedure to identify the possible range of parameters that fit the data and the use of the Nash-Sutcliff coefficient of efficiency (Nash and Sutcliff, 1970) as a measure of how well each set of parameters fit the full record.

Separately, Gilbert & Associates (2015) calibrated rainfall-runoff models for the Woronora River, Waratah Rivulet and O'Hares Creek using a version of AWBM. For this work, Gilbert & Associates adopted analysis of mean square error and the use of Nash-Sutcliff coefficient of efficiency as



measures of the goodness of fit of the flow sequence using the calibrated model parameters compared to the recorded data. To better account for the baseflow characteristics, Gilbert & Associates developed a version of AWBM that included a variable baseflow index (BFI) dependent on baseflow storage (BS) and rainfall excess. This variable BFI improved the mean square error.

McMahon (2015a) reviewed the work of Gilbert & Associates (2015) and noted that:

*“The procedure adopted by Gilbert & Associates to recalibrate a modified version of the AWBM catchment models for Waratah Rivulet, Woronora River and O’Hares Creek is appropriate. The revisions made to the standard AWBM model enhanced the model’s ability to capture the low flow characteristics in these catchments.”*

Data from modelling undertaken by Gilbert & Associates (2015) (provided by Metropolitan Coal) was analysed to assess:

- The modelled baseflow as a percentage of total runoff;
- The modelled baseflow as a percentage of rainfall;
- The modelled baseflow for conditions in which baseflow comprised the majority of flow. For illustrative purposes baseflow exceeding 75% of the total flow was arbitrarily adopted as an indicator of days on which baseflow constituted the majority of flow.

The results of the analysis are summarised in Table 3.18.

**Table 3.18: Modelled Baseflow from an AWBM Model**

Catchment	Catchment Area (km <sup>2</sup> )	Pre-Mining Monitoring	Estimated Baseflow Component (%)		
			% of Total Runoff	% of Rainfall	% for Days when Baseflow > 75% of Total Flow
Woronora River	12.4	Not undermined	14%	4%	6%
Waratah Rivulet	20.25	Undermined but no records prior to mining	25%	9%	13%
O’Hares Creek	73	Not undermined	21%	5%	8%

Because the results quoted from the work of WRM, Gilbert & Associates and HydroSimulations represent the result of rainfall-runoff modelling, they suffer from the fact that they are a product of the model conceptualisation and parameter selection and do not represent specific physical processes. Nevertheless, they illustrate the fact that, even when the AWBM model is further refined to reflect the low flow characteristics in these catchments, less than 50% of the total ‘baseflow’ represents low flow conditions in which there is only a small contribution from surface runoff, which is the flow regime potentially most vulnerable to diversion through mine-induced cracking.

### 3.7.5.3 Baseflow Summary

From a WaterNSW perspective, the baseflow contribution to streams from regional groundwater and superficial aquifers (particularly evident following surface runoff events) are important, as it is vulnerable to diversion through mine-induced cracking and is seen as an important flow component during droughts.

A range of baseflow estimates are described in the literature which may be related to spatial (catchment size) and temporal (length of data availability) scales. The analysis by Coffey (2016) together with analysis of Minchin and Brown (2016) (see Table 3.6) indicates that ‘baseflow’ is likely



to be in the order of 1-2% of total rainfall or about 8% of total runoff. A comparable percentage (11%) can be derived if the 'baseflow' of interest is taken to be flow that constitutes more than 75% of the total. The values of 24% to 33% derived by the numerical analysis conducted by WaterNSW are a reflection of the particular analysis method and include a large volume of 'baseflow' that occurs during major runoff events.

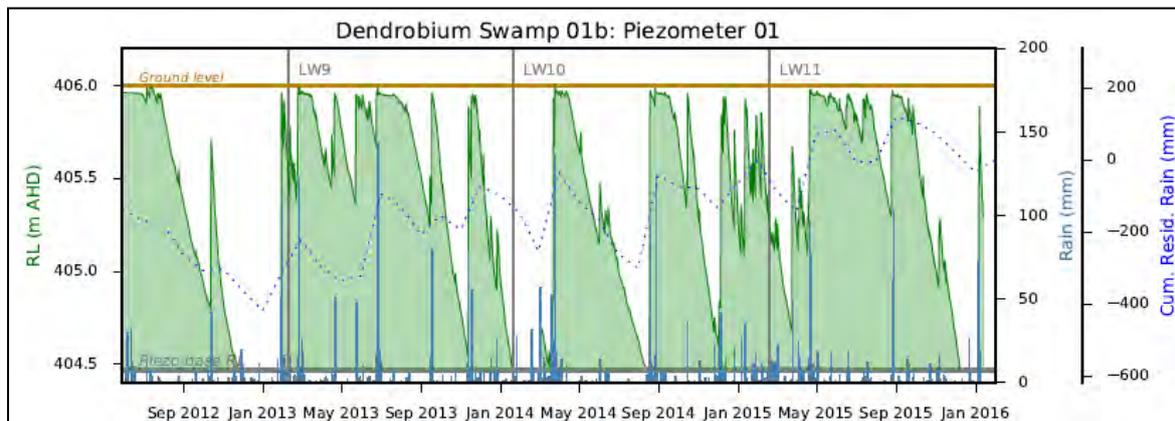
As illustrated by the review of modelled flows using rainfall-runoff models, the parameter BFI in an AWBM model is a function of model structure and parameter calibration. It does not represent a physical process that could be ascribed to particular physical processes that may be impacted by mining. From the perspective of WaterNSW, the important component of 'baseflow' is the flow during drought conditions which is vulnerable to diversion through mining induced cracking. The available data and analysis indicates that this component of baseflow is likely to be of the order of 10% of total flow.

### 3.7.6 Upland Swamp Hydrology

Appendix F provides an assessment of the hydrologic behaviour of upland swamps based on monitoring undertaken for Metropolitan and Russell Vale mines and Dendrobium Area 3 by Krogh (2015). Most monitoring has focussed on monitoring piezometric water level in swamps. This has been supplemented by:

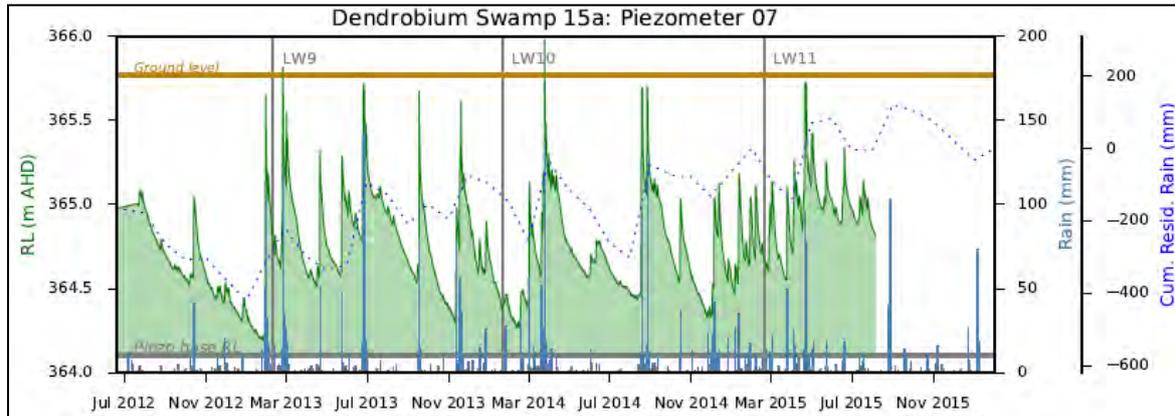
- Monitoring of the shallow groundwater in the sandstone adjacent to the swamp, by Metropolitan Coal;
- Monitoring moisture content by Illawarra Coal at some locations in Dendrobium Area 3;
- Concurrent monitoring of rainfall, pan evaporation, soil moisture and flow in three swamps by Krogh.

The monitoring shows that there is a range of different processes that occur in different swamps. In the case of swamps monitored by Metropolitan Coal, one swamp demonstrated a consistent hydraulic gradient indicating flow from the swamp to the sandstone, while another swamp demonstrated the reverse. Many swamps demonstrated a relatively constant rate of water level decline following rainfall, such as the behaviour shown in Figure 3.17, which can be mainly attributed to evapotranspiration, and possibly some drainage to the underlying sandstone. A minority of swamps demonstrated water level decline representative of a recession curve characteristic of a water storage draining to a fixed outlet level such as a rock bar (for example the behaviour shown in Figure 3.18).



Source: Minchin et al (2016)

**Figure 3.17: Dendrobium Swamp 1b Hydrographs for Piezometer 01**



Source: Minchin et al (2016)

**Figure 3.18: Dendrobium Swamp 15a, Hydrographs for Piezometer 7**

Krogh (2015) has made a significant contribution to the understanding of the hydrology of upland swamps and has carried out detailed monitoring of one swamp that has been impacted by mining as well as two swamps that have not been undermined. Monitoring included piezometric level, soil moisture, rainfall, pan evaporation and swamp outflow. On the basis of the monitored data, Krogh prepared preliminary water balance for the swamps. However, as acknowledged by Krogh, there are a number of limitations in the monitoring and the assumptions that underpin the water balance calculations.

McMahon's peer review of the Krogh's study (McMahon, 2015) considers the piezometric water level and soil analysis data to be credible, but has concerns about the flow and water balance analysis. However, McMahon questions whether the loss of flow will be evident downstream, and states that it is possible that some or all of the flow identified as lost at the swamp outlet may actually resurface downstream and be returned to the system.

Notwithstanding, the monitoring undertaken by Krogh represents a significant step forward in the understanding of swamp hydrology. However, given the recognised limitations of the monitoring and subsequent analysis, together with the lack of any concurrent groundwater monitoring, no conclusions should be drawn regarding the overall water balance of the swamps or whether apparent 'loss' of water from the swamp reports to a shallow groundwater system in the sandstone as indicated by the hydraulic gradient monitored in Metropolitan Swamp 101.

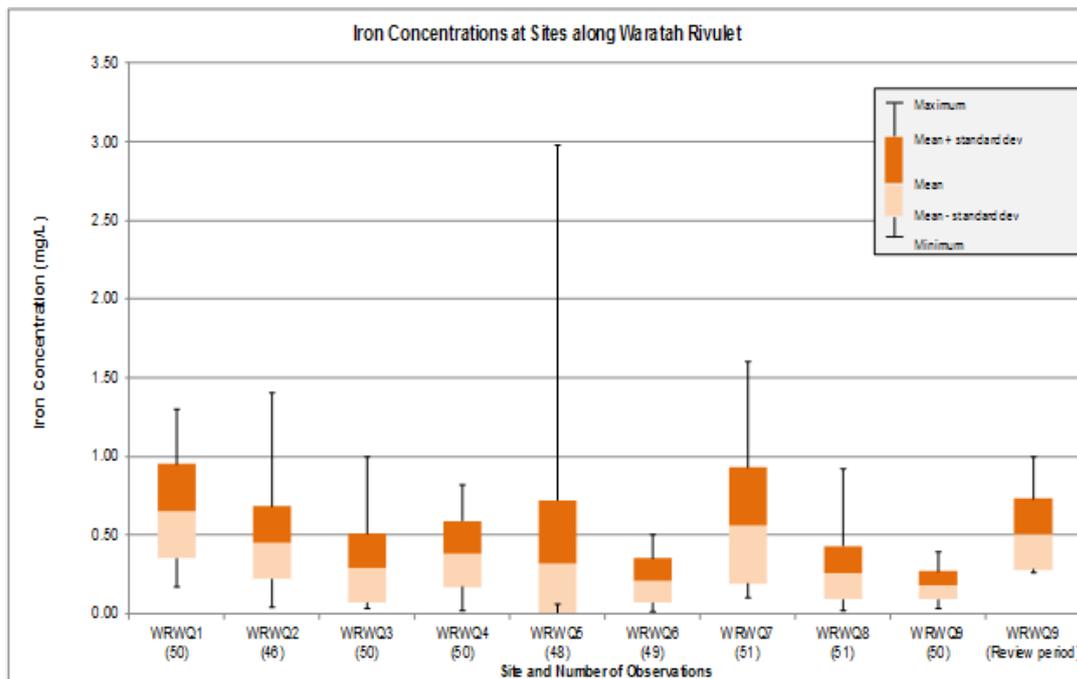
Evans & Peck (2014) reviewed the hydrographs for six of the headwater swamps in the Russell Vale Extension Project that had been subject to undermining between the late 19<sup>th</sup> Century and 1982. Only one of these swamps exhibited behaviour consistent with the hypothesised significant contribution to baseflow from upland swamps in general. This suggests that the dominant contribution to baseflow may be from valley-fill swamps rather than headwater swamps, not upland swamps in general as is commonly supposed. This observation is supported by the fact that very few swamps such as the hydrograph for Piezometer 7 in Dendrobium Swamp 15a (see Figure 3.18) show a recession curve that indicates drainage to a surface outlet. These observations reflect the findings of Western et al (2008) who studied the hydrology of several high altitude bogs in Victoria and concluded that the strong baseflows of peat catchment streams reflect storage in the underlying regolith, not releases from the peatland itself.



### 3.7.7 Water Quality

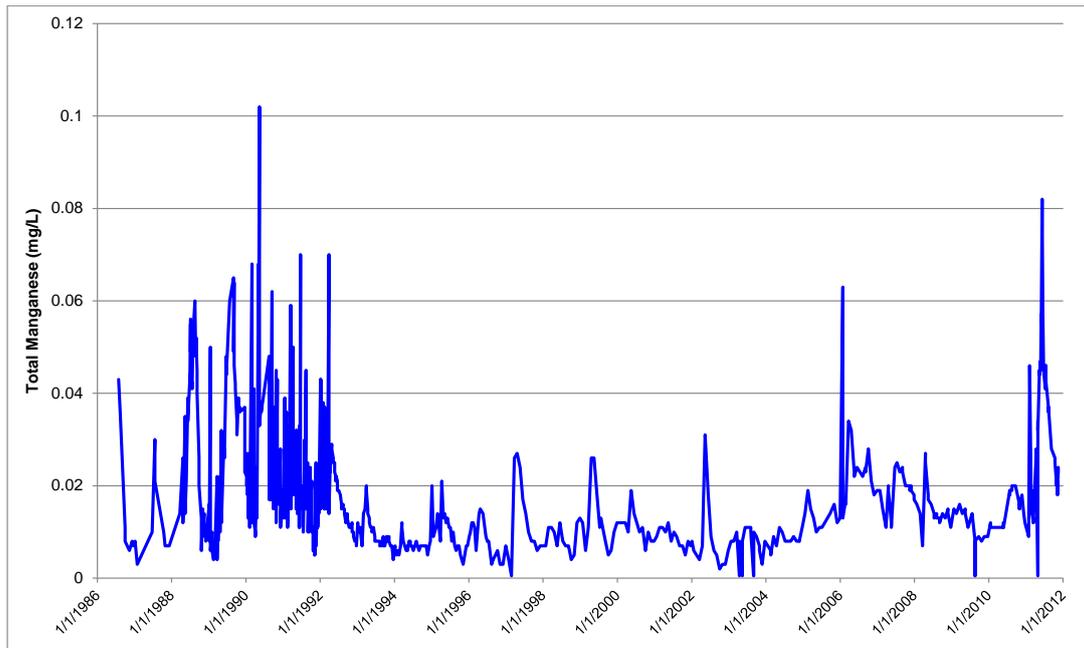
Water quality in the Special Areas is protected by buffer zones of pristine bushland around dams and their immediate catchment areas. Human activities near the drinking water catchments are prohibited or restricted. Buffer zones are made up of protected bushland, some of which has been protected for more than 100 years, allowing a large number of native species to thrive ([www.waternsw.com.au/water-quality/education/learn/special-areas](http://www.waternsw.com.au/water-quality/education/learn/special-areas)). As a result, water quality in the Special Areas is generally relatively pristine and of very high quality.

The various mining companies undertake routine monitoring on the major watercourses, ones not impacted by mining as well as those that are. Typically, the mines are required to demonstrate that mining has negligible impact on the water quality reaching the reservoir. The required monitoring includes baseline monitoring prior to mining. The available water quality data demonstrate that there are wide variations in water quality along, as well as over time, in each monitored river, as well in control catchments. This is illustrated by the example in Figure 3.19.

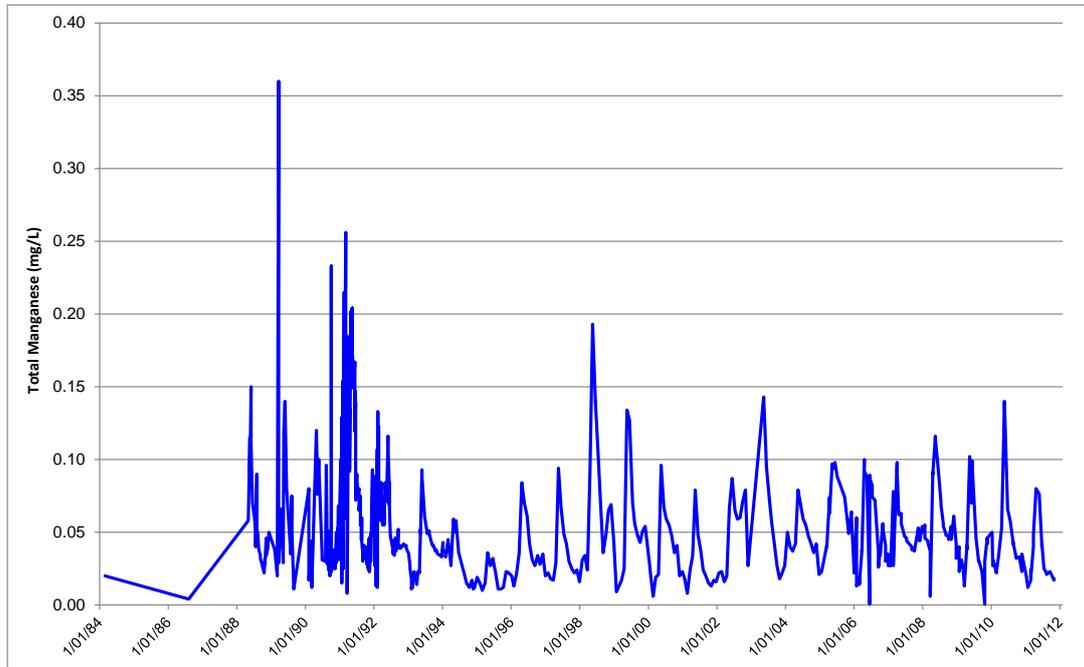


**Figure 3.19: Example of Water Quality Variation along Waratah Rivulet**

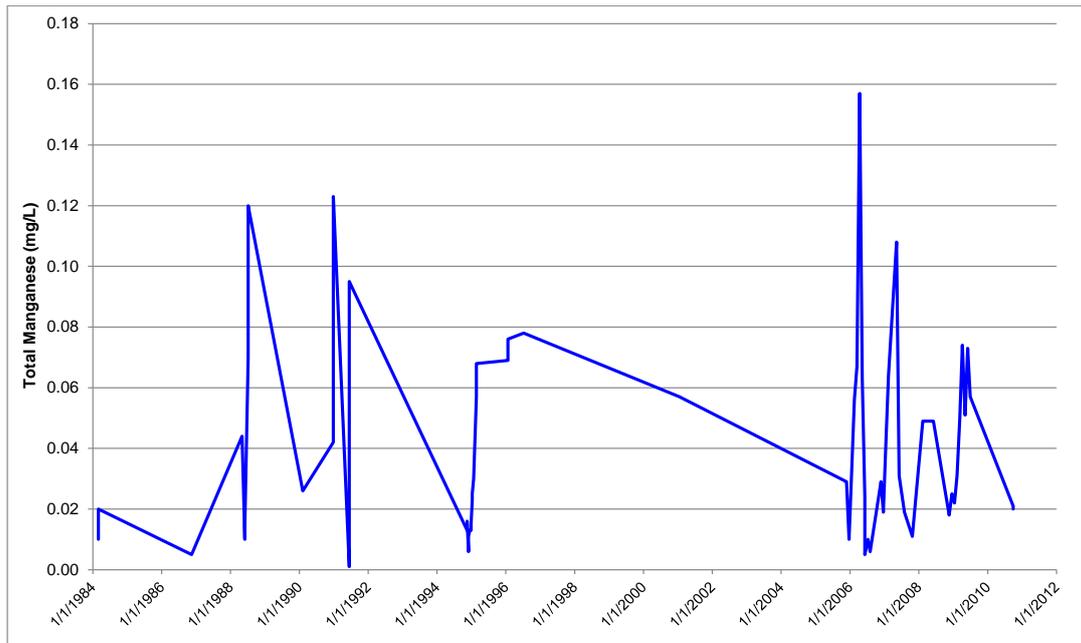
At a broader scale, the main concern of WaterNSW relates to the water quality in the reservoirs and the requirement to meet water quality supply obligations. WaterNSW routinely collects water quality samples from its reservoirs near the dam wall, often near the surface as well near the bottom. These samples are analysed for a variety of analytes including Iron, Manganese, Aluminium (both total and dissolved) as well as pH and dissolved oxygen. By way of example, Figure 3.20, Figure 3.21 and Figure 3.22 show the variation of total Manganese in near surface samples from Woronora, Cataract and Nepean Reservoirs.



**Figure 3.20: Variation in Concentration of Total Manganese in Near Surface Samples from Woronora Reservoir**



**Figure 3.21: Variation in Concentration of Total Manganese in Near Surface Samples from Cataract Reservoir**



**Figure 3.22: Variation in Concentration of Total Manganese in Near Surface Samples from Nepean Reservoir**

The two noteworthy aspects shown in these figures are summarised in the statistics in:

- Significant variation in the concentration of total Manganese over time;
- Significant variation between the water quality in the three reservoirs, with Woronora having significantly lower average and median, and a maximum recorded in Cataract that is about 3.5 times that recorded in Woronora.

**Table 3.19: Statistics for Near Surface Monitoring for Total Manganese in Woronora, Cataract and Nepean Reservoirs**

Statistic	Woronora	Cataract	Nepean
Observations	901	736	72
Minimum	<0.001	<0.001	0.001
Average	0.019	0.055	0.044
Median	0.015	0.044	0.031
Maximum	0.102	0.360	0.157

### 3.7.7.1 Creeks

The *Southern Coalfield Strategic Review* (NSW Government, 2008) reports that water quality of both quick flow and base flow in stream runoff is influenced by a number of factors. These include the organic and inorganic fabrics within swamps, groundwater-rock interactions in shallow and deep aquifers, and anthropogenic inputs (negligible in the Special Areas but increase downstream of the Special Areas).

*“Base flow is the main source of salts in stream flow. Runoff with a weak base flow component yields a very high quality water which is typically low in total dissolved salts (TDS commonly less than 100 mg/l) and weakly acidic (pH range of 5 to 7). Increasing contributions from base flow during dry and drought periods are reflected in a higher TDS, possibly as high as 250 mg/l, and a*



*pH range from 4 to 8. This variability is normal and consistent with a quasi-stable catchment system where water-rock interactions have been occurring over geologic time and minerals have been progressively leached away. The Panel notes, however, that unstable conditions can sometimes occur at a local scale through, for example, rapid changes in swamp geomorphology or through natural movements in the sandstone bedrock. The latter is especially noticeable when certain iron rich minerals facilitate 'iron springs' at discrete fractures or along strata bedding plane." (NSW Government, 2008, p16).*

### 3.7.7.2 Swamps

NSW Government (2008) notes that the hydrology of swamps in the Southern Coalfield is poorly studied and that there has been limited study of groundwater quality associated with swamps. The water quality of swamps is normally reflected in the water quality of the drainages immediately downstream, which generally exhibit very low dissolved salts.

### 3.7.7.3 Storages

WaterNSW provides raw (largely untreated) water from its various storage reservoirs to its suppliers via pipelines or canals to water filtration plants where it is then filtered, disinfected and distributed to customers. A multi-barrier approach is taken to protecting drinking water quality from the "catchment-to-tap". Water quality monitoring is undertaken within the catchment, at the reservoirs, and at the pre-treatment and post treatment phases.

In a discussion paper for the NSW Chief Scientist & Engineer, Emeritus Professor Fell (Fell Consulting, 2014) noted that:

*Regarding the quality of the water produced, the authorities are very reliant on the quality of inlet water to dams. For this reason, the Sydney Catchment Authority pays close attention to industrial and other operations, including the disposal of waste water in catchment areas. It manages Special and Controlled Areas surrounding some catchments in which pristine bushland is preserved to minimise wastes and sediments entering dams.*

*At the moment the treated water from Sydney Water comfortably meets Australian Drinking Water Health Guidelines. Fears have been expressed that if activities like long-wall coal mines and coal seam gas recovery proliferate within Special Areas and in catchments, surface water could become contaminated and pose a difficulty in ultimate water treatment. There is insufficient evidence at present of any soluble organic impact on water resulting from the subsidence caused by long-wall mining.*

## 3.8 Biophysical Environment

The biophysical environment is briefly described below including an overview of the aquatic and terrestrial flora and fauna. Particular attention is also given to upland swamps and streams given their significance to the environmental integrity of the Special Areas and the contribution of streams to water quality and quantity.

### 3.8.1 Climatic Influences on the Environment

One of the most significant drivers of biological processes, evolutionary change, erosional and depositional processes and ecosystem function is climate. In the wet-temperate environment of the Woronora Plateau these processes have been shaped over millennia to produce a diversity of physical features and ecosystems. Rainfall tends to decrease significantly from the Illawarra Escarpment with an isohyet band of around 1,600 mm - decreasing westward to 1,300 mm (Refer



Figure 3.9). Temperature variations tend to follow elevation patterns with the lower elevation areas to the west near Picton generally being warmer and the higher elevation areas of the Southern Highlands being cooler (NPWS, 2003).

In addition to precipitation, rainfall intensity and the regularity of rainfall significantly influence the moisture levels in catchment soils and the hydrological response of the local catchments (Merrick, 2008a). Long-term data show that late winter and early to mid-spring are generally the driest periods (refer Table 3.9), however this deficit is compensated by lower evapotranspiration rates in the cooler months. The characteristic evaporation to precipitation ratio of the plateau has significantly influenced the vegetation communities that exist and is particularly important in relation to the development and maintenance of swamp ecosystems. During the warmer months when there is a general moisture deficit evapotranspiration exceeds precipitation and in the cooler months the reverse occurs. In some rainfall-dependent swamp systems, the lower evapotranspiration rates in winter/spring allows for their development and maintenance as swamp ecosystems.

### 3.8.2 Fire History

The catchments of Woronora, O'Hares, Nepean and Avon were all extensively burnt during December 2001 and January 2002 (NPWS, 2003). These areas have withstood three fires since 1970 and the vegetation has naturally regenerated following these events (Bangalay Botanical Surveys, 2008). It is to be noted, however, that many of these vegetation communities are still in a successional stage and are yet to reach the climax community, which could take decades. These fire-related floristic changes are additional disturbances to changes that may result from longwall mining, seasonal variation or climate change

### 3.8.3 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. The vegetation has been mapped and described by NPWS (2003) and can be represented by eight broad vegetation groups (BVG). These groups are briefly described below in Table 3.20.

**Table 3.20: Broad Vegetation Groups (BVG) and their Characteristics and Habitat Description**

Vegetation Group	Characteristics and Habitat Description
Shale-Sandstone Transition Forests	Occurs on elevations less than 400 m on residual shale soils that overlie sandstone bedrock along the western boundary of the Special Areas. The drier environment in combination with the richer shale soil results in a grassy woodland and open forest that marks the gradual transition into the vegetation of the Cumberland Plain.
Elevated Mittagong Sandstone Woodland-Heath	In the far south west of the SA temperatures are cooler and the woodland is mainly dominated by <i>Eucalyptus sclerophylla</i> , <i>E. mannifera</i> and <i>E. radiata</i> with a shrubby mid-storey layer.
Scrubs on Sandy Alluvium	Alluviums derived from siliceous sandstone rock support low growing shrubs that form dense thickets and scrubs.
Tall Open Forests on Enriched Soils	This group are found on more fertile soils associated with fine-grained sedimentary rock such as the Narrabeen series, Wianamatta Shale and Tertiary basalt flow and intrusions. These forests are characterised by tall Eucalypts and a sparse shrub and small tree layer.



Vegetation Group	Characteristics and Habitat Description
Rainforests and Tall Moist Eucalypt Forests	Rainforests are mostly situated within an area less than 5 km from the Illawarra escarpment where rainfall remains high and the soils provide suitable nutrient supply from either the Narrabeen Shale or the richer basalt rocks found on the Robertson Plateau or Upper Cordeaux area. The Tall Moist Eucalypt Forests tend to be on the chocolate shale soils of the Narrabeen series in deeply protected topographic positions, such as incised gullies and southerly aspects.
Exposed Sandstone Woodlands and Heath	The dry open woodlands that occur on the sandstone plateau are the most extensive vegetation complex of the catchments. The shallow sandy soils are highly acidic and infertile, though support a highly diverse flora.
Sandstone Gully Forests	Four Sandstone Gully Forests have been described. Changes in rainfall and elevation result in slightly different gully assemblages.
Upland Swamp Complex	This vegetation group is found on the Woronora Plateau. Five vegetation communities were characterised by Keith and Myerscough (1993) as part of the upland swamp complex and reflect a moisture and nutrient gradient in the underlying soil. NPWS (2003) have further described two additional communities: Fringing Eucalypt Woodland (transitional area between upland swamp and sandstone woodlands) and Mallee Heath (occupies drier areas within upland swamps).

### 3.8.3.1 Threatened Flora Species, Endangered Populations and Endangered Ecological Communities

There are many threatened species, endangered populations and endangered ecological communities listed under the *Threatened Species Conservation Act 1995* (TSC Act) and the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), which are known to occur or may occur in the Special Areas. Due to the large number of floral species known or likely to occur in the study area, only the endangered populations and endangered ecological communities are listed below.

#### **Endangered Populations**

- *Woronora Plateau population of Callitris endlicheri (a tree)* - The population represents the coastal limit of the species' range. The population is restricted to a single outcrop of sandstone approximately 2 ha in area. The soils at the site are skeletal sandy loams (NSW Scientific Committee, 2016e). Listed as an endangered population under Schedule 1, Part 2 of the TSC Act.

#### **Endangered Ecological Communities (EEC)**

- *Coastal Upland Swamp in the Sydney Basin Bioregion* is associated with periodically waterlogged soils on Hawkesbury sandstone plateaux. The vegetation is dominated by sclerophyll shrubs and or sedges that may include tall scrub, open heath and sedgeland (NSW Scientific Committee, 2016c). This EEC was gazetted under the TSC Act in March 2012 and the EPBC Act in July 2014;
- *Cumberland Plain Woodland in the Sydney Basin Bioregion* occurs on soils derived from Wianamatta Shale and throughout the drier parts of the Woronora Special Area (Office of Environment and Heritage, 2016a). Listed under Schedule 1, Part 3 of the TSC Act
- *Southern Sydney Sheltered Forest on Transitional Sandstone soils in the Sydney Basin Bioregion*. The community is typically associated with sheltered heads and upper slopes of gullies on transitional zones where sandstone outcrops may exist, but where soils are influenced by lateral movement of moisture, nutrients and sediment from more fertile substrates (NSW Scientific Committee, 2016d). Listed under Schedule 1, Part 3 of the TSC Act;



- *O'Hares Creek Shale Forest Community* occurs on small outcrops of Hawkesbury shale in the Darkes Forest and occupies approximately 286 ha between the Cataract Special Area and Appin Road (Office of Environment and Heritage, 2016c). Listed under Schedule 1, Part 3 of the TSC Act;
- *Robertson Rainforest in the Sydney Basin Bioregion* is a cool temperate rainforest requiring highly fertile soils at altitudes of between 500-700 m. They have a restricted distribution in the eastern parts of the Southern Highlands (Office of Environment and Heritage, 2016e) and southern most areas of the Metropolitan Special Area. Listed under Schedule 1, Part 3 of the TSC Act;
- *Robertson Basalt Tall Open-forest in the Sydney Basin Bioregion* is an open forest or woodland restricted in the Metropolitan Special Area to the far south on Robertson Basalt (Office of Environment and Heritage, 2016d). Listed under Schedule 1, Part 3 of the TSC Act; and
- *Shale Sandstone Transition Forest in the Sydney Basin Bioregion* occurs at the edges of the Cumberland Plain, where clay soils from the shale rock intergrade with earthy and sandy soils from sandstone (Office of Environment and Heritage, 2016f). Listed as critically endangered under Schedule 1A, Part 2 of the TSC Act and critically endangered under the EPBC Act.

### 3.8.3.2 Longwall Mining as a Key Threatening Process

In July 2005 the NSW Scientific Committee made a final determination to list 'Alteration of habitat following subsidence due to longwall mining' as a Key Threatening Process (KTP) under Schedule 3 of the TSC Act. This is in recognition that longwall mining, such as in the Southern Coalfield, can have significant consequences on surface and groundwater hydrology, physical features, streams, swamps and biodiversity (NSW Scientific Committee, 2016b).

## 3.8.4 Terrestrial Fauna

### 3.8.4.1 Habitat Features

FloraSearch and Western Research Institute (2008) recognised five broad habitat types in the Woronora Special Area which included forest, heath and mallee, riparian and associated watercourse and upland swamp. From these broad habitat types, three are recognised by DECC (2007a) as being 'priority fauna habitat' for the Greater Southern Sydney Region:

- Upland swamps, which are covered in more detail in Section 3.8.6;
- Grassy Box Woodlands, which occur as isolated pockets on the western margin of the Metropolitan Special Area. The woodlands provide habitat for at least 18 priority species and another species thought to be locally extinct. These woodlands are habitat for nationally endangered species such as the Regent Honeyeater and Swift Parrot; and
- Alluvial Woodlands and Forests, which occur on deep fertile alluvial soils on creek banks and river flats of waterways throughout the Greater Southern Sydney Region and support four of the most threatened species in the region, such as the Booroolong Frog, Black Bittern, Large-footed Myotis and Regent Honeyeater.

Cliffs, rock benches, rock overhangs and elevated sandstone ledges also provide shelter and nesting sites for threatened, protected and regionally significant species such as snakes, geckos, insectivorous bats, Brown Antechinus, Rockwarblers and the Superb Lyrebird (DECC, 2007b). Cliff lines are associated with river gorges, but there are other cliff lines associated with steep topography around the river valleys, for example, in Dendrobium Coal Mine Area 2 (NSW Department of Planning, 2008). No regional mapping of the cliff lines is available (*ibid.*).



Water in streams and pools also provide critical habitat for threatened, protected and regionally significant terrestrial species. In particular, these species include amphibians, the Eastern Snake-necked Turtle, Platypus, Water Rat, and the Large-footed Myotis bat (DECC, 2007b).

### 3.8.4.2 Threatened Fauna Species

Thirteen threatened species were recorded in the Woronora Special Area including 2 amphibians, 1 reptile, 5 birds and 5 mammals (FloraSearch and Western Research Institute, 2008). In addition to these listings, DECC (2007c) recorded another 7 species (3 bird and 4 mammals) in the Dharawal State Conservation Area (SCA). A comprehensive survey of the Greater Southern Sydney Region by NSW Department of Planning (2008) listed 22 threatened species of which 11 (6 birds, 3 mammals, 2 amphibians) were not recorded in the Woronora Special Area and Dharawal SCA studies. Thus, the number of threatened fauna species that are likely to utilise habitats in the Woronora and Metropolitan Special Area are in the order of 30 or more.

Of particular interest for this Review are the threatened terrestrial species that are dependent on surface or groundwater for part of their life-cycle. As these species bridge the terrestrial/aquatic and upland swamp environments, they are referenced in each of the relevant sections within the 'Biodiversity Section' (Section 7). The species and their habitats are briefly described below:

- **Giant Burrowing Frog** (*Heleioporus australiacus*) - listed under the EPBC Act and the TSC Act as vulnerable. The Giant Burrowing Frog usually live along clear, small slowly flowing water courses which traverse plateaus and broad upland gullies. They also live adjacent to stream headwaters where they prefer permanently moist soaks and pondages, as well they may utilise upland swamps as a component of the range of habitats it is able to exploit. Many breeding sites have been known to be associated with shallow temporary ponds receiving seepage and the ponded sections of slow flowing creeks that drain ridges and plateaus. Giant Burrowing Frogs have not been recorded breeding in waters that are even mildly polluted and are adversely affected by small pH changes (NPWS, 2001; Cenwest Environmental Services, 2016);
- **Red-crowned Toadlet** (*Pseudophryne australis*) – listed under the TSC Act as vulnerable. The toadlet is known to occur only on the Triassic Sandstones occupying the upper parts of ridges living in the vicinity of permanently moist soaks or areas of dense ground vegetation or leaf litter along or near headwater stream beds. Small nests are formed within decomposing accumulated leaf matter through the early stages of tadpole development, then rainfall events flush the embryos from the nest and the tadpoles complete their development within transient pools (NSW National Parks & Wildlife Service, 2016);
- **Giant Dragonfly** (*Petalura gigantea*) – listed under the TSC Act and EPBC Act as vulnerable. The dragonfly has been recorded between the Cordeaux and Avon Rivers, south of the Cataract River between Cataract Reservoir and Wilton Road, and Dharawal Nature Reserve (Office of Environment and Heritage (OEH), 2016b). It is likely to occur in other areas, though has not been recorded in the OEH database. The Giant Dragonfly requires a zone of water at saturation in the top 0.5 m of substrate for the aquatic larval stages of the insect to survive. The larvae burrow into the peat to a mean depth of 0.37 m with some of their burrow needing to be in the zone of water saturation. From the time of egg laying, the larvae can erupt up to 7 years after the event (Baird and Burgin, 2010). Due to this significant lag period from egg laying to larval eruption this species is not a good indicator for determining habitat impact (Ian Baird, *pers. comm.* 2016);
- **Littlejohn's Tree Frog** (*Litoria littlejohni*) – listed under the TSC Act and the EPBC Act as vulnerable. The frog is known to inhabit forest, coastal woodland and heath. They breed in rocky streams, ditches, isolated pools and flooded hollows and creeks, deep permanent pools



in hanging swamps, rock-lined rivers. They are very sensitive to habitat changes and fire (Department of the Environment and Energy, 2016).

### 3.8.5 Aquatic Environments

As stated above, particular attention is given to upland swamps and streams given their significance to the environmental integrity of the Special Areas and for their contribution to water quality and quantity. Furthermore, adverse impacts on uplands swamps and streams from longwall mining-related subsidence have been observed and reported; thus, warranting a more considered review.

The aquatic environments in the Special Areas comprise a complex network of rivers, streams, standing water and upland swamps that are connected through a number of ecosystem, hydrologic and geomorphic processes. These processes operate at different time and space scales ranging from, for example, short-time, small space-scale cellular respiration to long-time, large space-scale evolutionary landform and genetic change. The aquatic environments are not closed systems and have significant interactions with the terrestrial landscapes. Further, not all aquatic systems follow along connected linear depressions. Valley-side swamps, largely fed from groundwater seeps, are often distal to valley depressions or drainage lines.

The drainage systems are highly diverse (refer Section 3.6.3) and the biota dependent on these systems is as diverse as the stream morphology, the surrounding boundary conditions and the localised climate.

The complexity and variation of the aquatic ecosystems in the Special Areas is magnified when consideration is given to their subterranean environments. The rich and diverse biota of the groundwater contributes to the maintenance of healthy riverine and swamp ecosystems, including water quality. Surface aquatic environments have attracted most of the attention in the literature, however increasing awareness of subterranean ecosystems and the risks they are facing nationwide and in the Special Areas is being acknowledged by, for example Hatton and Evans (1998), Serov *et al* (2012) and Hose (2008, 2009).

#### 3.8.5.1 Aquatic Flora of Flowing Streams

This section and the following section on fauna describe the aquatic environment of flowing streams with upland swamps being more fully covered in Section 3.8.6.

Aquatic flora in this context refers to submerged or emergent species of flowing streams. There is a general paucity of information on the characterisation and distribution of aquatic plants in the smaller creeks and streams of the Special Areas (NSW Department of Planning, 2008). A study of aquatic macrophytes<sup>2</sup> was undertaken in the Dendrobium Coal Mine Area 1, though the study was localised and while useful offers little in the way of assessing regional significance (*ibid.*).

#### 3.8.5.2 Aquatic Fauna of Flowing Streams

Aquatic invertebrates include several species of freshwater crayfish and a diverse range of smaller taxa, including freshwater shrimp, molluscs, worms and aquatic macroinvertebrates (Biosis Research, 2007). The aquatic macroinvertebrates<sup>3</sup>, in particular, have been well studied in the Special Areas - being the subject of project specific studies by government and consultant's

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<sup>2</sup> Plants that grow in or near water and are either emergent, submerged or floating.

<sup>3</sup> Organisms without backbones, which are visible to the eye without the aid of a microscope that live on, under and around rocks and sediments on the bottoms of lakes, rivers and streams



reports. The studies have covered a range of streams from the lowland rivers, such as the Nepean River and headwater creeks and tributaries. The main findings indicate that regulated flow has a profound impact on macroinvertebrate assemblages and that threatened species were not generally observed. Further, species assemblages differed to what was expected, were indicative of different river health conditions and showed significant within stream and between river variation (Bio-Analysis Pty Ltd, 2009). The smaller group of invertebrates, the meiofauna, are generally studied as part of the groundwater dependent ecosystem's biota.

The Sydney Hawk Dragonfly (*Austrocordulia leonardi*) is a dragonfly species that spends most of its life underwater as an aquatic larva, in deep and shady river pools, before metamorphosing and emerging from the water as an adult. It has not been recorded in the Special Areas, though records are known downstream of the Woronora Dam and on the Bargo River south of Picton (NSW Department of Primary Industries, 2016). Extensive sampling has failed to discover specimens in other locations suggesting that it has a highly restricted distribution (*ibid.*).

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 (NSW Department of Planning, 2008). Numbers of fish species and abundances at particular sites depend on a wide range of local environmental factors, as well as the connectedness between habitats that support the life-history stages of particular species. The large rivers have the majority of the fish species and generally the larger sized species, including the Macquarie Perch (*Macquaria australasica*). The Macquarie Perch is the only fish species listed as threatened that is known to occur in the Special Areas. It is listed as endangered under the *Fisheries Management Act 1994* and the EPBC Act. The Ecology Lab (2007) report on an earlier 2001 study noted that this fish species was restricted to a small number of large pools at the most downstream reach of Wongawilli Creek.

The smaller headwater streams, on the other hand, are often important habitat for smaller sized species such as the Australian Smelt (*Retropinna semoni*) and Mountain Galaxias (*Galaxias oldus*) and they have limited ranges within particular sub-catchments (NSW Department of Planning, 2008). Most fish species have very particular life-history requirements in terms of habitats, water flows and other environmental cues. Particular habitats, such as gravel beds, meadows of aquatic plants and deep pools are often critical as spawning sites, egg-laying habitats and/or feeding areas. In addition, several of the species in the Special Areas migrate significant distances along rivers and streams, often to complete part of their life-cycle (*ibid.*).

The headwater storages of the Woronora, Cataract, Cordeaux, Avon and Nepean Rivers are barriers to fish that spawn in the estuaries or at sea and are then unable to make recolonising migrations upstream of these impoundments (Bio-Analysis Pty Ltd, 2009). In addition, regulated flow has had a profound impact on assemblages of macroinvertebrates, which are an important source of food for many fish species.

### 3.8.5.3 Groundwater Dependent Ecosystems

Groundwater dependent ecosystems (GDEs) are defined as ecosystems which have their species composition and natural ecological processes wholly or partially determined by groundwater. They explicitly include any ecosystem that uses groundwater at any time or for any duration in order to maintain its composition and condition. Defining and recognising GDEs is important for projects, policy and legislative frameworks, including the *Water Management Act 2000* and Australian Government National Water Commission as part of the Coastal Groundwater Quality and Groundwater Dependent Ecosystem Project (Serov *et al.*, 2012).



Serov *et al* (2012) offer a classification scheme that separates GDEs into two main ecosystem types: subsurface ecosystems and surface ecosystems. For the purpose of this classification, groundwater is defined as water occurring naturally below ground level (whether in an aquifer or otherwise), including the saturated phreatic zone and the unsaturated vadose zone (*ibid.*).

The two main ecosystem types are described below (as per Serov *et al.*, 2012):

## **Subsurface Ecosystem**

The subsurface ecosystems include the subsurface phreatic ecosystems and baseflow stream<sup>4</sup> (hyporheic<sup>5</sup> zone) ecosystems. These ecosystems contain a broad range of organisms referred to as stygofauna and include communities of macroinvertebrates, vertebrates, meiofauna and bacteria (biofilm). Crustaceans dominate the larger stygofauna. Eastern Australia is recognised as an important area for stygofaunal diversity. The most significant and potentially sensitive groundwater dependent organisms are those that occur in shallow aquifers and cave ecosystems. Of relevance to the Special Areas are the values of stygofauna. Some of the organisms are rare or unique, the ecosystems are amongst the oldest surviving on earth and they add to local and regional biodiversity. In addition, despite their small size, stygofauna are cumulatively powerful in maintaining water quality - in alluvial aquifers they clean the water flowing through the sediments, and their burrowing and feeding keep flow pathways open.

The subsurface phreatic ecosystems that lie within unconsolidated alluvium (associated with rivers), fractured rock aquifers and porous sedimentary rock (such as sandstone), harbour a dynamic and diverse range of invertebrate communities that are composed of many major taxonomic groups found in the surface water habitats. There is a marked bias towards the crustacean and oligochaete groups.

Baseflow stream ecosystems include a combination of subsurface and surface ecosystems depending on the structure of the river bed sediments. Baseflow GDEs occur in both intermittent and permanent flowing streams and the stream and the aquifer are considered to be connected if there is no zone of unsaturated material between them. Under these conditions the surface water body can be affected by changes in the water table level and/or the groundwater level in the aquifer.

## **Surface Groundwater Dependent Ecosystems**

The surface (above ground) ecosystems include groundwater dependent wetlands<sup>6</sup> (such as upland swamps), baseflow streams (surface water ecosystems), estuarine and near shore marine ecosystems and phreatophytes (groundwater dependent terrestrial ecosystems such as the Broad Vegetation Group – ‘Sandstone Gully Forests’).

If groundwater is essential to the biota of a wetland and their ecological processes, then that wetland is groundwater dependent. In baseflow streams the groundwater and surface water cross an ecotone boundary and supports surface and subsurface riverine ecosystems by providing a permanent water source as either surface flow, flow within the sub-surface, or permanent pools

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<sup>4</sup> Baseflow streams (*sensu* Serov *et al* 2012) are considered to be supported entirely by groundwater discharge; that is, they are referred to as ‘gaining’ streams.

<sup>5</sup> Hyporheic zone is a region beneath and alongside a stream bed where there is a mixing of groundwater and surface water

<sup>6</sup> Groundwater dependent wetlands, in the context of the GDE, have been defined as land permanently or temporarily under water or waterlogged with a known or likely component of groundwater discharge in their hydrologic cycle (Serov *et al* 2012)



that provide refuge in time of low flow. Groundwater dependent terrestrial ecosystems do not rely on the surface expression of water to survive, instead, depend on the subsurface presence of groundwater.

Stygofauna are highly specialised, highly endemic and often ancient invertebrates that occupy shallow and deep aquifers and these habitats are being recognised as biodiversity hotspots (Hose, 2009 and Serov, 2013). Despite their small size, stygofauna are cumulatively powerful in maintaining water quality and quantity. In alluvial aquifers they clean the water flowing through the sediments and their burrowing and feeding keep flow paths open. Most stygofauna are crustaceans, animals well adapted to burrowing and living in coarse sediments and many species are found to be unique to a single aquifer (*ibid.*). As there is no light for photosynthesis, bacteria and fungi provide the base food source and as food is limited, stygofauna have slow metabolisms, low reproductive rates and life-spans two to three times those of similar surface dwellers (*ibid.*).

### 3.8.6 Upland Swamps

As described in Section 3.6.4, four types of upland swamps occur within the Special Areas. They bridge both the terrestrial and aquatic environments. While they comprise terrestrial vegetation and are home to many terrestrial faunal species, many upland swamps provide critical habitat for biota that are wholly, partially or opportunistically groundwater dependent. Upland swamps not located within drainage lines and more characteristically described as valley-side swamps are included in this section.

#### 3.8.6.1 Swamp Genesis and Evolutionary Processes

The morphological and functional characteristics of swamps and streams in the Special Areas are influenced by a number of variables with varying degrees of dependence. In the upper catchment areas where swamps and un-channelised valleys are located, the most dominant independent variables on erosional processes and hydrology are time (as in time-span), initial relief, geology (lithology and structure) and climate. The variables that act on landforms and hydrology in the upper catchment areas generally determine the nature of channel morphology and sedimentary processes further down the catchment (Schumm, 1977).

In turn, as time passes, vegetation composition and structure, are dependent on lithology/substrate and climate, which further influence other independent variables such as hydrology (e.g. discharge, water retention, runoff), sedimentation and soil formation processes, hydro-chemical processes, as well as hillslope, channel and valley morphology.

With a relatively high degree of variation in relief and hydrogeology in the Special Areas, a pronounced east-west rainfall gradient and the varying erosional and depositional sequences on slopes and in valleys, it is not surprising that there is a high degree of variation in aquatic/semi-aquatic systems. Recognising this variation and how it operates over different time and space scales is fundamental to understanding ecosystem function, resilience and thresholds,

In addition to these environmental variables, the Special Areas are subject to human-induced influences occurring to varying degrees both within and outside the area, Most notable of these are mine related impacts, infrastructure development, climate change and fire.

The Late Pleistocene-Holocene period appears to be the time of swamp genesis in the Woronora Plateau and montane regions of South East Australia (Young, 1986a; Dodson, 1987; Kershaw *et al.*, 1991; Tomkins and Humphreys, 2006; Fryirs *et al.*, 2014a; Fryirs *et al.*, 2014b and Hope and Nanson, 2015). Kershaw (1991), from studies in the Southern Tablelands, and Dodson (1987), from studies in the Barrington Tops, NSW, have determined the change from a cold and arid glacial



environment to one much warmer and wetter influenced sediment release and accumulation, vegetation community structure and type, precipitation rates and peat accumulation. Kershaw (1991) believes that superimposed on the climatic cyclic variation were additional environmental influences affecting sedimentation and vegetation, in particular, increased fire incidence from burning by Aborigines. Evidence from upland swamps on the Woronora Plateau indicate these systems are less sensitive to peri-glacial climate change, due to the absence of substantial climatic change in the these lower elevation areas during at least the past 11,000 years Young (1986a) and Young (1986b) suggest they are just relics of past periglacial climates.

Abundant annual rainfall (1,600 - 1,300 mm) generates substantial surface water flows and groundwater seepage into the depressions, maintaining a water table perched above the low permeable sandstone bedrock. The flow of water and the sediment it carries into these depressions over thousands of years have led to the accumulation of infertile sandy peats and blackened sandy loams several metres deep (Young, 1986a).

Sediment accumulation is a distinctive feature of peat forming systems (Cowley *et al.*, 2016). Biotic processes such as organic matter accumulation within the sediment matrix, are fundamental to the water and carbon storage functions that are distinctive features of these peat forming systems (*ibid.*). Natural controls that aid aggradation relate to catchment characteristics. These include valley constrictions and terminating rock bars, that allow large volumes of sediment to accumulate behind them, and gentle valley slopes (Fryirs, 2002) and vegetation (Prosser and Slade, 1994, Brierley *et al.*, 1999 and Zierholz *et al.*, 2001). In concert with aggradation are decreases in stream power<sup>7</sup> and an increased density of vegetation (increasing hydraulic roughness) – all factors favouring positive feedback mechanisms that perpetuate deposition (Bull, 1997).

Many upland swamps have evolved, over millennia, following sequences of aggradation and degradation of valley material (Brierley and Fryirs, 1999; Brierley and Fryirs, 2000; Tomkins and Humphreys, 2006). Fryirs and Brierley (1998b) have collectively referred to these systems as 'cut-and-fill landscapes'; meaning their evolution is characterised by geomorphic processes of sediment accumulation over long periods of time (fill) and valley incision of sediment release (cut) over relatively short periods of time.

Factors that initiate a naturally eroding state include internal threshold boundaries (Page and Carden 1998, Tomkins and Humphreys 2006); intrinsic controls (Fryirs and Brierley 1998a); extremes of climatic events (Warner 1995) and fire, especially when followed by intense rainfall (Tomkins and Humphreys 2006). Bull (1997) surmises that initiation of degradation may be too complex to be attributed to a single cause.

### 3.8.6.2 Distribution

Virtually all the upland swamps in the Special Areas lie on the Hawkesbury Sandstone where vertical drainage is impeded by the sandstone with flow along horizontal bedding planes and are restricted to the headwaters of creeks on coastal sandstone plateau up to 600 m in elevation (Young, 1982). In upland valleys, low permeability sandstone perches water for the development of swampy conditions.

### 3.8.6.3 Vegetative Characteristics

The upland swamps in the Special Areas are landform features that are readily distinguished from the surrounding sandstone woodlands and forests by the structure of the vegetation. By

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<sup>7</sup> Rate of energy dissipation against the bed and bank of a stream per unit downstream length



comparison the headwater creeks, valley-side seeps and higher order valleys are generally treeless heaths and sedgeland (Keith and Myerscough, 1993 and NPWS, 2003).

Most vegetation studies of upland swamps have reported spatial heterogeneity in floristic composition and structure (Keith and Myerscough, 1993 and Keith, 2004). A number of distinctive vegetation communities that comprise the Upland Swamps Complex have been described by NPWS (2003) for the Woronora, O'Hares and Metropolitan Catchments and include the 'Tea Tree Thicket', 'Banksia Thicket and the Sedgeland-heath Complex' (Sedgeland, Restioid Heath, Cyperoid Heath), as well as the 'Fringing Eucalypt Woodland' and 'Mallee-Heath'.

On the Woronora Plateau, soil profile development varies considerably in relation to waterlogging (Young 1986a) and initial observations by Keith and Myerscough (1993) suggest that this variability in soil and drainage characteristics relates to patterns in swamp vegetation. It is likely that variation in soils corresponds to a resource gradient of moisture and nutrients with the abundance and availability of mineral ions in the soil influenced indirectly by waterlogging, consequent anaerobic conditions and inhibited microorganism activity (Keith and Myerscough 1993).

In view of these variables, Keith and Myerscough (1993) have shown that Cyperoid Heath, for example, is widespread on relatively deep organic sands in wet areas surrounding drainage lines of large swamps and the wettest parts of smaller swamps. The community is also characterised by a dense stratum dominated by large cyperaceous sedges, with occasionally emergent spreading shrubs. On the other hand, Keith and Myerscough describe sedgeland as being restricted to local seepage zones on shallow soils around the margins of larger swamps and on sandstone benches perched on the sides of gullies. It has no spreading shrubs, but is instead dominated by a continuous stratum of small restionaceous and cyperaceous sedges. Further, Restioid Heath is a widespread wet heath community occurring where drainage is moderately impeded and on relatively drier sites than the preceding communities. It has an open stratum of short spreading shrubs interspersed with short slender shrubs, forbs and small sedges. Finally, Banksia Thicket occurs patchily around the periphery of large swamps on damp soils and is characterised by a tall dense shrub stratum.

In general, levels of soil nutrients are highest in Tea Tree, intermediate in Cyperoid Heath and Banksia Thicket and lowest in Sedgeland and Restioid Heath. This trend corresponds almost exactly with the toposequence<sup>8</sup> of those communities. High nutrient status may be explained by a large input of nutrient ions from runoff and downwash and by the abundance of clay and organic particles which provide a large number of exchange sites for mineral cations. Conversely, Restioid Heath and Sedgeland occupy higher parts of the toposequence where soils are periodically dry, preventing the accumulation of large amounts of peat and their low clay content provide few exchange sites for mineral nutrients which are leached downslope. Banksia Thickets, which occupy the highest parts of swamp sequences, tend to have soils that are drier and sandier, yet they have intermediate levels of total Phosphorous, conductivity and exchangeable cations. The Banksia Thickets also have higher levels of organic matter as a result of a greater rate of litterfall and may also be able to extract nutrients from deeper parts of the soil profile (Keith and Myerscough, 1993).

In relation to fire, Keith and Myerscough (1993) observed that the boundaries delineating Banksia Thicket may shift after fire (some species requiring fire for seed germination) and speculated that fires influence the relative occurrence of upland swamp communities that occur in drier habitats, including Banksia Thicket, Restioid Heath and Sedgeland. Recurring fires are commonplace in

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<sup>8</sup>A sequence of soils in which distinctive soil characteristics are related to topographic situation



contemporary Upland Swamps and there is evidence to suggest that fires were also part of the historic evolutionary history.

#### **3.8.6.4 Threatened and Significant Flora Species Associated with Upland Swamps**

The uplands swamps provide habitat for the threatened *Pultenaea aristata* (Prickly Bush-pea), which is listed as Vulnerable under the TSC Act. It generally occurs on the drier margins of swamps where it is widespread and common in the Woronora Special Area (Bower, 2015 and NSW Scientific Committee, 2016c).

#### **3.8.6.5 Threatened and Significant Fauna Species Associated with Upland Swamps**

Upland swamps, as 'priority fauna habitat', are key habitat for at least 12 priority fauna species, including the threatened Eastern Bristlebird, Beautiful Firetail, Turquoise Parrot, Giant Burrowing Frog, Red-crowned Toadlet and Littlejohn's Tree Frog (DECC, 2007a, c), Rosenberg's Goanna and the Endangered Green and Golden Bell Frog. Of these species, the Giant Burrowing Frog, during its larval stage, is dependent on the swamps for its survival (Baird, 2012). As well they are home to protected and regionally significant fauna species (DECC, 2007b). The upland swamp, Maddens Plain, supports the most extensive swamp system in the Greater Southern Sydney Region and is listed on the Directory of Important Wetlands in Australia (Environment Australia, 2001). The Eastern Ground Parrot, once thought to be locally extinct has been rediscovered within upland swamp landscapes of the Woronora River catchment (Illawarra Coal, 2009 and NSW Scientific Committee, 2016c).

Key obligate, groundwater dependent fauna species/communities include the Giant Dragonfly, the stygofauna and the Freshwater Burrowing Crayfish (*Euastacus australasiensis*). The crayfish may occur in both valley infill swamps and headwater swamps and may be locally abundant in individual swamps.



**Advisian**

WorleyParsons Group



## 4 Subsidence

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### 4.1 General

Subsidence is the term given to the deformation of the ground in response to underground mining. The term has its origins in the word 'subside' meaning to 'go down to a lower level'.

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 (Figure 4.1). The angle was found to vary between coalfields and commonly referred to as the angle of draw.

Prior to 1990 the basis of understanding of subsidence in Australia was predominantly the experience documented in the United Kingdom and to a lesser extent the USA and Europe. An excellent summary of understanding at that time is contained in Whittaker and Reddish (1989) which outlines the basis of almost all subsidence predictions undertaken to this day.

In the early 1990s field experience in Australia found that there were other types of subsidence effects not captured by Whittaker and Reddish (1989). These effects included:

- Significant horizontal movements beyond the angle of draw, commonly termed 'far field effects';
- Inward movement of valley walls, commonly termed 'closure'; and
- A tendency for uplift of the floor of a valley relative to the valley walls, commonly called 'upsidence'.

All of these effects were seen as 'anomalous' to the smooth surface profile predicted by the methods outlined in Whittaker and Reddish (1989). Consequently all of these movements have been incorporated into the standard methods by way of 'correction' and adjustment rather than capturing the combined mechanisms.

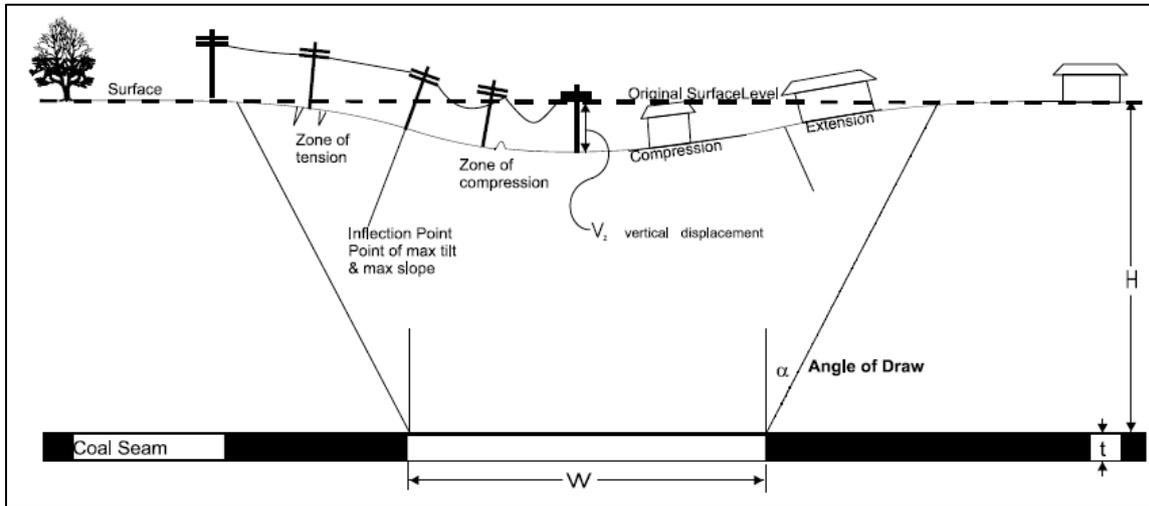
The review provided here is focussed on subsidence as a consequence of large scale voids due to longwall mining at depth (at least 100 m below surface). This type of subsidence is commonly divided into one of two components:

1. **Systematic Subsidence** - also known as conventional or classical subsidence. This describes the expected ground behaviour in the absence of 'anomalous' influences of far field effects, closure or upsidence. It also excludes the influence of any specific geological structure such as faults or dykes.
2. **Non Systematic Subsidence** -also known as non-conventional or site-centric subsidence. This describes the unexpected ground behaviours that cause a deviation from the expected systematic behaviour, i.e. far field movements, closure, upsidence or geological structures.

Further discussion on these subsidence components follows.

### 4.1.1 Systematic Subsidence Theory

The behaviour of a single longwall panel forms the basis for the conventional model of subsidence behaviour. This is typically characterised by a reasonably “smooth” profile at the surface, which extends for some distance beyond the edge of the panel at the surface (Figure 4.1).



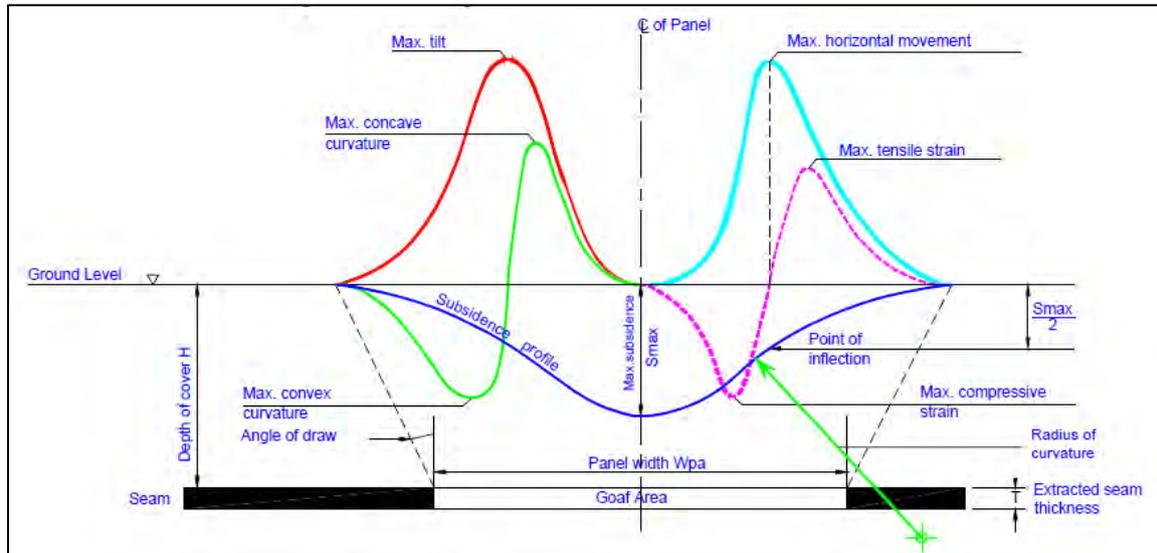
Source: MSEC (2007b)

**Figure 4.1: Typical Shape of Systematic Subsidence Profile from Longwall Mining**

Although originally used to describe vertical movement the term ‘subsidence’ is now more generally used to describe a range of mining induced ground movements. These movements are typically described using a set of parameters which include MSEC (2009):

- **Vertical subsidence (S)**, which is vertical or horizontal movement of a point, usually expressed in mm;
- **Horizontal movement (H)**, which is horizontal movement of a point, usually expressed in mm;
- **Tilt (G)**, which is the change in the slope of the ground surface as a result of differential vertical subsidence, usually expressed in mm/m;
- **Curvature (R)**, which is the rate of change of tilt, and is calculated as the change in tilt between two adjacent points. Curvature is usually expressed in units of 1/km.
- **Strain (E)**, which is calculated as the change in horizontal movement between two points on the ground, divided by the original horizontal distance between them. Strain is typically expressed in units of mm/m, and are termed tensile (positive strain) if the distance between two points increases, or 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 subsidence is 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.

Locations where the maximum and minimum values of the above parameters occur above a mined longwall panel are illustrated in Figure 4.2.



Source: MSEC (2007b)

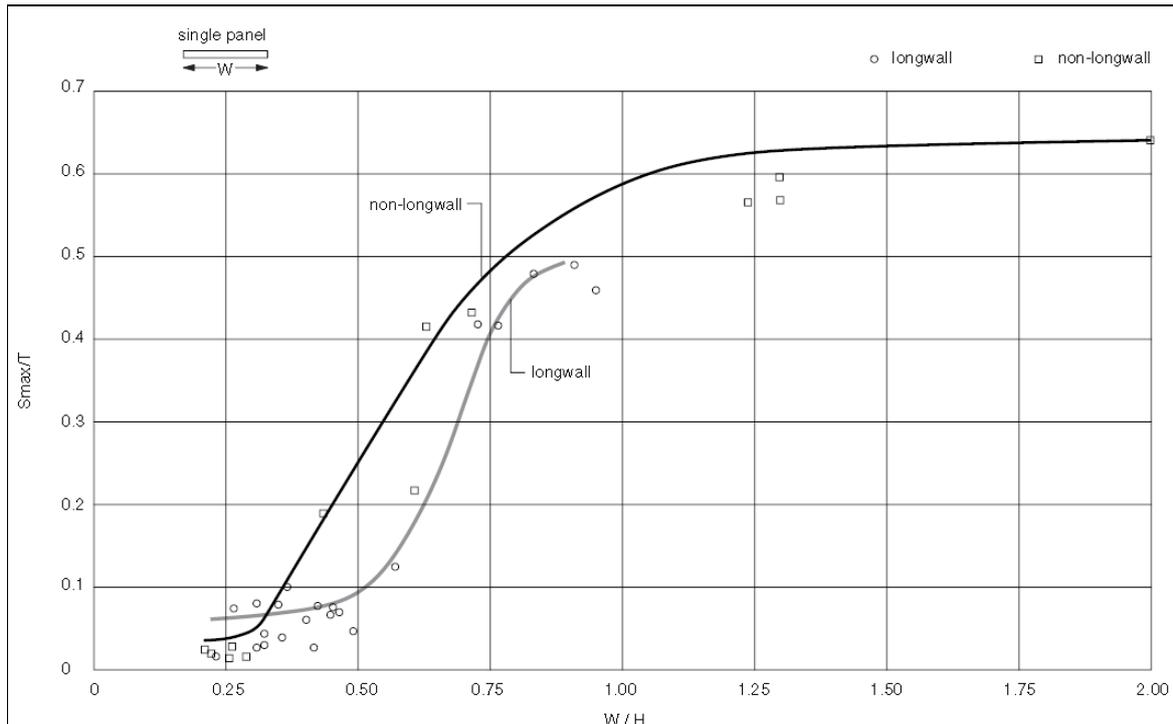
**Figure 4.2: Variation of Parameters which are typically used to describe Systematic Subsidence**

The magnitude and extent of subsidence at the surface due to longwall mining is controlled by panel width, overburden thickness, the extracted coal seam thickness, goaf stiffness, chain pillar width and overburden geology (Holla and Barclay, 2000b).

Figure 4.3 illustrates a commonly adopted comparison to reconcile panel depth of cover ( $H$ ), panel width ( $W$ ) and seam thickness ( $T$ ) with the maximum vertical subsidence ( $S_{max}$ ). This empirical comparison shows how panel width may affect subsidence above a single longwall panel. From this figure it is evident that wider panels and shallower depths of cover may result in more significant subsidence at the surface. The same can also be said for extraction of thicker seams.

It must be noted that the maximum value of subsidence above an extracted longwall panel is typically less than the extracted thickness, due to bulking of the caved material. According to SCA (2013), the maximum possible subsidence value is often considered to be approximately 0.6 times the extracted seam height as shown in Figure 4.3, although values as high as 0.8 have been reported in Australia and elsewhere. For example, a value of around 0.7 was recently reported for Dendrobium in MSEC (2016).

The largest possible subsidence will be recorded for a particular panel if the width exceeds the critical width. Such a panel is said to super-critical. Panels narrower than the critical width are said to be sub-critical, and will develop a maximum subsidence which is less than that subsidence for critical and super critical panels. Because the subsidence will reduce as the width of sub-critical panels is reduced, minimising panel width is a commonly employed method for minimising surface subsidence.



Source: Holla and Barclay (2000b); SCA (2013)

**Figure 4.3: Influence of panel width and depth on surface subsidence**

## 4.1.2 Non-Systematic Subsidence Theory

According to NSW DoP (2008), systematic subsidence theory is based on the assumption that:

- the surface topography is relatively flat;
- the rockmass is uniform with no influence from large scale structures;
- the surrounding rock mass does not contain any extremely strong or extremely weak strata.

NSW DoP (2008) and Holla and Barclay (2000b) suggest that the following items are common factors that result in non-systematic subsidence, this being deviations from the smooth profiles expected from systematic subsidence:

- Valleys and gorges may alter the in-situ stress regime and cause bulging, cracking and shearing in the valley floors, downslope movement of the walls, and tensile cracking/opening of joints in the valley walls;
- Massive overburden may sag and span tens to hundreds of metres without failing, causing increased abutment/gate road compression. Massive strata may also cave sporadically rather than regularly to produce vertical steps in the subsidence profile. Surface uplift of the order of tens of millimetres can also occur around the edges of excavations due to rotation of thick beds over the goaf;
- Gate road foundation settlement or failure may occur due to various mechanisms. Gate road system failure may take a considerable period of time to develop, especially where it is associated with 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. This behaviour is mainly confined to bord and pillar based systems;
- 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.



The term 'non-systematic' is used here to simply reflect movements that are not readily categorised as systematic. The term non-conventional is commonly used in place of non-systematic by some researchers such as Kay and Waddington (2014). Galvin (2016) considers that non-systematic or non-conventional movements are, in fact, predictable and should be termed site-centric subsidence behaviour to reflect that these are localised effects.

MSEC (2007a) comments that by far the greatest number of irregularities (non-systematic or site-centric behaviour) in subsidence profiles 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 the reduced subsidence or the relative uplift within a valley compared to conventional subsidence behaviour. Upsidence is a result of anticlinal bulge beneath the valley, which spreads out on each side of the valley 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 slumping of unconsolidated deposits.
- **Compressive strains**, which occur at the base of valleys as a result of valley closure and the buckling or shearing of the near surface strata.
- **Tensile strains**, which occur in the crests of the valleys as the result of valley closure movements.

The study of non-systematic subsidence in valleys and gorges has been discussed by numerous authors including ACARP (2001), ACARP (2002), Mills (2007), MSEC (2007a), MSEC (2008b) and Kay *et al.* (2011). Factors which influence valley related movements are noted to include:

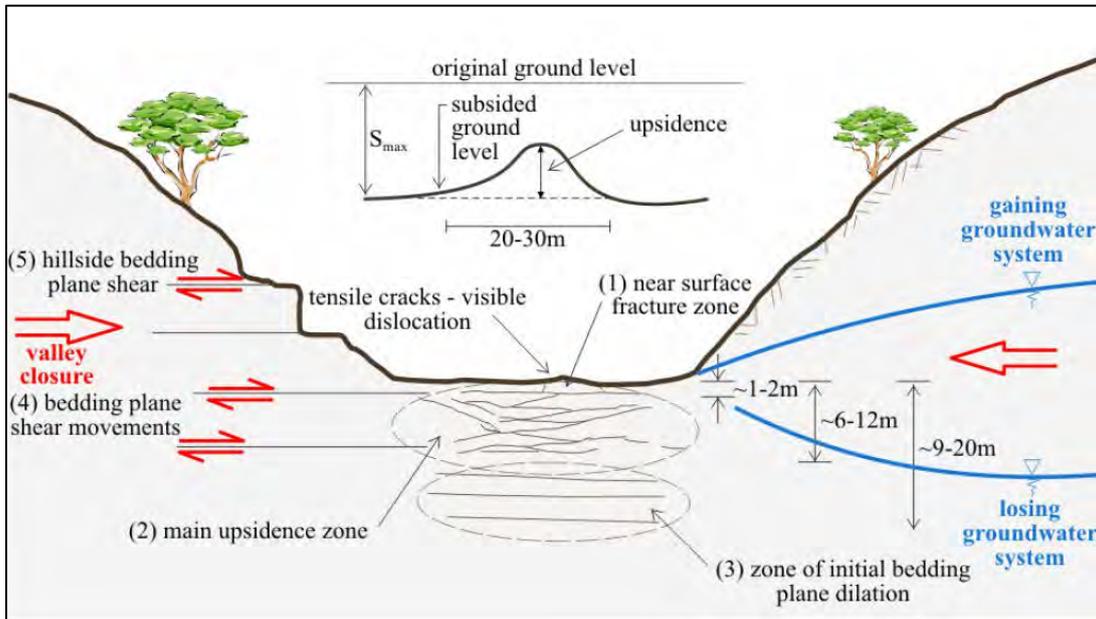
- The in-situ horizontal stress which may increase or decrease bulging or shear of overlying relatively unconfined strata, as undermining changes stress.
- Unfavourable geological conditions in the floor, particularly weak or thinly bedded shale layers, faults, cross bedded strata, or unfavourable joint orientations which strike between 30° and 60° to the strike of the valley.
- Deeper valley depths and wider valley widths.
- Three-dimensional effects, such as deviations in river valleys which create laterally unconfined "headlands" within the valley.

Typical effects in valleys floors due to undermining are shown in Figure 4.4 and include:

- Upsidence near the centre of the valley as a result of valley bulging and buckling. Although the valley floor is often in compression, upsidence often manifests as a tension cracks which forms on the upper side of the buckling slab.
- The formation of low angle conjugate shears and dilated bedding planes beneath the valley floor which may increase storativity and permeability. This zone is often reported as extending to a depth of approximately 15 m, and has been studied in depth by ACARP (2009).
- Shearing along bedding planes extending back into the valley walls, with the largest shear deformations said to typically occur near to the base of the gorge. The mechanisms for bedding shears, due to stress redistribution in valley walls, are shown in Figure 4.5.

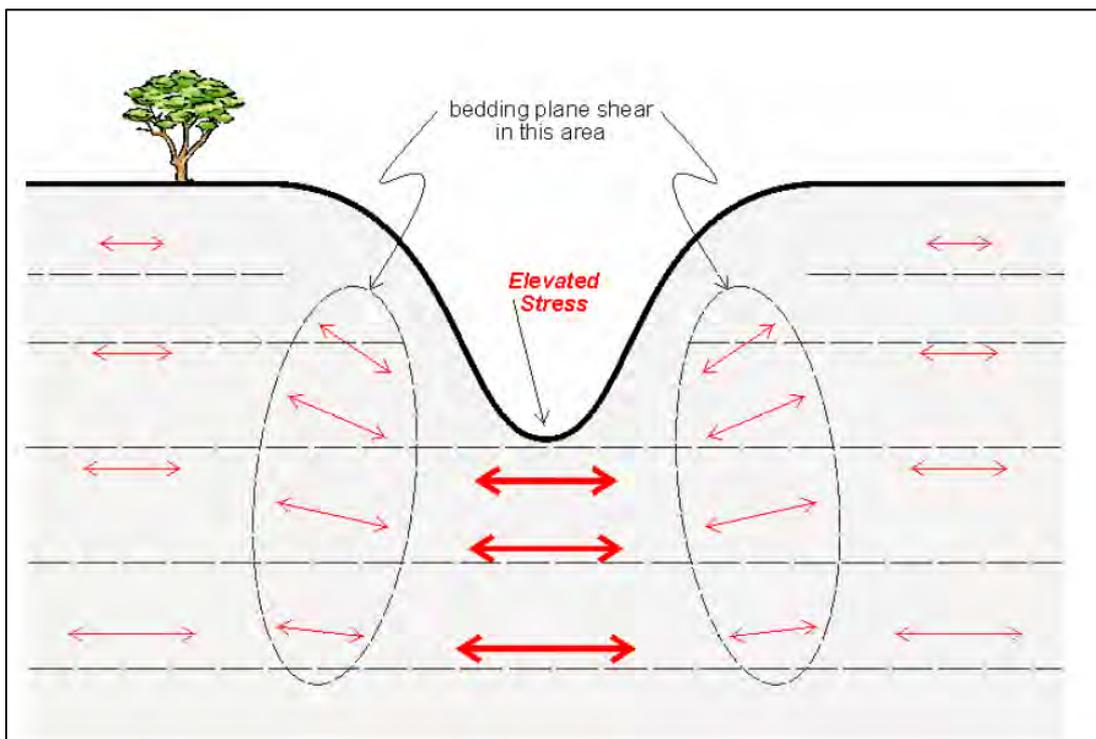


- McNally and Evans (2007) suggests that valley closure and upsidence is thought to be particularly active in the Southern Coalfield of NSW as a consequence of the plateau and gorge terrain, the extent of total-extraction mining and the high horizontal stresses within the bedrock mass.



Source: Mills (2007)

**Figure 4.4: Typical Non-Systematic Subsidence Effects in Valleys Floors due to Undermining**



Source: ACARP (2009)

**Figure 4.5: Locations of Bedding Shears in Valley Sides to Redistribution of Horizontal Stress beneath the Valley**



## 4.1.3 Far-Field Subsidence

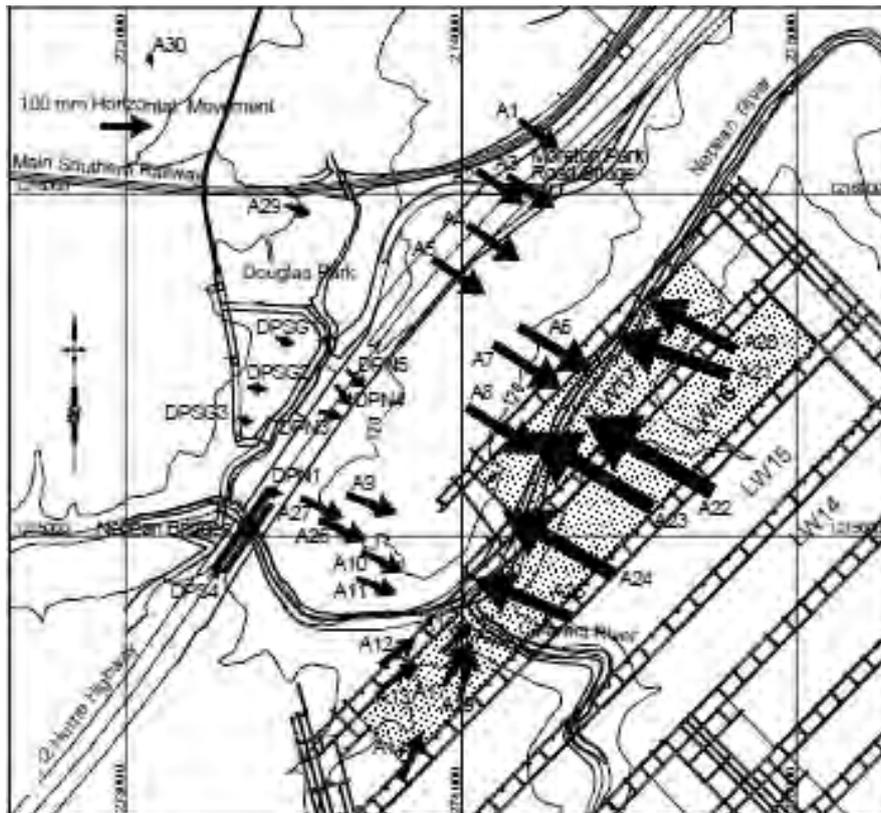
NSW DoP (2008) reports that far-field horizontal surface displacements have been detected in the Southern Coalfield for up to several kilometres from the limits of mining. These regional-scale movements are generally greatest at the goaf edge and decrease with increasing distance from the goaf. Although this behaviour is not fully understood by subsidence engineers, NSW DoP (2008) lists a range of possible causes of valley closure, upsidence and far-field horizontal movements which 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.

An empirical database of observed incremental far-field horizontal movements is shown in MSEC (2009). This data shows that far-field displacement of up to 20 mm have been observed at distances of 2,000 m from extracted longwalls. It is said that such movements tend to be bodily movements towards the extracted goaf area and are accompanied by very low levels of strain, which are generally less than 0.1 mm/m. Similar observations were reported by IESC (2014b) which notes that the effects of far-field horizontal displacements may extend for some kilometres from the edge of a longwall mining area but are of low magnitude.

Hebblewhite (2001) discusses far-field horizontal displacements that were measured at the Hume Highway during mining of adjacent longwall panels at the Tower Colliery (Figure 4.6). Both panels were approximately 450 m deep and their orientation was parallel to the highway.

Total horizontal displacements during mining of two panels were measured to be ~135 mm at the highway, which was located at a distance of 450 and 650 m from the longwalls. The effective angles of draw from the goaf edges to the highway were 45° and 56°, and significantly higher than the typically adopted 26.5°. It was thought that valley effects combined with shearing of a large rigid block along a bedding shear may have caused these large displacements at the highway.



Source: Hebblewhite (2001)

**Figure 4.6: Far Field Horizontal Movements at the Hume Highway due to Mining at the Tower Colliery**

Other cases of far-field subsidence are reported by ACARP (2001) and ACARP (2002). At Stanwell Park, it was reported that underground mining caused cracking of a viaduct that was 130 m from the Goaf edge of a 144 m deep longwall panel (providing an effective angle of draw of 42°). At least two of the piers of the viaduct were said to be constructed on a severely jointed and faulted rock zone.

Instances of significant far-field horizontal displacements are reported by IESC (2014b) at Ulan in the Western Coalfield, where horizontal displacements were 20 mm at distance of 1.8 km from an extracted longwall panel, and at a mine in the Southern Coalfield, where horizontal displacements decrease linearly from 100 mm at the goaf edge to zero at a distance of 1.5 km away.

## 4.2 Subsidence Prediction Methods

Methods for predicting subsidence essentially fall into two categories:

- Empirical methods, whereby observations of previous subsidence events are correlated with key parameters such as geometry, site geology and other factors. These methods typically only predict the surface shape and are consequently called profile methods.
- Mechanistic methods, which involve consideration of loss of volume, stress change and induced strains.

More information on prediction methods and shortcomings of the empirical profile method in particular are described in Swarbrick *et al.* (2014). Extracts from this publication are provided below.



## 4.2.1 Empirical Prediction Methods

Empirical profile methods are currently the most widely used predictive methods due to their proven performance over the last 100 years or so. Empirical profile method milestones include the early theories of the 1880s in Europe, the development of the 'angle of draw' concept in the 1950s and the examination of survey of over 100 collieries by the National Coal Board of the UK in the 1960s and 1970s (NCB, 1975).

Modern empirical profile methods essentially comprise dimensionless relationships that estimate maximum subsidence and the subsidence profile as functions of panel width, panel depth, pillar width and seam thickness. These relationships are essentially a series of design curves based on profile measurements. Once the profile has been predicted tilt is derived as the change in subsidence with horizontal distance. Strains are not directly derived from the subsidence profile but commonly estimated from curvature, this being the rate of change of tilt with horizontal distance. A common conversion factor for the Southern Coalfield is curvature in 1/km multiplied by a constant (typically 10 to 20) gives an estimate of strain in mm/m.

As additional longwalls are excavated adjacent to each other there is generally an increase in subsidence above adjacent areas that have already been extracted. This effect is common in many forms of ground interaction with the magnitude of interaction usually in proportion to the proximity of the disturbance. It was recognised by Waddington and Kay (1995) that these interactions could be represented as the superposition of incremental effects. Waddington and Kay (1995) found that the empirical prediction of separate incremental effects was more reliable than empirical predictions of the combined effects. This approach is termed the incremental profile method and the Waddington and Kay (1995) method is currently recognised as one of the most accurate in Australia.

Other profile methods commonly used in Australia are that described by NCB (1975), Holla and Barclay (2000b) and the Surface Deformation Prediction Software System (SDPS) prediction software described by Newman *et al.* (2001).

## 4.2.2 Mechanical Prediction Methods

The most common mechanical prediction methods are:

- **Finite Element Methods (FEM)** whereby the entire rockmass is represented by a continuum of interconnected regions (or elements) that deform in accordance with prescribed stress-strain laws.
- **Boundary Element Methods (BEM)** whereby the rockmass and void boundary is represented by a linear array of stress – strain elements which describe an infinite field of material extending outwards from the element.
- **Finite Difference Methods (FDM)** this being similar to FEM but the elements are simplified linear representations of stress and strain and elemental forces are solved explicitly for flexibility and speed.
- **Discrete Element Methods (DEM)** whereby the rockmass is represented as a series of deformable 'blocks' connected to each other by deformable 'joints' or connecting interfaces each controlled by separate stress-strain laws.
- **Discrete Particle Methods (DPM)** whereby the rockmass is represented as an interconnected mass of particles, generally of varying size and properties designed to replicate the intact mass and defects.



Examples of mechanistic methods as applied to subsidence prediction include:

- FEM – Siriwardane and Amanat (1984), Kay *et al.* (1991), Singh *et al.* (1986), Pells (2011) and Yao *et al.* (1993) using a range of different FEM software packages.
- BEM – Kay *et al.* (1991) included two BEM methods based on the Displacement Discontinuity Method. Other BEM models include the laminated model as described by Salamon (1991) and Heasley and Barton (1998).
- FDM – Kay *et al.* (1991), Alejano *et al.* (1999), Gale (2005), Unver and Yasitli (2006), Shahriar *et al.* (2006) and Sainsbury *et al.* (2010) using the software package FLAC by Itasca (2D and 3D).
- DEM – Kay *et al.* (1991) and Keilich *et al.* (2006) who all used the software package UDEC by Itasca and O'Connor and Dowding (1992) who used a hybrid form of DEM called NURBM, designed to overcome some UDEC limitations.
- DPM – Zhao and Jin-an (2011) using the software package PFC by Itasca.

An example of mechanistic numerical modelling as applied to the Southern Coalfield can be found in Keilich (2009).

Mechanistic models are largely confined to research applications or applied to localised conditions that are not adequately captured by empirical, observational methods. This is largely due to the time and effort required to set up the model geometry, input parameters and to calibrate to observed behaviour.

## 4.3 Effects of Subsidence on Hydrogeological Conditions

### 4.3.1 Fracturing above Longwalls

Removal of coal by longwall mining creates a void resulting in strata deformation, fracturing and subsidence of the overburden as the rocks move downward towards the void. The collapse of the immediate roof and sagging of the overburden causes separation and opening of existing fractures, joints and bedding planes and formation of new fractures in the overburden and at the surface. As the immediate roof strata collapses into the goaf, the rocks above it lose support and sag to fill the void. As the excavation is widened, the roof has to cave to a greater height in order to dome out and arrest the fall (Figure 4.3). If caving does not propagate to the surface, the overlying strata may still sag downwards to cause shearing and dilation of bedding planes.

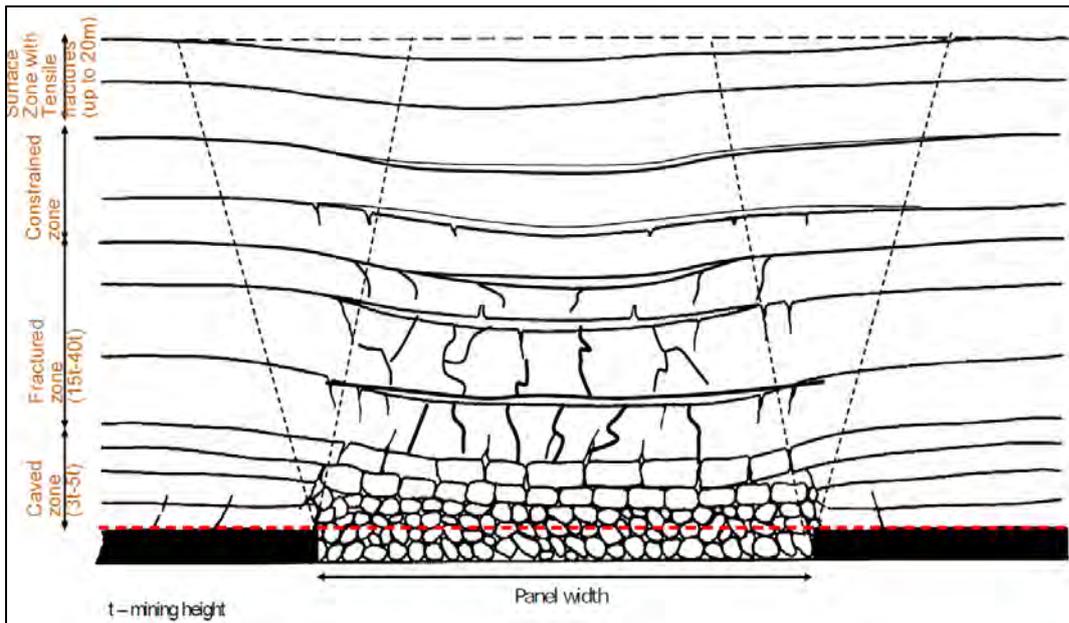
A commonly adopted approach to characterising the fractured rockmass above an extracted longwall panel is to divide the rockmass into conceptual zones and assume that each zone has a different degree and type of fracturing as a result of subsidence. Detailed reviews of various models have been presented by Singh and Kendorski (1981), Forster and Enever (1992), ACARP (2001), ACARP (2002), Kendorski (2006), ACARP (2007), MSEC (2009), IESC (2014b), Parsons Brinkerhoff (2015) and Galvin (2016) (illustrated in Figure 4.7). The naming and numbering of zones varies for different models. However, it appears that four zones from the mined seam upwards are commonly recognised in these models. These include:

- **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 the 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 discontinuous vertical cracks (usually 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.



Source: ACARP (2007)

**Figure 4.7: Typical Zonation of Strata above an Extracted Longwall Panel**

The extent of our understanding of these zones and the mechanisms within them is limited by our ability to quantify these effects. Common methods such as extensometers only interpret vertical deformations at discrete points. Piezometers provide a measure of the consequences of these on water pressure changes and not of the type and magnitude of change. Additionally, instruments become lost due to cable damage or other subsidence effects. This makes interpretation of the severity of the impact uncertain.

More recently there has been a focus on height of fracturing (HoF) as a measure of these impacts. HoF is primarily assessed from direct measurement of impacts. The most common means of assessing HoF data is predominantly from extensometer measurements but has also been inferred from pore pressure response.

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 from conceptual models of the lateral extent of impacts. To date the existing methods for predicting HoF are typically empirical and based on observations and approximations. NSW Department of Planning (DoP) (2008) notes that the following geological conditions may affect the height of connective fracturing (as defined below):



- Highly-laminated strata tend to fall like a deck of cards and so have a low bulking factor, resulting in the caved zone extending to a considerable height;
- Falls comprising blocky material, such as sandstone, tend to bulk up and choke off quickly;
- Caving may be arrested by the presence of a competent bed in the roof.

Further details on geological factors which influence caving behaviour can be found in Appendix C of IESC (2014b).

In areas nearer the zone of extraction, such as the caved zone, both vertical and horizontal cracking is thought to be substantial and therefore significant increases in vertical and horizontal permeability are expected, as well as increases in porosity. However it is suggested by ACARP (2008) and others that higher within the profile there may be limited vertical connectivity within the fractured or constrained zone which is argued to result in little to no increase in vertical permeability and therefore vertical fluid flow even though increases in horizontal permeability may be substantial. This observation has prompted the use of the term Height of Connected Fracturing (HoCF) by some researchers to differentiate between fracturing that is vertically connected and hence has an increase in vertical permeability. This is different to HoF which includes regions nearer the surface where vertical fractures may form but may not be connected and therefore vertical permeability is relatively unchanged.

Extensometer and piezometer measurements are common approaches to inferring HoF and HoCF however both methods are limited. Extensometers provide some information on vertical deformations at discrete points. However they also respond to anchor slippage and other deformations such as horizontal movement. Therefore they should be regarded as only providing an indirect measurement of HoF. They do not provide direct information of HoCF. 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 HoCF as depressurisation may be the result of increased horizontal permeability alone.

ACARP (2008) reports that vertical fracture connectivity is greater in stiff sandstone rich strata relative to strata containing many coal and tuffaceous units. This was related to the ability of the overburden to flex and displace onto the goaf rather than fracture and rotate about the ribsides. ACARP (2008) also adds that clay may have the effect of constraining the fracture network either due to the fact that it can strain without fracturing or it is able to heal fractures by expansion of the clay. The nature of this is likely to be site specific and dependent on the clay material. It is also suggested by ACARP (2002) that if the strata includes a number of claystone layers, it is possible that these may swell on contact with water and may self-heal any fractures that might be caused by mine subsidence. However, SCA (2013) reports that the self-healing properties of claystone are not well understood, and will be limited if the dominant clay mineral is kaolinite such as the Bald Hill Claystone unit (David, 2015). Additionally, it is reported the ability to self-healing is probably limited by the aperture of the fractures.

ACARP (2008) suggests that caving and cracked beam subsidence movements tend to occur up to a height of 1-1.7 times the panel width. Many authors including Forster (1995), ACARP (2003), ACARP (2007), Tammetta (2013) and Ditton and Merrick (2014) have proposed various relationships which related the height of fracturing in Australian longwall mines to various geometric and/or geological factors. The derivation of these models are summarised in Table 4.1. In a study reported by Parsons Brinkerhoff (2015) it was shown that predicted caving heights varied widely over a Dendrobium longwall for the different methods, ranging from 122 m up to 357 m (Figure 4.8). Based on this study Parsons Brinkerhoff (2015) made the following conclusions:



- Boundaries between zones of disturbance are both gradational and controlled by overburden geology, such that vertical strain can be greater in bedded claystone units. It may be appropriate to factor in partitioning of strain (and horizontal permeability increase) in some cases.
- Estimates of heights of fracturing can vary widely depending on the estimation method used and the field evidence used to support or calibrate it. It is important to select a method that is suited to the geological environment.
- Currently, regional numerical groundwater modelling requires vertical discretisation of the overburden into a number of layers with distinct pre- and post-mining hydraulic parameters. If parameters are used to simulate hydrogeological impacts (as opposed to using boundary conditions such as drains), then the parameters need to be distributed in accordance with the estimated heights of fracturing zones and the estimated increases in permeability and storage.

As noted earlier, the most common methods for estimating height of fracturing are by extensometer and from interpretation of piezometer data. Extensometers, however, are designed to only measure vertical strain and this is averaged between anchor points. Horizontal movement can also be detected by extensometers but must be inferred as being vertical due to the design of the instrument. Piezometer data will potentially detect change in permeability that could be due to either vertical or horizontal separation. However the extent to which this occurs is limited by interpolation between discrete measurement points in the case of vibrating wire piezometers, or the averaged pressure change over the screen of a standpipe piezometer.

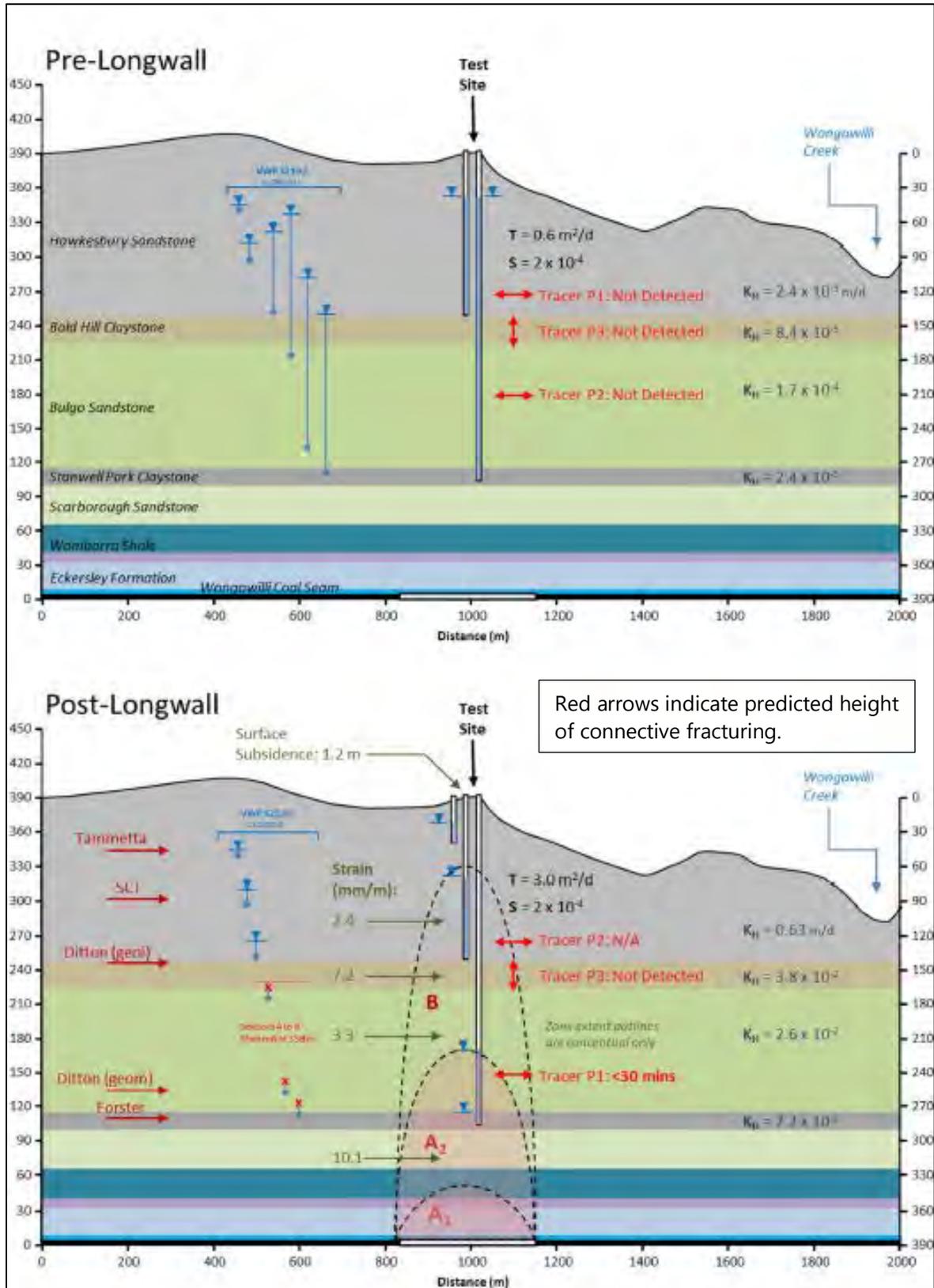
**Table 4.1: Summary of Models Developed in Australia for Predicting Height of Fracturing above Longwall Panels**

Study	Scope	Main Conclusions <sup>1</sup>
ACARP (2007)	Study focused on the Central Coalfield of NSW. Reviewed previous studies, examined the mechanics of strata deformation above longwalls and developed an estimate for fracture zone height with respect to mined seam thickness.	Constrained zone: variable Fracture zone: to ~33 T Caved zone: to ~10 T
Mills (2011)	An ACARP report, field and modelling study focused on the Springvale Colliery. The study reviewed field responses in deformation, pore pressure and permeability due to longwall mining. Carried out 3D coupled numerical models using COSFLOW.	Surface zone: ~20 - 30 m below ground level (mbgl): <1 mm/m vertical strain; increase in hydraulic conductivity (K) from x 5 to 30. Constrained zone: ~75 T; <3 mm/m vertical strain; increase in K from x 3 to x 10. Fractured zone: ~33 T; >10 mm/m vertical strain; increase in K from x 20 to x 1000 Caved zone: ~10 T; >30 mm/m vertical strain; increase in K from x 1,000 to x 2,000.
Tammetta (2013)	Provides overview of surface and subsurface monitoring of longwalls, and summarises the characteristic styles of ground movement as a result of mining.	Broadly define heights of disturbance zones 1 to 6 (which broadly correspond to zones A to D (defined in Figure 4.7 above) in terms of multiples of panel width (W): Zone 5 (no disturbance): >3W Zone 4 (vertical relaxation): 1.6W to 3W Zone 3 (vertical dilation): 1.0W to 1.6W Zone 2 (large movement): to 1W Zone 1 (caved): to 20 m above seam



Study	Scope	Main Conclusions <sup>1</sup>
Ditton and Merrick (2014)	Developed an empirical formula to estimate the <b>height of desaturation</b> (HoD) as a result of connective fracturing, based on data from 33 locations worldwide. H is defined as the height below which there is complete groundwater drainage as indicated by pressure head reducing to zero in a short period after undermining.	For ordinary locations: <b>HoD = 1438 ln (4.315 x 10<sup>-5</sup>U + 0.9818) +26</b> <b>U = WT<sup>0.4</sup>H<sup>0.2</sup></b> Where U is a variable based on the panel geometry, W = panel width; T = mined thickness; H = cover depth
ACARP (2007)	Developed analytical models to predict heights of fracture zone based on both panel geometry and geology.	Developed two predictive analytical models: Geometry model: <b>A = 2.215 W<sup>0.357</sup> H<sup>0.271</sup></b> <sup>0.372</sup> Geology model: <b>A = 1.52 W<sup>0.4</sup> H<sup>0.535</sup> T<sup>0.464</sup> t<sup>0.4</sup></b> Where W, H, T are variables related to the panel geometry and t' is related to overburden (strata unit thickness). Zone A-B strain threshold – 8 mm/m.

Source: Parsons Brinkerhoff (2015)



Source: Parsons Brinkerhoff (2015)

**Figure 4.8: Model for Pre-Mining and Post-Mining Sub-Surface Fracturing at Dendrobium**



Examples of sub surface deformation monitoring have been reported by Holla and Armstrong (1986), Holla and Barclay (2000b), ACARP (2003), ACARP (2007), ACARP (2008) and Parsons Brinkerhoff (2015). A common approach to characterising the fracturing and disturbance in each zone is convert measured displacements into strain values. Typical vertical strain values for different zones reported by Ditton and Merrick (2014) are summarised in Table 4.2, showing that vertical strains tend to decrease for greater heights above the extracted panel. The proposed strain values from Ditton and Merrick (2014) appear to be reasonably consistent with the results from Parsons Brinkerhoff (2015) as shown in Figure 4.8, but higher than the vertical strains reported by ACARP (2007), where a strain of 1% is reported for the fractured zone. Often these vertical strain values are used to characterise a hydrogeological response, as is detailed in the following sections.

ACARP (2008) concluded that the frequency, networking and aperture of fractures increases with increasing overburden strain and subsidence. Therefore, whilst panel width typically controls the height of fracturing, the network connectivity and conductivity of fractures is controlled by the magnitude of strain and subsidence. Panel width, depth and seam thickness influence strain and subsidence.

**Table 4.2: Typical Vertical Strain Values for Different Zones above Extracted Longwall Panels**

Zone Type	Zone	Fracture and Groundwater Response Description	Typical Vertical Strain (mm/m)
Surface Cracking Zone (un-constrained)	D	Vertical cracking due to horizontal strains extending to maximum depths of 10 - 15 m. Surface waters may be diverted below affected area and resurface downstream where interaction with B & C Zones occur	<3
Elastic Deformation Zone (dilated bedding & constrained)	C	Generally unaffected by stains with some bedding parting dilation. Horizontal strains constrained by overlying/underlying strata. Groundwater levels may be lowered temporarily due to new storage volume in voids between beds, but likely to recover at a rate dependant on climate. Elastic Zone may not be present if B or A Zones extend up to Surface Zone.	<3
Discontinuous Fracture Zone (dilated bedding & constrained)	B	Minor vertical cracking due to bending that do not extent through strata units. Increased bedding parting dilation and similar groundwater leakage may occur to B Zone, however, losses likely to be recharged by surface hydro-geological system	<8
Continuous Fracture Zone (unconstrained)	A	Major vertical cracking due to bending that pass through strata units and allow a direct hydraulic connection to workings below. Full depressurisation of groundwater occurs in the Zone that may recover in the long term once mining is completed.	>8
Caved (included in the A Zone)	A	Caved strata up to 3 to 5 x Mining Height above the workings. Collapsed roof bulks in volume to provide some support to overlying strata.	>80

Source: Ditton and Merrick (2014)

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. Consequently groundwater models that attempt to mimic this behaviour have significant increases in horizontal permeability but little to no change in the vertical permeability in the constrained zone, such as predicted by Tammetta (2015). This is despite the limited ability by instrumentation to differentiate between vertical and horizontal effects.



Commonly the term 'connected fracturing' is used to differentiate between vertical and horizontal effects. Connected fracturing is where new vertical connections have formed to cause an increase in vertical permeability. The Constrained Zone is commonly defined as being non-connected fracturing with 'Elastic Deformation' or 'Discontinuous Fracture Disconnected cracking' as described by Ditton and Merrick (2014) or as having 'negligible enhancement of vertical permeability' as described by Galvin (2016). Consequently a useful term that describes the height of impact on groundwater systems is the Height of Connected Fracturing (HoCF). The HoCF generally corresponds to the 'A' zone while the HoF corresponds to the 'B' zone in most concept models.

### 4.3.2 Comparison of Tammetta (2013) and Ditton and Merrick (2014) Height of Fracturing Models

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

The Tammetta (2013) model is derived from direct observations from 18 locations worldwide, seven of which are located in Australia. Observations are measurements in groundwater pressure from vibrating wire piezometers (VWPs) or standpipe piezometers and are located directly over mining. The Tammetta (2013) model captures the height above workings where there is a significant contrast in pre- and post-mining groundwater pressure measurements. This measure is described by Tammetta (2013) as the 'height of complete groundwater drainage'. This measure was compared to more direct measures of vertical deformation where possible. The height of complete groundwater drainage was taken as the location where a major change in ground movement was observed pre and post mining. This is considered by many to be equivalent to a HoCF model or the height of the 'A Zone'.

The Ditton and Merrick (2014) HoF model was derived from examination of 34 observations, 32 of these being from NSW. The Ditton and Merrick (2014) HoF model is split between prediction of the height of the Fracture Zone, termed *A* and the height of the zone above the *A* zone where there is significant bedding partings and fractures called the *B* zone. The *B* zone is stated by Ditton and Merrick (2014) as being within the Constrained Zone.

Observations of the *A* and *B* zones were made by Ditton and Merrick (2014) based on extensometer readings, piezometers and borehole logs. The distribution between observation type is unknown. This study is an update of the ACARP study by Ditton and Frith (2003) which was originally based on only seven sites.

Ditton Geotechnical Services (2016) subsequently updated the Ditton and Merrick (2014) model to improve prediction of the height of the *B* zone when compared to the same database of observations.

The Ditton and Merrick (2014) model purports to include the effects of geology by assuming the presence of a stiff overlying beam near the top of the fracture zone that limits the heights of the *A* and *B* zone. Model development included consideration of:

- Maximum tensile and compressive stress within the overlying beam;
- The thickness and location of the overlying beam;
- The modulus of the collapse strata;
- The break or caving angle this defining the zone within which caving is assumed to occur.



While these factors were considered in development, the resulting *A* and *B* zone models excluded any direct measure of tensile strength, goaf modulus or caving angle. Instead a single additional empirical term was added to the original form of the model published in ACARP (2003). This term was simply the 'effective thickness' of the overlying beam with an exponent derived by fitting to the data.

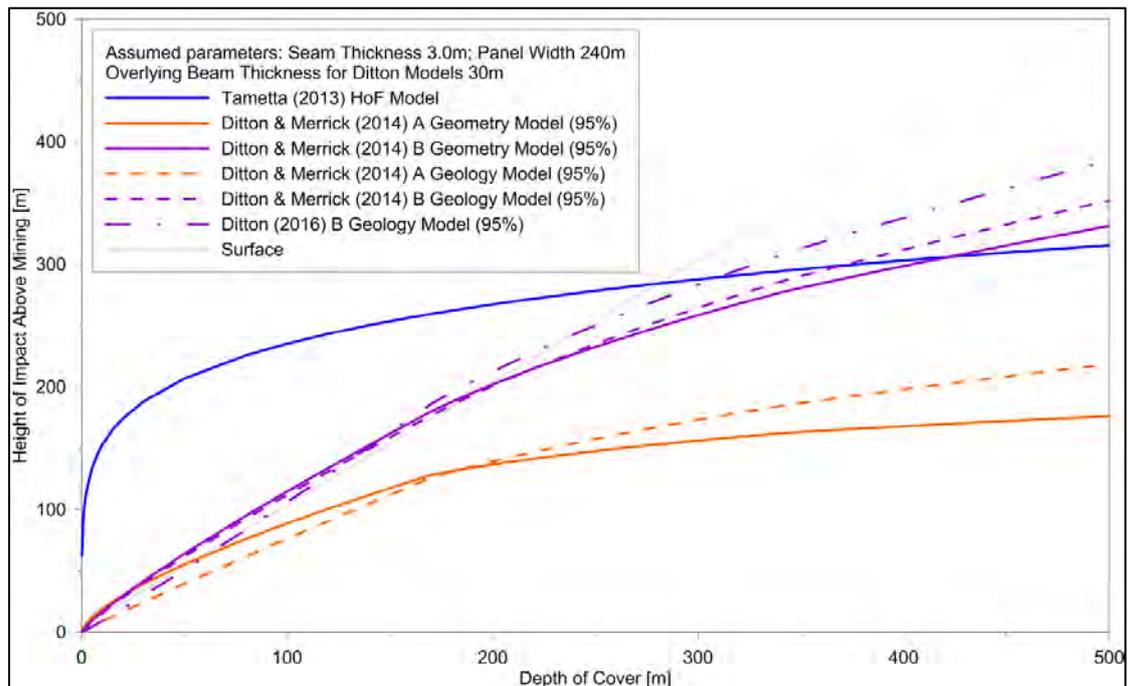
The effective thickness,  $t$ , was chosen such that it minimised the error prediction within prescribed limits. These limits were a minimum thickness specific to the respective coalfield and a maximum thickness based on a correlation with the observed height of the spanning unit. This correlation was derived from a best fit analysis of the 34 observation sites.

In summary, the Ditton and Merrick (2014) 'Geology' Model assumes that:

1. A spanning unit of sufficient thickness and strength exists within the strata overlying the void to limit both the height of the *A* and *B* zones.
2. This unit exists at a height above extraction based on a correlation such that the height of the *A* and *B* zones are limited in accordance with the database observations.

Significantly the Ditton and Merrick (2014) model assumes that the limiting beam thickness and location is based on a correlation and not on site specific geology. It is also implied that one or more spanning units has influence on both the height of both *A* and *B* heights.

Ditton and Merrick (2014) also developed a model which ignored the effect of the spanning unit. They refer to this model as the 'geometry' model. Plots of the Tammetta (2013) and Ditton and Merrick (2014) 'geometry' or 'geology' models for heights *A* and *B* are shown in Figure 4.9. Included in this figure are updates to the Ditton and Merrick (2014) model published in Ditton Geotechnical Services (2016) which updated the height of *B* only. These models have been plotted in terms of height of impact against depth of cover as the seam thickness and panel width are generally constant for mining areas. The plot assumes a typical seam thickness of 3.0 m and panel width of 240 m consistent with mining in the Southern Coalfield. The overlying beam thickness for the Ditton models was assumed to be 30 m. In all cases the plots include the Ditton and Merrick (2014) corrections that are reported to capture the 95% percentile of predicted height.



**Figure 4.9: Comparison of Tammetta (2013), Ditton and Merrick (2014) and DGS (2016) models**

Examination of Figure 4.9 reveals the following for the adopted seam thickness and panel width:

- The Tammetta (2013) model predicts significantly higher HoF for depth of cover up to 250 m and less thereafter compared to Ditton and Merrick (2014) and DGS (2016) models;
- The Tammetta (2013) model suggests that a minimum depth of cover of 280 m is required to avoid HoF reaching the surface;
- The Ditton and Merrick (2014) model suggests a minimum depth of cover of around 200 m to avoid the B zone reaching the surface;
- The Ditton and Merrick (2014) model suggests that the A zone based on the 'geology' model never reaches the surface while the 'geometry' model needs less than 50 m cover to present continuous fracturing to the surface;
- For the values used in this comparison, the inclusion of 'geology' in the Ditton and Merrick (2014) model increases the predicted heights of the A and B zone for depths of cover greater than 180 m rather than reduces them as expected;
- The recent update to the B model given in DGS (2016) predicts a higher height than the Ditton and Merrick (2014) model.

In summary, the Tammetta (2013), Ditton and Merrick (2014) and DGS (2016) models all have the following characteristics:

- They are empirical models designed to give a best fit of their respective databases using correlations of simple geometric measures, these being the height of seam extraction (T), the panel width (W) and the depth of cover (H);
- They are limited by the coverage of their databases;
- They ignore any site specific geological conditions;
- They require significant error corrections to encapsulate all of the input observations;
- The observations upon which empirical relationships have been derived are not absolute but are based on interpretation.



The Tammetta (2013) and Ditton and Merrick (2014) models provide an indication as to the likely extent of subsidence effects. However they do not incorporate site specific effects, such as geology or uncommon geometries that may result in significantly different fracturing behaviour to these predictions. In addition both methods rely on measurement techniques that do not reliably predict HoF or HoCF. These methods, therefore, have a high degree of uncertainty associated with them and may be more appropriate as a qualitative rather than quantitative assessment of expected impacts.

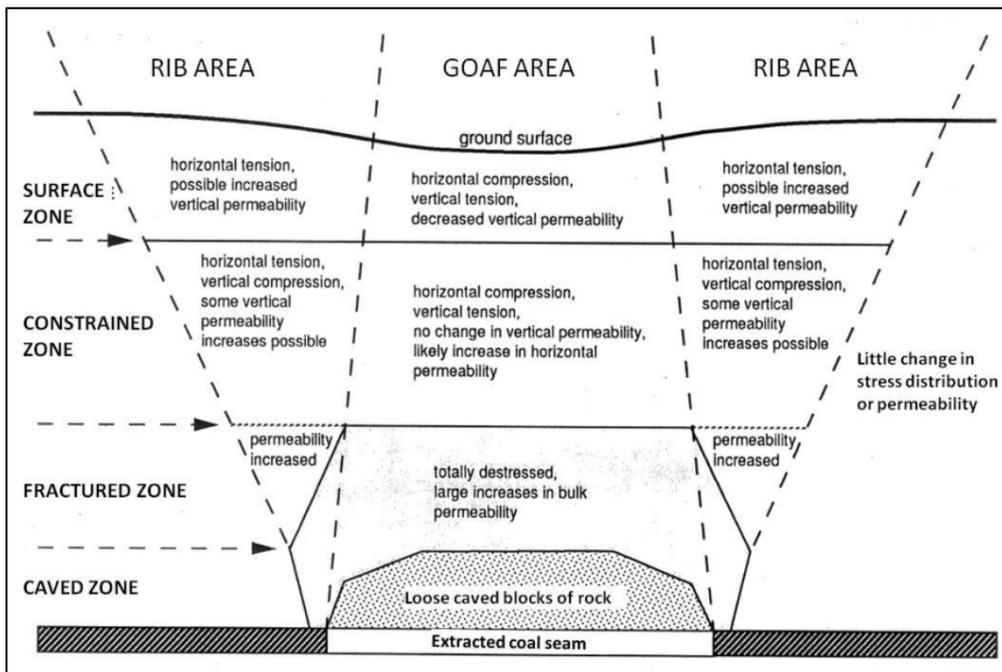
### 4.3.3 Changes in Permeability due to Subsidence

Whilst subsidence predictions typically focus on the mechanics associated with sub-surface deformations and caving mechanics, hydrogeological assessments of mining projects are concerned with rock permeability, hydraulic connectivity and groundwater flows through the subsided overburden and surrounding areas (SCA, 2013).

Water flow in many types of sedimentary rocks occurs primarily through the fracture network rather than through the less-permeable intact rock fabric. Mining induced fracturing and opening of existing fractures enhances rock mass permeability and hydraulic conductivity. Where connective fracturing is created, hydraulic conductivity significantly increases. However, the height of the fracture zone does not necessarily imply that connective fracturing occurs through the entire fracture zone. For example, thick strong beds may only develop vertical cracking on the underside which may not continue through the entire unit, and fractures may or may not line up cracking in adjacent units.

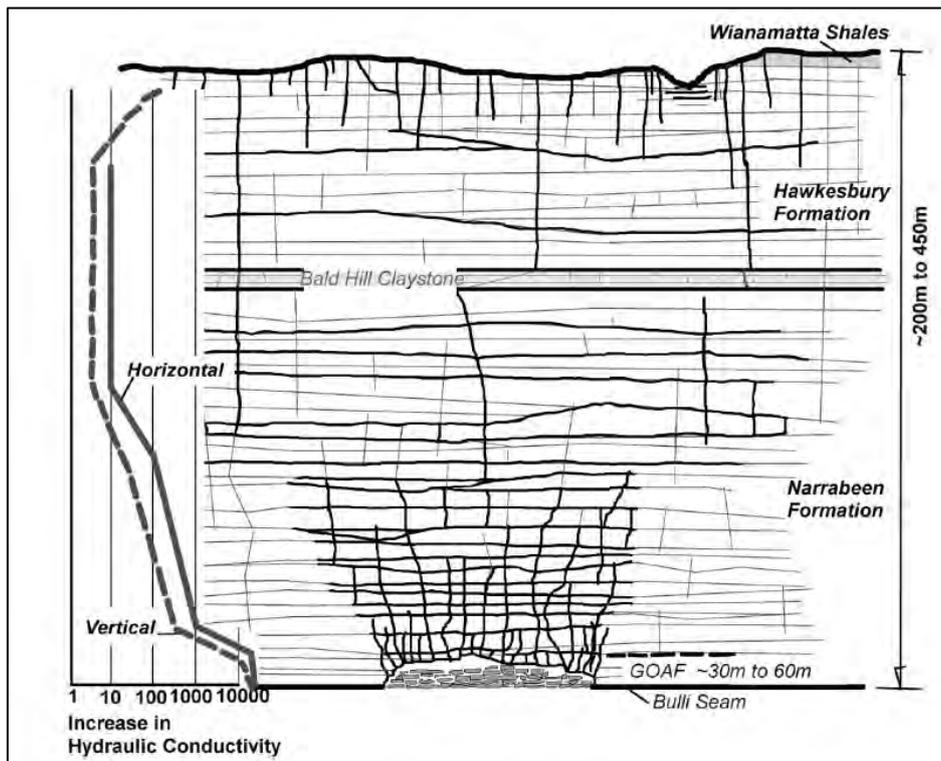
Because subsidence can greatly alter the hydraulic characteristics of the overburden, it follows that hydrogeological behaviour is closely coupled with the sub-surface deformations. One of the earlier known models which qualitatively describe permeability changes above an extracted longwall panel is shown in Figure 4.10. Whilst this model is a generalised one that assumes uniform overburden conditions, Forster (1995) considered it applicable to most normal underground mining situations with modifications being made to the zone thicknesses for different areas. It is noted that the Forster (1995) was derived from supercritical panels overlain by massive conglomerate strata overlain by sediments of Lake Macquarie. Therefore the ability to extrapolate to conditions different to these may be somewhat limited.

Commenting on the “zonation” approach, Pells and Pells (2012b) suggest there is no information to justify demarcation of specific zones, and that available data only justifies the postulation of gradational permeability changes throughout the profile. An alternative model from Pells and Pells (2012b) is shown as Figure 4.11.



Source: Forster (1995)

**Figure 4.10: Postulated Changes in Permeability above an Extracted Longwall Panels, based on Newcastle Coal Measures at Wye State Mine, NSW Central Coast**



Source: Pells and Pells (2012b)

**Figure 4.11: Schematic of Postulated Impact of Longwall Mining on Horizontal and Vertical Permeability**

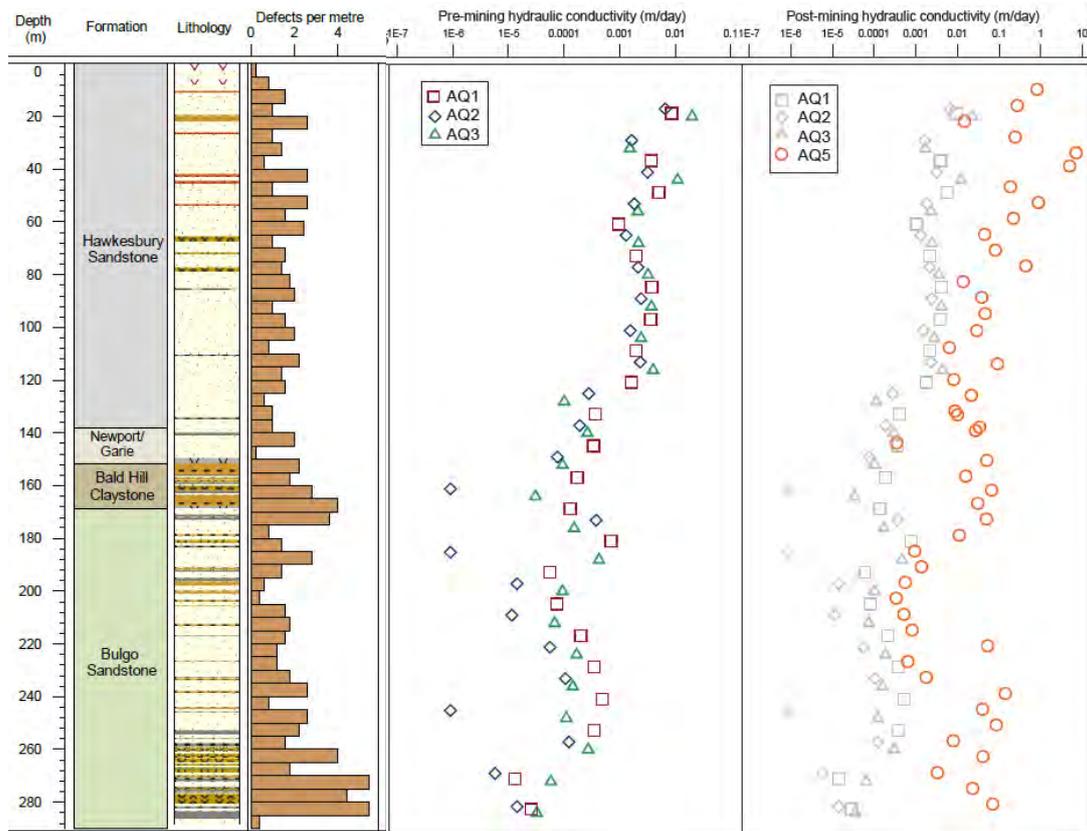


A study conducted by Parsons Brinkerhoff (2015) investigated the permeability changes due to longwall mining by conducting pre and post-mining packer testing above an extracted longwall panel at the Dendrobium Mine in the NSW Southern Coalfield. Results from these are shown in Figure 4.12, and were summarised previously in Figure 4.8. 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.

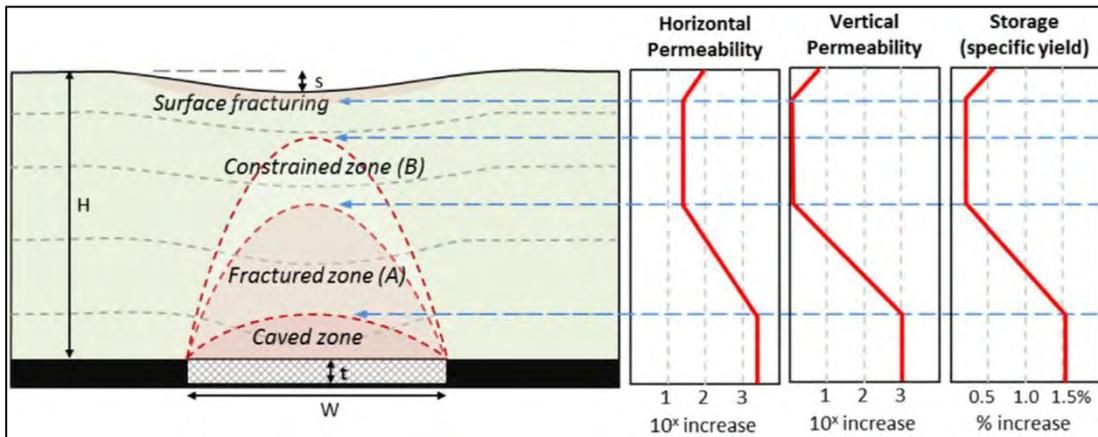
Based on results of testing shown in Figure 4.12 combined with results from cross-hole tracer testing, Parsons Brinkerhoff (2015) made the following conclusions, with respect to the model shown in Figure 4.13:

- Packer testing indicated that vertical dilation caused the horizontal permeability ( $k_h$ ) to increase through to the surface by up to two orders of magnitude;
- Vertical permeability ( $k_v$ ) increased within the fractured zone such that fractures became desaturated;
- Although the tracer tests used in this study did not allow precise estimates of  $k_v$ , observations of groundwater levels after the passing of Longwall 9 indicated that  $k_v$  increased to much less of an extent within the constrained zone;
- Subsidence causes an increase in fracture storage throughout the overburden. The increase in fracture storage over the area of a longwall can equate to a significant volume compared with the local catchment water balance. It is therefore important to include storage increase in numerical models;
- It is also seen that the model from Parsons Brinkerhoff (2015) in Figure 4.12 reflects the comments from Pells and Pells (2012a), noting that permeability changes are likely to be gradational (Figure 4.11).



Source: Parsons Brinkerhoff (2015)

**Figure 4.12: Pre-Mining and Post-Mining Hydraulic Conductivities above an Extracted Longwall Panel at Dendrobium Mine, Southern Coalfield, NSW**



Source Parsons Brinkerhoff (2015)

**Figure 4.13: Model for Fracturing and Change in Permeability above an Extracted Longwall Panel at Dendrobium**

Investigations into post-mining permeability due to longwall extraction have also been undertaken by Holla and Barclay (2000b). Their data suggests there was an increase in permeability in each section of the post-mining borehole compared with the equivalent section of the pre-mining borehole. Only two sections in the pre-mining borehole measured a permeability in excess of 50 Lugeon units, compared to 7 units in the post-mining borehole. However, the authors note that there was little or no correlation between the actual number of fractures and the measured



permeability in either borehole, nor was there a recognisable correlation between the relative change in the number of fractures and change in permeability.

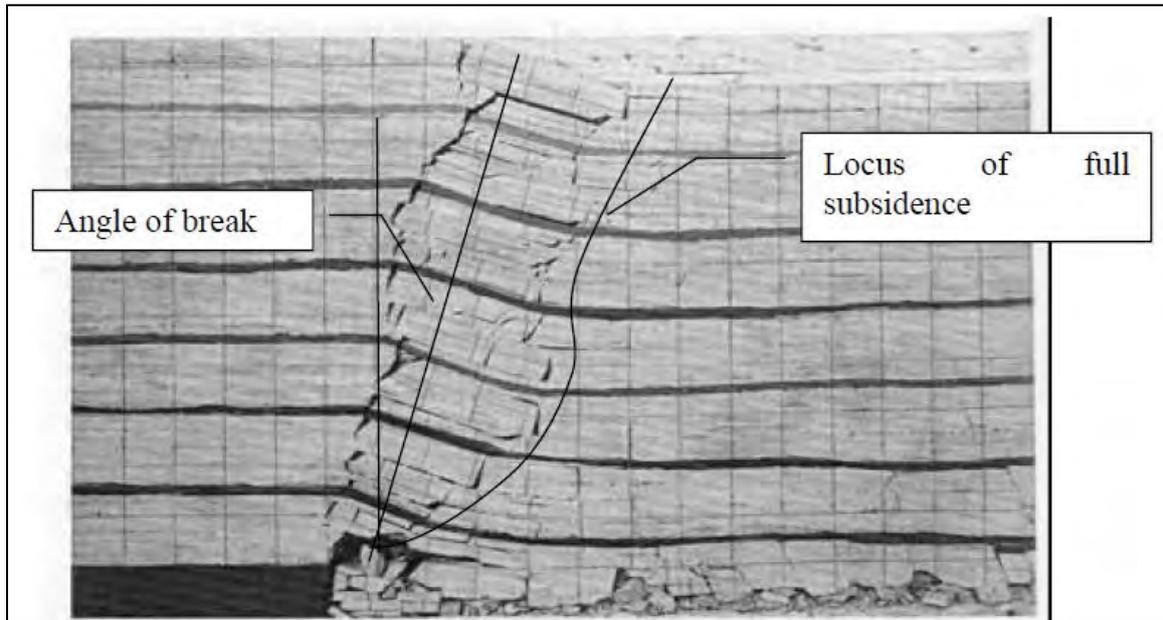
Additional discussion on permeability changes above extracted longwall panels is provided in ACARP (2001), ACARP (2007) and Pells and Pells (2012b).

Pre-mining and post-mining permeability above shallow longwall panels overlain by soil deposits was investigated by ACARP (2006). Changes to permeability in the soil deposits were measured by analysing the rate at which water was lost from a series of trenches excavated through the soil. Comparison of the trench infiltration rates successfully indicated a significant increase in water exfiltration due to cracking of the soil and upper weathered coal measures. However, the results depended heavily on whether or not the trench intersected a subsidence crack. Pits that were not cracked generally indicated no increase in the local permeability, even though one pit was less than 3 m away from a subsidence crack. This indicates there is not a generic reduction in soil water levels in the soil horizon, with the changes limited to being within close proximity of a crack. For supercritical longwalls, it was also suggested that cracks defining the angle of break or angle of full subsidence may extend to the surface and form a highly transmissive zone (Figure 4.14). It was also noted that loose sandy soils have a greater ability to absorb ground movement without significant cracking, and that remobilisation of the soil into the cracked areas can help to close cracks.

Through the use of computer modelling, ACARP (2008) investigated the permeability changes above gate roads immediately adjacent to extracted longwall panels. From this study it was concluded that:

- Overburden permeability is not significantly impacted beyond the panel edge;
- In the cases studied, the permeability was not impacted 50 m outside the rib-line;
- Flow networks created adjacent to extracted longwall panels are typically related to depressurisation of coal seams, which induces overburden seepage;
- Overburden permeability remains essentially unchanged from the in-situ state, however, pore pressure distribution may be modified.

Given that bedding shears may extend laterally for a considerable distance from the goaf, there is potential that these features may act as flow conduits and direct flow horizontally towards the goaf if they have significant aperture. It is unclear if these effects have been considered by ACARP (2008).



Source: ACARP (2006)

**Figure 4.14: Connective Fracturing Extending to Surface Corresponding to the Angle of Break and Angle of Full Subsidence**

#### 4.3.4 Changes in Aquifer Characteristics due to Subsidence

A void created after coal extraction induces a pressure gradient towards the void. This changes the direction of groundwater flow towards the void which progressively depressurises the surrounding rockmass.

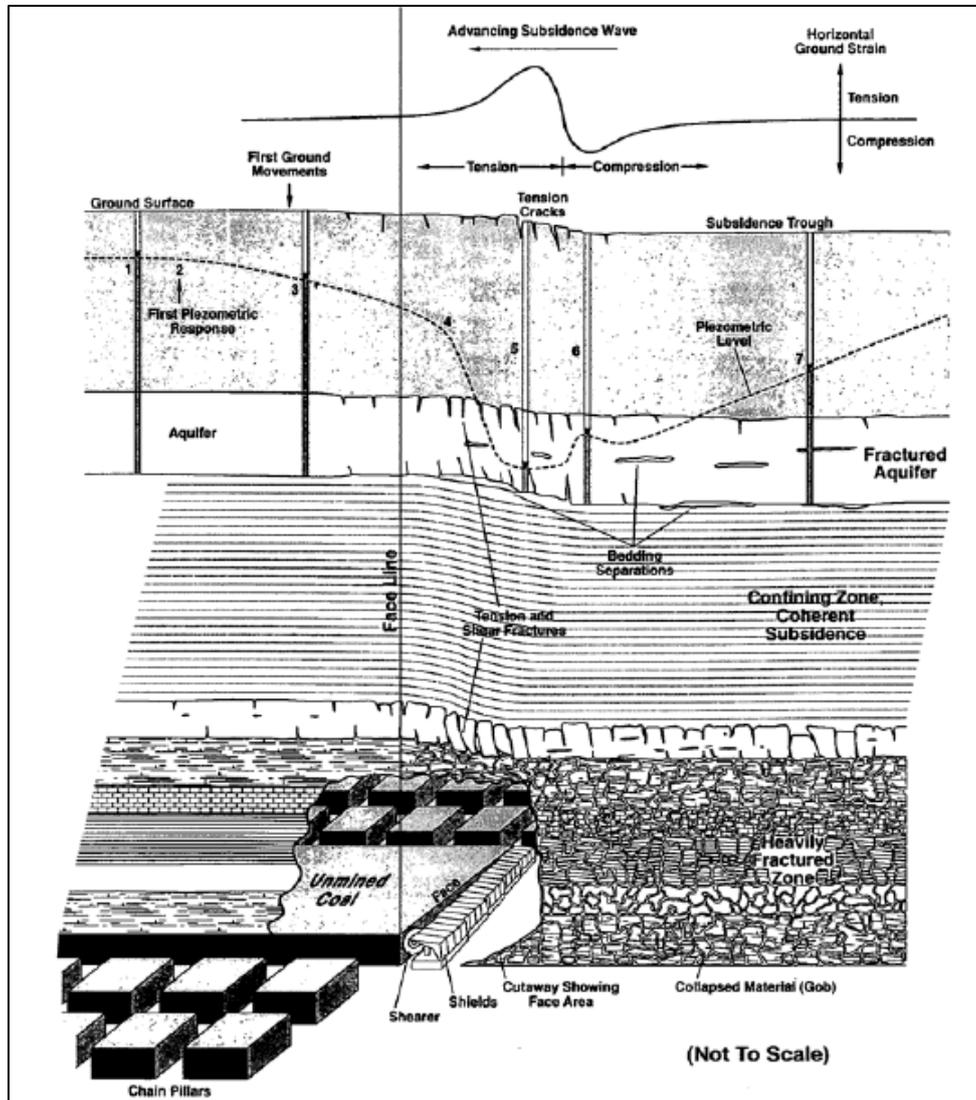
The model from Booth *et al.* (2000) in Figure 4.15 shows that during panel extraction, depressurisation occurs in advance of the face in response to induced tension caused by an advancing or travelling "subsidence wave". Pressure drawdown then accelerates at a point as the longwall face approaches, followed by a pressure increase as the groundwater table gradually recovers after mining passes.

Although the model from Booth *et al.* (2000) is based on longwall mining in the US, similar drawdown patterns were observed during longwall extraction at the Springvale Colliery in the Western Coalfield of NSW. Figure 4.16 shows the data for a number of piezometers that were installed at different heights above a chain pillar prior to longwall mining a 3.2 m section of the Lidsdale Lithgow Seam (LLS) at a depth of approximately 350 m below surface. From this data it was concluded that:

- Piezometer P9, at a depth of 25 m below surface, did not show an impact from mining;
- For piezometers P9 to P5 it was generally observed that deeper piezometers experienced greater head loss;
- The deepest piezometers, P4 to P1, underwent less head loss than higher piezometers P7 to P5. This was attributed to depressurisation of piezometers P4 to P1 from driving roadways below the piezometers;
- Basal piezometers P3 to P1 ceased to function as the longwall passed. This was attributed to damage to piezometers caused by large subsidence induced strains;

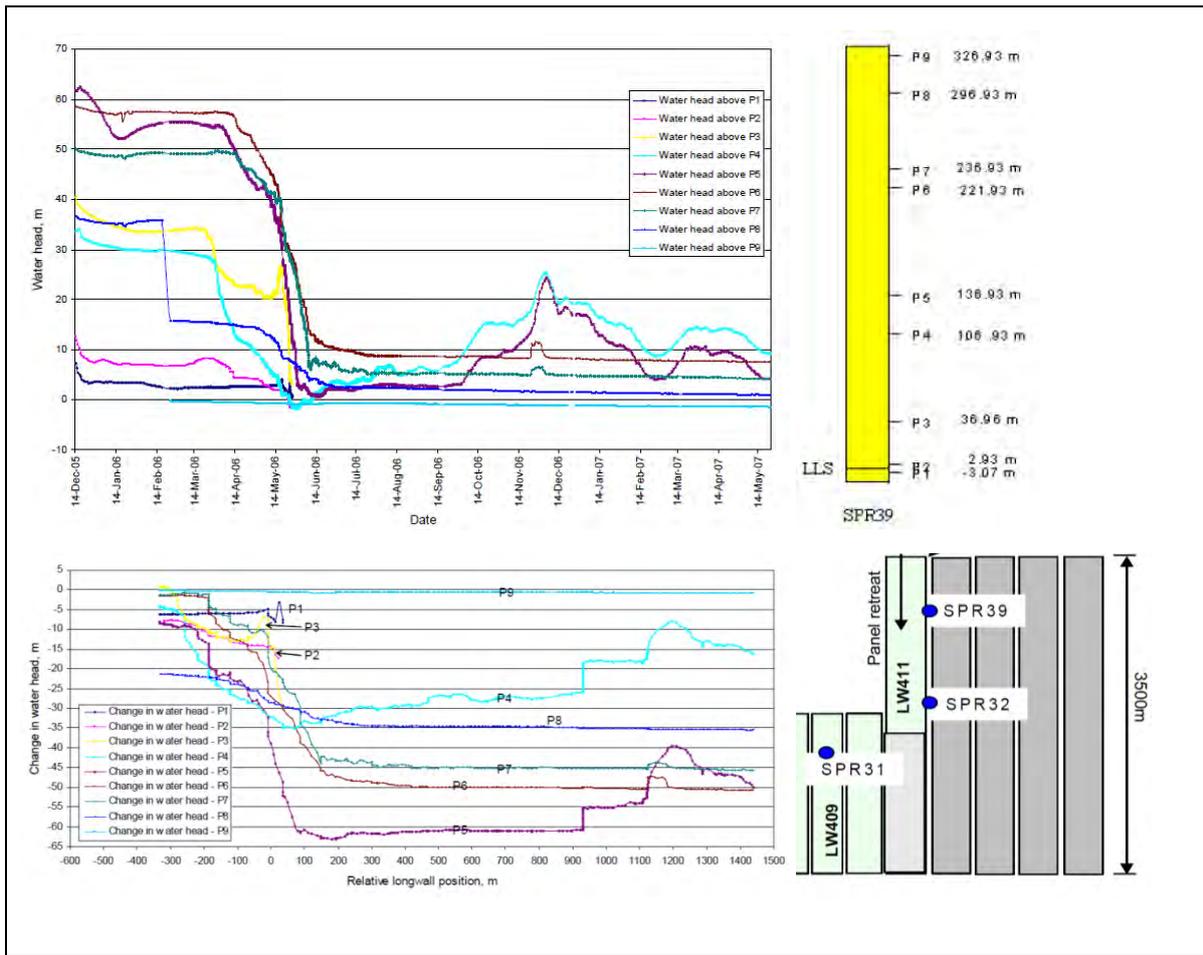
- Piezometer P4 and P5 showed anomalous transient head increases between October 2006 and February 2007. This was said to indicate that these units may have been installed in a confined aquifer system.

Piezometer data which shows similar trends, with decreasing heads a result of longwall mining, are also presented by Holla and Barclay (2000b), Pells and Pells (2012a), Heritage Computing (2013), HydroSimulations (2014), Ditton and Merrick (2014), Parsons Brinkerhoff (2015) and numerous articles cited in McNally and Evans (2007).



Source: Booth et al. (2000)

**Figure 4.15: Typical Groundwater Response during Longwall Panel Extraction**

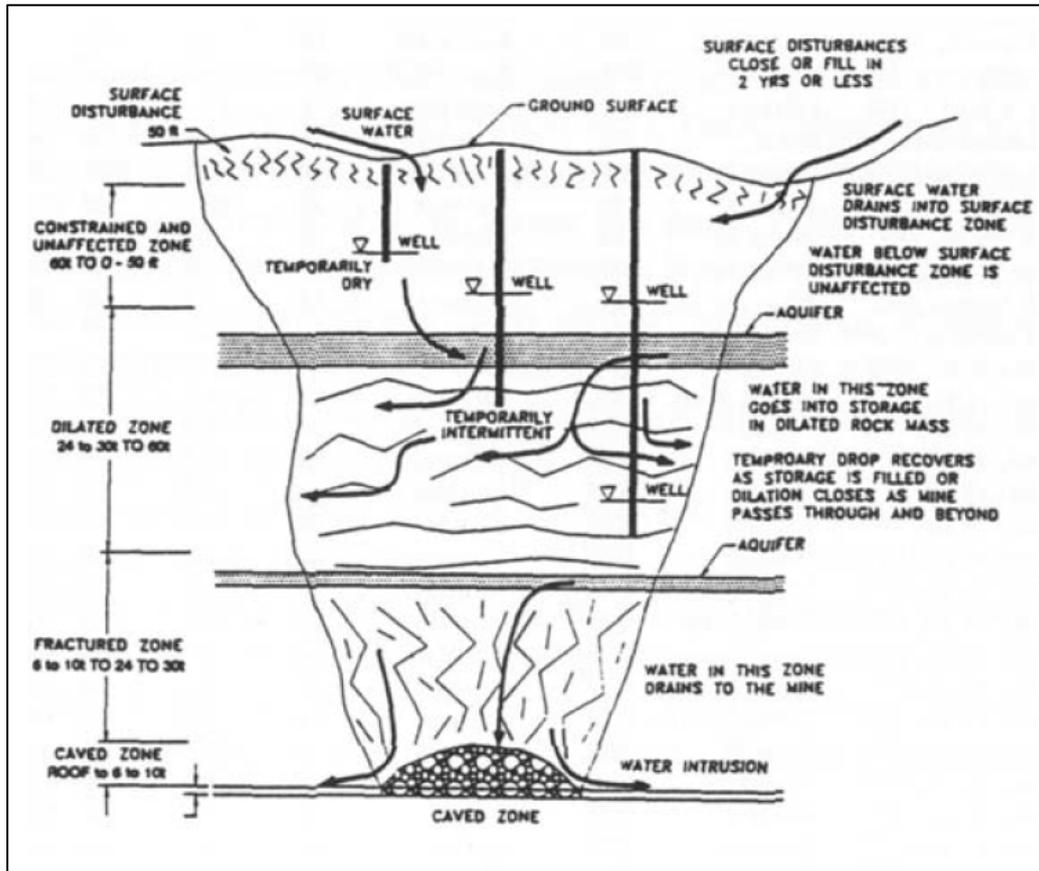


Source: ACARP (2007)

**Figure 4.16: Groundwater response measured during longwall panel extraction at the Springvale Colliery**

Similar to the models discussed previously which describe sub-surface deformations, a number of “zoned” models have also been proposed to describe the depressurisation in discrete zones above longwall panels. Kendorski (2006) provides a review of a model initially developed in 1993 based largely on mining experience in the United States (Figure 4.17). The various zones identified by Kendorski are described as having the following characteristics:

- **Caved zone** - complete disruption of the pre-mining rock structure with complete drainage of groundwater;
- **Fractured zone** - continuous open fractures with complete drainage of groundwater;
- **Dilated zone** - strata dilation increases the storativity and impacts groundwater levels. There is no direct or effective hydraulic connection to lower strata;
- **Constrained and unaffected zone** - strata are unaffected by mining and subsidence deformations and undergo no change in permeability;
- **Surface fracture zone** - temporary opening of fractures.



Source: Kendorski (2006)

**Figure 4.17: Kendorski’s 1993 Model for Groundwater Depressurisation above an Extracted Longwall Panel**

Although this model was originally developed in 1993, Kendorski (2006) provides a review of numerous studies that have been undertaken since the model was initially developed, and concludes that the model still remains valid based on the observations from other authors. Other zoned models are discussed by IESC (2014b) and Galvin (2016). Galvin ultimately concludes that zoned models may be very useful conceptually; however the end user must be aware of important limitations, being:

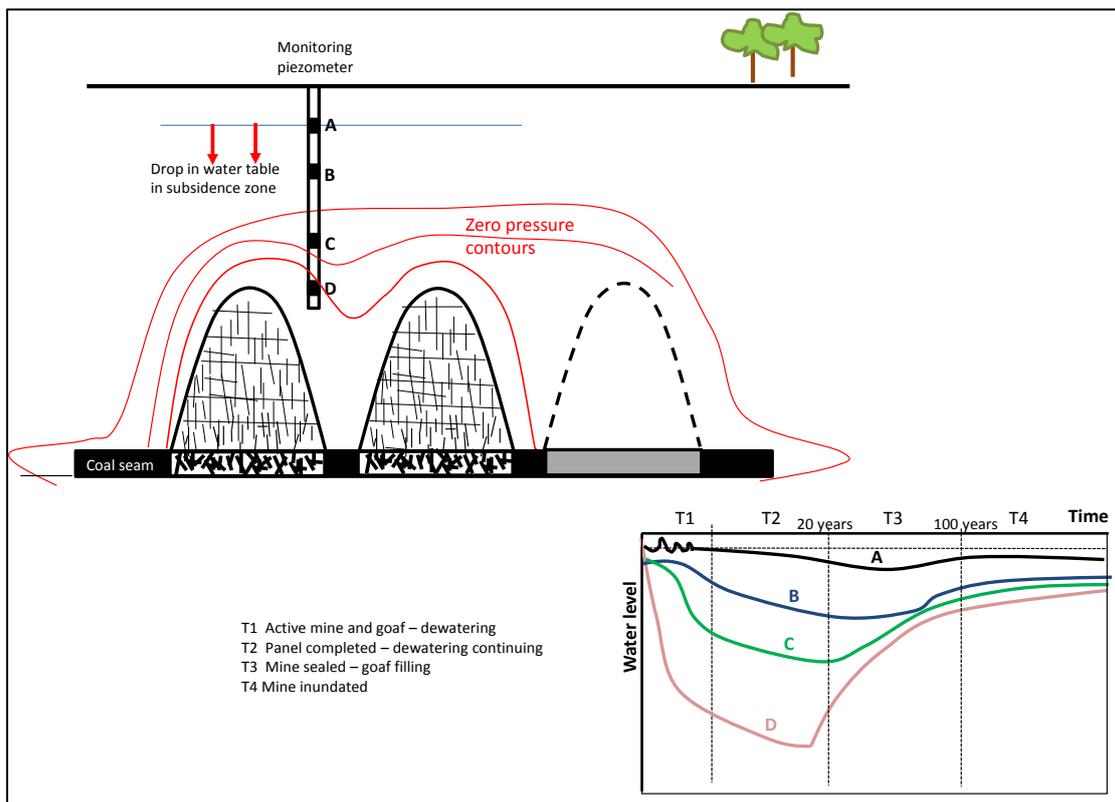
- None account for the effects of horizontal-to-vertical stress ratio and the important impact this can have on permeability, conductivity and the formation of a constrained zone;
- None account for discontinuous subsidence associated with bridging strata;
- In reality, behaviour types, permeability and the lateral extents of affected areas changes gradationally as depth of mining increases relative to panel width;

Although the zoned models qualitatively assess the impacts within the various zones, they typically do not account for transient impacts as depressurisation propagates outwards from the unsaturated void over time. SCA (2013) suggests that the period from active mining to post-closure can typically be broken down into four stages, with reference to Figure 4.18:

- During active mining in phase T1 (approximately 1 year), fracturing occurs rapidly above the panel and pressure changes propagate upwards and laterally, at rates dependent on the hydraulic diffusivity. Near-surface aquifers may or may not respond to undermining during this period depending on the prevailing geological conditions, and deeper strata will tend to be more affected;



- Following extraction of adjacent panels during phase T2 (approximately 20 years), depressurisation extends laterally and vertically as mine workings are dewatered. The largest lateral extent of depressurisation occurs in the coal seams. Both deep and shallow aquifers may become impacted, with maximum drawdown occurring in the deeper zones. Water levels immediately above the fractured zone may start to recover (point D in Figure 4.18);
- In phase T3 expansion of areas of depressurisation continues, mostly vertically. Water levels in the deep and intermediate zones may start to recover, whilst shallow groundwater may experience ongoing drawn down. SCA (2013) comment that for some mines in the Southern Coalfield, near-surface drawdown may still be occurring over 100 years after mining has ceased;
- In phase T4, the mine becomes inundated and the groundwater system slowly approaches a new equilibrium with water levels slightly lower compared with the original pre-mining conditions.



Source: SCA (2013)

**Figure 4.18 Hypothetical Changes in Head Levels above Extracted Longwall Panels over Time**

Kendorski (2006) reports that near-surface groundwater levels may be lowered because of drainage to the mine, but normally this is retarded by an intermediate low-permeability zone, and is only a problem for deeper wells that penetrate through the low-permeability zone to the lower fractured zone. 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. For example, ACARP (2002) suggests that:

*"Where there is no direct [hydraulic] connection between the surface and the seam, the presence of aquicludes, and the high horizontal stress field, tend to prevent permanent drawdown, and the groundwater levels recover with subsequent rainfall events"*



However, there is limited field data to support this.

Pells and Pells (2012a) demonstrated that the velocity of a depressurisation wave is proportional to the hydraulic diffusivity of the formation. Due to this relationship, Pells and Pells (2012b) argue that although vertical flow will be impeded by low permeability horizontal strata layers, these layers will not entirely prevent vertical flow. This is consistent with comments from SCA (2013) who suggest that the difference in hydraulic conductivity between geological formations, particularly where there are layers with low permeability, means that it can take years or decades for water level changes to transmit to the surface, and development of perched conditions does not indicate that vertical flow has stopped. Pells and Pells (2012b) also suggest that reductions in hydraulic conductivity due to desaturation of jointed rock masses probably has a major impact on the time it takes for pressure changes to transmit from the level of extraction to near-surface groundwater systems.

Shallow groundwater systems may also be affected by systematic or non-systematic surface cracking, or if sub-vertical connected fracturing extends to the surface. Near surface effects on shallow groundwater aquifers have been discussed by NSW OEH (2012), Parsons Brinckerhoff (2012) and Water NSW (2016).

Pells and Pells (2012b) comment that an expectation of continuing post-mining ground water recovery is reflected in many publications, however, full recovery does not always occur. It is suggested that once mining has completed, and the mine and shafts fill with water, groundwater levels will return toward pre mining conditions, although the time and nature of recovery will vary from site to site. Pells and Pells (2012b) provide data which shows that in one particular bore which is 226 m below ground level, the head level remains approximately 40 m below pre-mining levels 15 years after panel extraction. They also note that effects tend to be more temporary for shallow piezometers. Similar concepts are reported in IESC (2014b) based on various works from Professor Colin Booth, who reports that for a number of mines in the United States:

- Water levels should also recover as water flows back into the temporary potentiometric depression created by the subsidence fracture effects. However, this recovery depends on connection to sources of recharge and on the ability of the aquifer to transmit water back into the affected area;
- Water levels (or piezometer head levels) in wells that penetrate the lower fractured zone do not usually (fully) recover, and many sites exhibit permanent piezometric head losses;
- Permanent changes in groundwater flow may be caused by the increases in permeability, because of hydraulic gradient changes or leakage through fractured aquitards.

McNally and Evans (2007) note two sites in the Southern Coalfield of NSW where groundwater levels were said to have recovered soon after mining, however, levels did not return to the full pre-mining levels at either site. It was also noted at one site that the post-mining groundwater table was flatter due to the enhanced permeability of the strata. It is notable in the literature that reported monitoring has rarely (or never) been sufficiently comprehensive or continued for long enough after completion of a mine to characterise post-mining groundwater recovery or to confirm that new equilibrium conditions have been established.

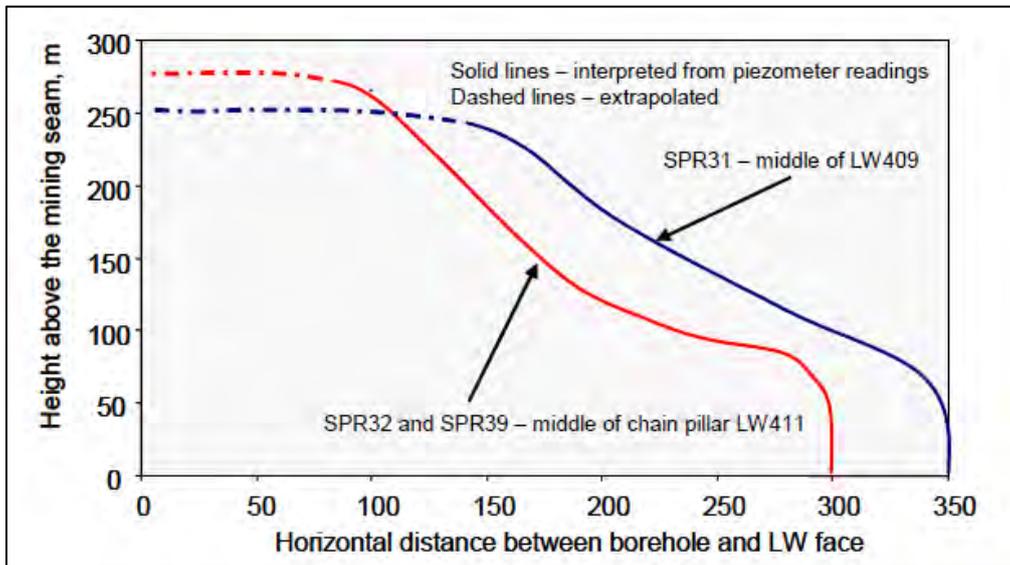
The lateral extent of depressurisation outside of the extraction footprint was investigated by ACARP (2007) during longwall extraction. By monitoring piezometers ahead of mining (Figure 4.19), it was concluded that depressurisation:

- Occurred furthest ahead of the face at the level of the extracted seam;
- Commenced at the extracted seam level 350 m ahead of mining;



- Occurred further ahead of mining in the centre of panel compared to the edge of panel.

These findings agree with comments from SCA (2013) in relation to Figure 4.18, where it is shown that the lateral extent of depressurisation will be greatest at the extracted seam level.



Source: ACARP (2007)

**Figure 4.19 Groundwater response and initiation of depressurisation ahead of the advancing longwall face**

Although the results from ACARP (2007) indicate that immediate depressurisation may extend 300 m beyond the mining footprint, the extent of depressurisation will continue with time. This is evident in the end of panel hydrogeological report for longwall Panel 8 at Dendrobium. The report from Heritage Computing (2013) shows that upon completion of Panel 8, the pressure head within the extracted Wongawilli seam had reduced by more than 40 m at a distance of more than 2 km beyond the extraction limit. The authors note that such a large reduction in head levels did not occur within the Wongawilli seam near to the extracted longwall, as significant depressurisation was said to have already occurred due to mining of nearby panels. Far-field head losses in the overlying Bulgo and Hawkesbury Sandstone units were measured to be considerably lower and generally less than 10 m.

Similar effects from far-field depressurisation effects are also evident in that data from ACARP (2007) shown in Figure 4.16. In this figure the data for piezometers P1 and P2 at extracted seam level had effectively zero water prior to mining of the Panel 11 (i.e. at the end of 2005). This depressurisation was presumably associated with prior mining of Longwalls 9 and 10 located more than 1 km to the southwest. The effects from far-field depressurisation are also from the VWP in the overburden, as it is commonly observed that prior to mining of Longwall 11, deeper VWPs often had lower head levels than higher VWPs (compare for example P3 against P5). Under virgin pre-mining conditions, it would typically be expected that deeper VWPs would have larger water heads.



## 4.4 International Experience with Mining near Water Bodies and Major Aquifers

The longwall mining technique is used throughout the world to extract coal directly beneath or within close proximity to large water bodies.

A review of longwall operations extracting coal near water bodies in the United Kingdom and the United States was reported by McNally and Evans (2007). It is reported that a longwall mine extracting coal 80 m below a limestone aquifer experienced several inrushes of groundwater which caused significant disruptions to mining. It is noted however that mines in the UK are typically at a much greater depth, and are overlain by less permeable strata. British practice with respect to mining near major water bodies is listed by McNally and Evans (2007) as requiring:

- A minimum cover of 105 m;
- Tensile strains less than 10 mm/m at the base of major aquifers, which should not be less than 45 m above the worked seam.

In the United States, McNally and Evans (2007) note that the hydrogeological consequences of longwall mining on rural bore water supplies has been of interest in Pennsylvania, West Virginia, and Illinois. It is reported that of the 1,884 undermined property owners in western Pennsylvania, 28% experienced loss or contamination of water whilst 10% reported surface cracking. In southwestern Pennsylvania during longwall mining of multiple panels at a depth of approximately 250 m, water level were monitored at a depth of 45 m below surface and showed that:

- Water levels typically fell by 3 to 7.5 m, but completely drained in one well;
- Water levels dropped most over the centre of panels, and continued to fluctuate when adjacent panels were mined;
- Levels began to decline about 60 m ahead of the face and fell most rapidly as the face passed;
- Wells located more than 150 m from longwall panel were unaffected by mining;
- Four out of the five wells recovered to within 3 m of the original water levels within 12 months of undermining; and
- There was a slight increase in groundwater pH.

At the Rend Lake Mine in Illinois, USA, DSC (1989) reports that longwall mining of a 2 m thick seam at depth of 200 m beneath a reservoir was successfully undertaken with no water issues. The reservoir was said to be lined with clay and silt sediments underlain by shale beds. At Rufford Lake in the UK, longwall mining employed panel widths of 200 to 250 m to extract a 1.8 m thick coal seam at a depth of 420 m below the lake. The cover sequence included a major sandstone aquifer and limestone near to the surface with abundant clay-filled fissures. In 1972 the lake was drained due to concentrated strains on a suspected fault passing beneath the lake. Despite draining the lake, no particular problem was reported due to additional mine water inflows.

Two cases are reported by the DSC (1989) where major structure caused inrush from overlying water bodies. The first was in Japan where a fault was reported to have provided a hydraulic connection from the sea bed into a mine. The cover sequence was noted to be shallow and comprised of 47 m of sandstone overlain by 25 m of sandy clay. The second reported instance of inrush occurred in Canada during gate road extraction at a depth of 287 m beneath the sea. It was suspected that a major structure provided the hydraulic connection to the mine.



Holla and Barclay (2000b) 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. A summary of the requirements from different countries is provided in Table 4.3. These values are, on average, approximately double the strain limit of 4 mm/m that SCA (2013) suggest is the limit below which water inflow is unlikely to occur (based on experience with UK and Australian undersea mining).

Holla and Barclay (2000b) comment that the strain-limiting approach does not necessarily take into account overburden composition and the potential for thick beds to act as aquicludes, and that limiting surface strain is probably at best only a means of controlling the general strata disturbance.

**Table 4.3: Requirements for Total Extraction under Water Bodies**

Country	Minimum Cover Thickness	Maximum Seam Thickness	Maximum Permitted Tensile Strain	Qualifications
UK	105 m	1.7 m	10 mm/m	Minimum thickness of carbonaceous strata of 60 m.
Japan	60 m with no unconsolidated clay deposits	0.8 m	8 mm/m	Mining must be in sections with dams.
Chile	150 m	No restrictions	5 mm/m	Thickness of available seam 1.4 m.
Canada, Nova Scotia	213 m	No restrictions	7.7 mm/m	Thickest available seam 2.7 m.

Source: Holla and Barclay (2000b)

A review on the effects of underground mining the USA is provided by IESC (2014b). Based on the works of Professor Colin Booth throughout Pennsylvania and Illinois in the USA, commonly observed impacts of longwall mining included:

- Mining-induced permeability changes, in the order of 1 to 2 orders of magnitudes;
- Groundwater levels in the subsidence zone typically recover slightly as a result of post-subsidence compressional stresses;
- Permanent changes in groundwater flow may be caused by increases in permeability, hydraulic gradient changes and/or leakage through fractured aquitards; and
- Many sites exhibited permanent piezometric head losses, particularly in wells that penetrate into the lower fractured zone.

IESC (2014b) also cites a number of studies from Professor Anthony Iannacchione in Pennsylvania. From these studies it was reported that tension cracks were a dominant cause of reported land impacts in Pennsylvania between 2005 and 2008, and out of 55 streams investigated by the Pennsylvania Department of Environmental Protection between 2003 and 2008, only two were reportedly not affected by longwall mining.

During a review on undersea coal mining, Allonby *et al.* (1985) cite a number of examples where inrush has occurred as a result of longwall mining beneath the sea bed. A number of examples are summarised in Table 4.4. Generally speaking, shallow cover depths and the presence of fault structures appear to be the major factors leading to inundation.



**Table 4.4: Historical Record of Some Major Inundations of Undersea Coal Working**

Country	Date	Name of Colliery	Cover (m)	Total Dead	Cause of Inrush
Canada	1909	Mabou (Nova Scotia)	33.5	-	Working close to the seabed
Canada	1911	Port Hood	287	-	Large fault
Chile	1881	Two mines flooded		-	Close to the seabed and vicinity of the fault
Japan	30/12/1900	Santagumi	14	25	Working very close to the seabed
Japan	11/03/1910	Santagumigata	15	75	Working very close to the seabed
Japan	12/04/1915	Higashimiso	72	235	Fault
Japan	6/02/1942	Chosel	37	183	Fault
UK	28/07/1837	Workington Colliery (Main Band) Cumberland	27.5	27	Only 7.3 m of the cover thought to be rock
UK	1883	Mostyn Colliery, North Wales	22-29		The colliery was closed due to sea water breaking into workings

Source Allonbyc et al. (1985)

### 4.5 Historical Impact Limits

There has been debate and conflicting attitudes towards mining near Sydney’s main water storages as far back as circa 1880, as documented by Mills (2015). A chronology of events and prescribed mining limits is summarised as follows:

- Ongoing debate occurred between NSW Metropolitan Water and the Department of Mines (later Metropolitan Water and Sewerage and Drainage Board (MWS&DB)) throughout the late 1800s regarding the mining limits around Sydney catchments areas. Although NSW Metropolitan Water had influence over surface activities which may impact water quality, they were limited to making comments on the granting of mining leases beneath water storages;
- Around 1903, concerns were raised relating to the possible effects of undermining the structures and storages with the construction of Cataract Dam, and NSW Metropolitan Water subsequently proposed that no mining be conducted within a quarter of a mile (about 400 m) of the dam. The Department of Mines disagreed, and permitted mining within this zone under stipulated conditions limiting minimum pillar sizes, stipulating shaft and adit locations and limiting secondary pillar extraction. Marginal (setback) zones around the stored waters were defined using an angle of draw measured at 10° from vertical;
- In 1950 proposed changes to lease conditions based on international experiences were recommended including allowing a greater percentage of extraction to occur based on a minimum overburden thickness. NSW Metropolitan Water protested against the proposals, seeking a larger marginal zone and special protection measures in the case of geological faults;
- In 1959 the NSW Metropolitan Water took the audacious step of asking the Department of Mines to exempt the whole catchment area from the leasing provisions of the *Mining Act*. The request was refused;
- In 1960 NSW Metropolitan Water objected to a number of mining applications, advising against mining under stored waters or water supply structures or within a rationally determined setback zone;
- Over the next few years a compromise was reached which included increasing the size of the setback zone and special provisions for geological features (predominantly faults and dykes). In 1961 an agreement was reached that the angle defining the marginal zone would be



increased from 10 to 35° from the vertical, projected down to seam depth from the full supply level. This resulted in a setback that was equal to 0.7 times the seam depth;

- During 1962 further discussions centred on the size of the barriers to be left below the various dam structures;
- By 1963 the MWS&DB was still advocating that no mining be allowed beneath the stored waters and retaining structures except for controlled access roads and that additional buffers be provided against geological features. The Department of Mines did not agree to fully implement the Board's requirements;
- The debate continued for another nine years until 1973 when the Reynolds Commission was tasked with investigating the effects of mining on the stored waters of the five dams located in the Southern Coalfield of NSW;
- The Reynolds Commission concluded that mining should be allowed beneath the stored waters with the following conditions:
  - The marginal zone around stored waters should be defined using an 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 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.

Discussion of a barrier pillar considered for mining near to the Cataract Reservoir at the Russell Vale Colliery is presented in Mills (2015). The barrier pillar was designed, in accordance with DSC requirements, using a 35 degree angle of draw, which is approximately equal to 0.7 times the depth of cover. It is noted factors ranging in size from 0 to 1.2 have been implied or accepted in historic legislation, although actual references are not supplied in the Mills (2015) review. At seam level the factor of 0.7 times the depth of cover is said to provide about a 200 m horizontal offset beyond the footprint of the reservoir at full supply level, with a vertical offset of more than 300 m.

Mills (2015) notes that they are not aware of any uncontrolled inflows from the surface at an underground coal mine in Australia with overburden depths greater than 170 m, and there are many examples where lesser overburden depths have provided an effective barrier between the workings and the surface. Furthermore, the only known instances of inflow events, at depths less than 170 m, were noted to have occurred for working directly below stored water, and not beyond the footprint of the full supply level.

For the proposed expansion at the Gujarat No. 1 Colliery, Hebblewhite (2013) comments that a horizontal protection barrier of at least 0.7 times depth has been applied between mining and the Full Supply Level (FSL) of Cataract Reservoir, and the adopted value was considered reasonable.



However, Hebblewhite comments that the presence of goafed material from old workings within the barrier pillar brings into the questions adequacy of the nominated pillar width.

A review of mining under water bodies and natural features, including flood-prone land, is presented by Holla & Barclay (2000) and Galvin (2016). In order to prevent incidents of inrush from occurring, it is stated that guidelines have been developed in various countries for limiting surface and sub-surface strata disturbance, which is most countries, is solely based on limiting rockhead strain as was discussed in a previous section. Many successful cases of mining under water bodies are said to have occurred by limiting the maximum rock head tensile strain to a value within the range of 5 mm/m–10 mm/m. Two instances are cited where mining (longwall and bord and pillar) was undertaken directly beneath the Cataract Reservoir by placing limits on panel dimensions and chain pillar widths.

Babcock and Hooker (1977) present guidelines based from the United States for total extraction near surface and buried water bodies. For total extraction, as is practiced in many of the longwall operations in the Southern Coalfield of NSW, the authors recommend that (note that units have been converted to metric):

1. Any single seam of coal beneath or in the vicinity of any body of surface water may be totally extracted, whether by longwall mining or by pillar robbing, provided that for each 0.3 m thickness of the seam to be extracted, a minimum of 18 m of solid strata cover exists between the proposed workings and the bed of the body of surface water.
2. Where more than one seam exists, all may be worked by total extraction provided that for each 0.3 m of aggregate coal and rock thickness of all seams to be extracted, a minimum thickness of 18 m of solid strata cover exists between the proposed workings in the uppermost seam and the bed of the body of surface water. When subsidence observations have been carried out and satisfactory calculations of surface tensile strains can be made, any number of seams may be mined by total extraction provided that the maximum cumulative tensile strain beneath the body of water does not exceed 8.75 mm/m.
3. Where a single seam has already been mined by total extraction in accordance with the provision that for each 0.3 m thickness of mineral and rock extraction, a minimum 18 m of solid strata cover should exist, no other underlying seam should be mined by total extraction. Where the cover between two seams is 60 times or greater the extractable thickness of the lower seam, such a lower seam should be mined by partial extraction, as though the upper seam represents a body of water.
4. Where natural or artificial deposits, which are highly permeable or may flow when wet, exist between the bedrock and the bed of the body of surface water, these should be excluded from the thickness of solid strata, except where it has been demonstrate that such deposits would not be likely to flow when wet and could be considered as impermeable.
5. Where a fault which might connect mine workings with a body of surface water and which has a vertical displacement greater than 3 m, or an intrusive dyke, having a width greater than 3 m, is known to exist or is met with during development, no seam should be total extracted within 15 m horizontally on either side of such fault or dyke.



## 4.6 Gaps in Existing Knowledge

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

- There are no reliable methods for detecting the 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. Microseismic investigations can usefully identify where major cracking is occurring within overburden formations, but cannot discern their geometry. Piezometric and extensometer data are also important in inferring HoCF and should be routinely used;
- Despite the application of numerous empirical, analytical and, less commonly, numerical theoretical models, there are no current 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 reliably incorporate the effects of geology or material properties such as rockmass strength;
- HoF prediction methods are focussed on data obtained directly above a longwall panel with limited data away from the centre 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;
- 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. Instead, groundwater depressurisation occurs 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;
- There are no established methods for reliably predicting safe offset distances for water bodies;
- 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 trialled to enable subsidence bowls in complex terrains to be progressively mapped and their impacts studied.



**Advisian**

WorleyParsons Group



## 5 Groundwater

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General information on the groundwater related environmental impacts and consequences of coal mining and subsidence is provided in Section 5.1 below. A detailed appreciation of the physical changes when there is subsidence and deformation of overlying strata and the associated impacts on hydrogeological conditions is provided in Section 4.2. The individual literature reviews for cited groundwater references are mostly provided in Appendix B but there are additional reviewed documents in Appendices A and C.

Section 5.2 briefly describes the difficulties in quantifying impacts limits for groundwater while Section 5.3 provides an assessment of groundwater monitoring and other knowledge gaps.

### 5.1 Impacts and Consequences of Coal Mining

Several review studies (e.g. McNally-Evans, 2007 and NSW Chief Scientist & Engineer, 2014) have emphasised that no coalfield-wide hydrogeological baseline study is available to assess baseline conditions (post dam construction) or baseline conditions prior to the commencement of longwall mining and the onset of widespread subsidence. In addition there is no systematic long term groundwater monitoring being carried out across the broader Special Areas with a specific purpose of monitoring cumulative or regional mining impacts.

The largest spatial monitoring network across the region (covering an area in excess of 150 km<sup>2</sup> and only monitoring the Hawkesbury Sandstone and several superficial aquifers) is associated with the Kangaloon Borefield project (URS, 2009a) in the upper Nepean and upper Avon catchments. This area is unaffected by coal mining and provides a useful water level and water quality data set to assess natural hydrological and hydrogeological processes. The other major monitoring networks across the region are all project networks associated with mine developments to which WaterNSW has had limited or no access to the monitoring data. The lack of comprehensive baseline information makes it difficult to identify and quantify the regional impacts of coal mining. Often local impacts of coal mining are difficult to predict, let alone the cumulative impacts of more than 150 years of coal mining using various mining techniques.

A range of potential impacts on groundwater systems may occur a result of coal mining activities. Many of these have been recognised on a local scale within mined portions of the Southern Coalfield:

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



The primary focus for this Review is the impact of subsidence and the consequences for streamflow, water quality and catchment yield.

The degree to which each of these impacts is likely to occur within superficial aquifers, regional aquifers, and deeper groundwater systems is described in the following sections.

### 5.1.1 Superficial Aquifers

The superficial aquifers across the Special Areas are:

- Quaternary alluvium (unconsolidated sediments along valley floors);
- Quaternary colluvium (thin unconsolidated sediments on hillside and plateau locations – main component of upland swamp substrates).

The area of Quaternary alluvium is small (eg mapped upland swamps comprise 4.8% of the catchment areas – see Table 3.9) and unconsolidated sediments rarely occur in the lower catchments along the incised valleys or near any of the dams. The only mapped occurrences occur in the higher plateau areas. It is considered unlikely that superficial aquifers in the alluvium would be impacted by coal mining activities. However, if subsidence and cracking did occur beneath an alluvial deposit then a large proportion of the contained shallow groundwater could be lost into the underlying Hawkesbury Sandstone if falling water levels are impacting the sandstone aquifers and regional water table.

The Quaternary colluvium is more at risk of impact due to subsidence and coal mining activities even though this groundwater system is mostly disconnected from the regional Hawkesbury Sandstone aquifer. Subsidence and cracking across the plateau areas, if located beneath headwater and hillside swamps, will cause the shallow groundwater in the thin colluvial deposits to drain and swamps will quickly dry out. Summary impacts and consequences are provided in Table 5.1.

**Table 5.1: Superficial Aquifer – Potential Subsidence Impacts and Consequences**

Impact on Superficial Aquifers	Consequences
Falling water levels (perched aquifers will only persist for short timeframes after rain)	<ul style="list-style-type: none"> <li>▪ Loss of wetter headwater and hillside swamps.</li> <li>▪ Large wetting and drying cycles in affected swamps.</li> <li>▪ Changed flora and fauna composition of affected swamps.</li> </ul>
Loss of storage (stored groundwater will drain)	<ul style="list-style-type: none"> <li>▪ Same consequences as for falling water levels.</li> </ul>
Increased drainage to the Hawkesbury Sandstone	<ul style="list-style-type: none"> <li>▪ Increased recharge to the regional sandstone aquifer.</li> <li>▪ Unlikely to increase storage in the Hawkesbury Sandstone if water levels are also falling in this aquifer and there is increased discharge from the aquifer.</li> </ul>
Loss of streamflow	<ul style="list-style-type: none"> <li>▪ 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.</li> </ul>

### 5.1.2 Regional Aquifers

As stated in Section 3.5.1, the regional aquifers across the Special Areas are:

- Tertiary volcanics;
- Triassic Hawkesbury Sandstone and Gosford Sub-Group rocks.



The regional aquifer located in the Tertiary volcanics to the south of the Special Areas will not be impacted by coal mining and subsidence as it is located in areas where there are no economic coal resources.

In contrast, the regional aquifers in the Triassic Hawkesbury Sandstone and Gosford Sub-Group rocks are likely to be impacted in a numbers of ways due to the fact that these formations directly overlie all the historic, existing and prospective underground coal mines across the Special Areas. These aquifers are typically portrayed in the literature to be located within the constrained zone directly above longwall panels. However in some areas (such as at Dendrobium) recent studies (Coffey, 2012b) suggest there may be no constrained zone but rather a fracture zone that extends to surface. The upper 20 m of outcropping sandstone are prone to widespread tensile cracking due to the flexing and stretching of the surface imposed by subsidence of the uneven terrain.

Because this formation outcrops across almost the entirety of the Special Areas landscape, the near surface impacts and water cycle consequences of mining induced subsidence are likely to be substantial, particularly if mining industry assertions of the aquifer’s protection due to the maintenance of claystone aquitards and constrained zones prove to be incorrect. A list of potential impacts and consequences is provided in Table 5.2.

**Table 5.2: Regional Hawkesbury Sandstone Aquifer – Potential Subsidence Impacts and Consequences**

Impact on Regional Hawkesbury Sandstone Aquifers	Consequences
Falling water levels/piezometric levels in plateau areas	<ul style="list-style-type: none"> <li>▪ Loss of hillside springs and stream baseflow.</li> <li>▪ Loss of or changed terrestrial ecosystems that are partially groundwater dependent.</li> <li>▪ Reduced groundwater resource potential.</li> </ul>
Loss of storage capacity and change in groundwater storage characteristics in plateau areas	<ul style="list-style-type: none"> <li>▪ Increased secondary porosity and permeability.</li> <li>▪ Most likely to be a loss of volume if water levels fall and there is increased discharge.</li> <li>▪ Other consequences the same as for falling water levels.</li> </ul>
Increased recharge and discharge (due to increased fracture flow and groundwater velocities)	<ul style="list-style-type: none"> <li>▪ If enhanced cracking occurs at surface then increased rainfall recharge across the plateau areas.</li> <li>▪ If enhanced cracking and upsidence occurs along the valley floors then changed surface water-groundwater interaction processes and the potential for stream losses and increased downstream groundwater discharge.</li> </ul>
Increased drainage through the Bald Hill Claystone to the underlying Narrabeen Group groundwater system	<ul style="list-style-type: none"> <li>▪ Decreased horizontal flow and less natural discharge from the Hawkesbury Sandstone.</li> <li>▪ Loss of low salinity groundwater into the poorer quality Narrabeen Group groundwater system.</li> </ul>
Changed groundwater flow patterns	<ul style="list-style-type: none"> <li>▪ Loss of groundwater discharge to stream sections that previously provided important baseflow contributions.</li> <li>▪ Changed geochemistry and salinity distributions within this groundwater system.</li> <li>▪ Loss of or changed riverine ecosystems that are partially groundwater dependent.</li> </ul>
Loss of groundwater to areas outside of the drinking water catchments (i.e. less topographic control on regional groundwater flow)	<ul style="list-style-type: none"> <li>▪ Same consequences as for changed groundwater flow patterns.</li> </ul>



Impact on Regional Hawkesbury Sandstone Aquifers	Consequences
Loss of streamflow to shallow aquifers in valley areas	<ul style="list-style-type: none"> <li>Reduction in overall streamflow volumes.</li> <li>Losses will locally increase groundwater storage volumes, although a proportion of this water may return as stream baseflow lower in the catchment.</li> <li>Losses are expected to be more pronounced where Hawkesbury Sandstone rather than older Narrabeen Group rocks are the underlying rock type.</li> </ul>
Poorer quality baseflow discharges to streams	<ul style="list-style-type: none"> <li>Decreased pH and increased iron concentrations in groundwater discharge to streams.</li> <li>Smothering effect of colloidal and bacterial iron affecting riverine ecosystems.</li> </ul>

### 5.1.3 Deeper Groundwater Systems

These deeper groundwater systems comprise both minor aquifers and aquitards across the whole of the Special Areas. The three systems are:

- Triassic Narrabeen Group rocks (below the Gosford Sub-Group);
- Permian Illawarra Coal Measures;
- Permian Shoalhaven Group rocks.

The impacts to the Triassic Narrabeen Group rocks are likely to be similar to the overlying Hawkesbury Sandstone but more pronounced, especially in the fractured zone immediately above longwall panels. Once the confining claystone layers in the sequence are compromised then there will be greater vertical groundwater flow. Summary impacts and consequences are provided in Table 5.3.

**Table 5.3: Narrabeen Group Groundwater System – Potential Subsidence Impacts and Consequences**

Impact on Narrabeen Group Groundwater System	Consequences
Falling water levels/piezometric levels	<ul style="list-style-type: none"> <li>Unconfined groundwater conditions could develop in each of the sandstone units.</li> <li>Substantial water level declines, especially in the fractured zone (doesn't necessarily equate to groundwater storage losses).</li> <li>Groundwater gradients could flatten or reverse in the vicinity of the artificial lakes with potentially increased water losses.</li> </ul>
Changes in groundwater storage capacity and characteristics	<ul style="list-style-type: none"> <li>Increased secondary porosity and permeability.</li> <li>Minimal – storage will be recharged by fresher water from the Hawkesbury Sandstone and reservoirs.</li> <li>Storage volumes may in fact increase with increased fracturing and increased gradients.</li> <li>Potentially improved water quality.</li> </ul>
Increased drainage through the claystone units (Bald Hill, Stanwell Park and Wombarra) to the deeper Narrabeen Group groundwater system and then into the Illawarra Coal Measures	<ul style="list-style-type: none"> <li>Increased vertical flow and diminished horizontal flow.</li> <li>Increased flows to mining voids.</li> </ul>
Changed groundwater flow patterns	<ul style="list-style-type: none"> <li>Changed geochemistry and salinity distributions within individual aquifers and aquitards.</li> <li>Very complicated – other consequences uncertain.</li> </ul>



The groundwater system in the mined coal seams of the Permian Illawarra Coal Measures is largely removed with the total extraction of coal. The groundwater in the adjoining formations (above and below) will drain into the mining voids. Drainage from above will be accelerated due to the increased fracturing and subsidence in the caved zone and overlying fractured zone. Drainage from below may also occur due to stress induced cracking of the floor strata to some 30 m to 50 m depth (J Galvin pers com). Summary impacts and consequences are provided in Table 5.4.

**Table 5.4: Illawarra Coal Measure Groundwater System – Potential Subsidence Impacts and Consequences**

Impact on Illawarra Coal Measure Groundwater System	Consequences
Falling water levels/piezometric levels	<ul style="list-style-type: none"> <li>▪ Unconfined groundwater conditions develop throughout the sequence.</li> <li>▪ Mining voids become sinks for all groundwater.</li> </ul>
Changes in groundwater storage capacity and characteristics	<ul style="list-style-type: none"> <li>▪ There is a large or total loss of groundwater volume with the mining and removal of the targeted coal seams.</li> <li>▪ After the cessation of mining abandoned mine workings will provide large artificial (sub-surface) water storages.</li> <li>▪ Potentially improved water quality in the short-medium term as overlying groundwater systems drain.</li> </ul>
Changed groundwater flow patterns	<ul style="list-style-type: none"> <li>▪ Changed geochemistry and salinity distributions within mined seams and mining voids.</li> <li>▪ Very complicated – other consequences uncertain especially where multiple seams have been mined at different times.</li> </ul>
Streamflow	<ul style="list-style-type: none"> <li>▪ Once abandoned workings and goafs fill and overflow, some stream baseflow discharges may occur as water drains from adits and other mine entry locations that are not sealed (note that in some instances seals cannot be installed to sustain the increased pressure heads and therefore seals may be designed to transmit water). Because the entry for mines in the Southern Coalfield is either by shaft or to the east of the escarpment, flow from abandoned workings is unlikely to affect streams in the Special Areas.</li> <li>▪ Poor water quality discharges could occur across the landscape (particularly the escarpment areas) in the longer term.</li> </ul>

As there are no mining proposals below the Wongawilli Coal Seam within the Illawarra Coal Measures at present, there are not expected to be any impacts to the deeper Permian Shoalhaven Group rock groundwater system.

### 5.1.4 Conceptual Understanding of Changed Groundwater Flow Processes

Longwall mining causes substantial porosity and permeability changes in the geological strata above and generally within the angle of draw of the mined longwalls. These physical changes in the strata change the characteristics of shallower aquifers, aquitards and deeper water bearing zones. Multiple (side-by-side) longwalls generate broader cumulative effects.

The literature commonly invokes four conceptual zones associated with subsidence (see Section 4.2.1). From mine to surface these are:

- Caved/collapsed zone;



- Fractured zone;
- Constrained zone; and
- Surface (tensile cracking) zone.

However, (Pells and Pells 2012b) suggest there is insufficient proof to justify demarcation of specific zones, and that available data is more indicative of gradational permeability changes throughout the profile. The zonation approach has been adopted for the following discussion on conceptual understanding of potential groundwater impact and consequence processes but its unconfirmed status is noted.

The **caved/collapsed zone** at the base of the goaf area is generally assumed to comprise loose blocks of rock detached from the roof to occupy the cavity formed by longwall mining. This high permeability zone is known to contain large voids and forms a sink for all the water that drains from and through the overlying strata. During the period of active mining, this water needs to be pumped out to maintain safe mining conditions.

As longwall mining proceeds, the roof strata is inferred to sag and collapse into the void to form an arched **fractured zone** above each longwall panel exhibiting much higher permeability and porosity than the pre-mining host rock. Aquitards are commonly compromised as greater vertical connectivity of strata occurs and groundwater drains to the caved/collapsed zone. Major depressurisation of groundwater occurs in this area and steep vertical gradients result as groundwater drains into and collects in the caved/collapsed zone.

The Height of Fracturing (HoF) zone in the Southern Coalfield area is the subject of much debate and different modelling approaches. A thorough discussion of the models commonly used to predict impacts associated with longwall mining is discussed in Sections 4.2.1 and 4.2.2. For the current 305 m wide longwall panels at Dendrobium, some models predict that the HoF and connected fracturing extends above the Bald Hill Claystone and into the overlying Hawkesbury Sandstone (Parsons Brinckerhoff, 2015b and see Figure 4.8).

Overlying the fractured zone is inferred to be a **constrained zone** where strata are assumed to be laterally constrained by mainly compressional forces, and have absorbed most of the strain energy without suffering significant fracturing or alteration to the original physical properties. Some bed separation, slippage or fracture movement is expected in this zone as well as discontinuous vertical cracks. Understanding the groundwater characteristics and then the migration and flow processes through this zone before, during and after mining is fundamental to minimising surface to seam water connectivity.

Finally, subsidence causes extensional fracturing within the **surface tensile zone** which typically is thought to extend to depths of 15-20 m below the surface. These fractures can be less than 1 mm to more than 50 mm wide and extend for tens of metres. Open fractures near surface have a dramatic effect on the hydrology of upland swamps and perennial streams. Fracturing is most prevalent in valley areas where perennial streams that were traditionally gaining streams may become losing streams (either temporarily or permanently). A proportion of baseflows can return in downstream areas (usually heavily laden with iron-rich oxides from enhanced oxidation from rock-water interaction and natural shallow groundwater inflows). Lost stream flows report to the regional aquifer and a small proportion is suspected to report to deeper groundwater systems and eventually to the mine workings.



In plateau areas, the voids created by this extensional fracturing would typically extend to (or to just above) the regional water table in the Hawkesbury Sandstone. Enhanced rainfall recharge to the regional water table is expected after an initial drop in water levels in the regional sandstone aquifer due to the additional storage volume created by fracturing and subsidence.

There are numerous comments in mining compliance reports that this zone does not connect with the deeper fractured zone, however many of the statements are lacking sufficient water level and water quality proofs (eg Minchin et al, 2016). With steep vertical gradients, increased mine inflows after heavy rain, and numerous monitoring data now suggesting that a small proportion of modern water is reporting to mine workings at Dendrobium (eg. Ziegler and Middleton, 2011), it cannot be discounted that there are some (small) interconnected fracture systems from the surface zone through the constrained zone and into the fractured zone and finally the caved zone. Some models even predict that there may be no constrained zone but rather a fractured zone that extends to surface.

Given the large volume of groundwater in storage in all regional groundwater systems, the time for surface waters to make their way through the tortuous fracture network (even after mining) and over a vertical distance of more than 300 m is expected to take decades or longer.

There are several lines of evidence as to whether shallow groundwater and surface water is currently reporting to operational mines. The water level/pressure, geochemical and isotopic data sets are inconsistent:

- Declining water levels and pressure data together with steeper hydraulic gradients suggest that groundwater is draining (or at the very least that there is an increased potential for groundwater to drain vertically);
- Geochemical data sets are relatively unchanged based on the available period of data suggesting that groundwater migration volumes and rates are slow;
- Tritium isotope data suggests some modern water is present in mine water (but at Dendrobium this could be explained by other water sourced for operational purposes (Minchin and Brown, 2016). There is negligible modern water in the intermediate and deep aquifers above the Dendrobium mine workings);
- There is a strong correlation between heavy rainfall and mine inflows suggesting connectivity (but the effect of hydraulic loading and unloading caused by increased water levels and increased volumes in the regional sandstone aquifer has not been considered).

Data from vibrating wire piezometers (VWPs) surrounding active mines shows that steeper vertical gradients establish between regional sandstone aquifers and deeper groundwater systems as depressurisation expands due to mining. The piezometric levels in the deeper systems are rarely observed to recover within monitored timeframes. Whilst dewatering of upper aquifers is frequently observed to be rapid and more dramatic than deeper aquifers, it remains uncertain whether water levels in the regional sandstone aquifer will recover and over what timeframe (SCA, 2013).

A qualitative summary of the observed and predicted changed groundwater flow processes for each of the groundwater systems overlying active longwalls and associated subsidence zones is provided in Table 5.5.



**Table 5.5: Summary of Changed Groundwater Flow Processes**

Groundwater System Classification	Sub-Type	Subsidence Zone	Changed Groundwater Flow Processes
Superficial Aquifers	Alluvium	Surface	<ul style="list-style-type: none"> <li>No observed changes to date.</li> </ul>
	Colluvium	Surface	<ul style="list-style-type: none"> <li>Increasing drying cycles as water tables rise then fall more quickly after rain.</li> <li>Increased recharge to the regional sandstone aquifer.</li> </ul>
Regional Aquifer	Hawkesbury Sandstone	Surface	<ul style="list-style-type: none"> <li>Increased recharge across the plateau areas.</li> <li>Changed surface water-groundwater interaction processes and the potential for stream losses and increased groundwater discharge.</li> </ul>
		Constrained	<ul style="list-style-type: none"> <li>Enhanced flow to hillside springs before water levels fall and springs slowly disappear.</li> <li>Small component of vertical flow as water levels fall.</li> </ul>
		? Fractured	<ul style="list-style-type: none"> <li>Hillside springs quickly disappear.</li> <li>Moderate component of vertical flow as water levels fall.</li> </ul>
Deeper Groundwater Systems	Narrabeen Group rocks	? Constrained	<ul style="list-style-type: none"> <li>Moderate component of vertical flow as water levels fall.</li> </ul>
		Fractured	<ul style="list-style-type: none"> <li>Aquitards become fractured and there is less impedance to vertical flow.</li> <li>Large component of vertical flow as water levels fall.</li> </ul>
	Illawarra Coal Measures	Fractured	<ul style="list-style-type: none"> <li>Very large component of vertical flow as water levels fall.</li> </ul>
		Caved/Collapsed	<ul style="list-style-type: none"> <li>Large groundwater volumes drain from overlying fractured zone and accumulate in the goaf areas.</li> <li>Suspected flow contributions from constrained and surface zones.</li> </ul>
	Shoalhaven Group rocks	Not affected	

## 5.2 Potential Impact Limits

All overlying groundwater systems are likely to be impacted by longwall mining. The severity of impact and what is tolerable in terms of water resource loss (to both surface water and groundwater) are key questions for WaterNSW. In particular, being able to quantify the impacts to baseflow and catchment yield are the most important considerations for WaterNSW, as these impacts may ultimately lead to a cumulative reduction in catchment yield which then impacts on the reliability of Sydney’s drinking water supply.

The groundwater systems overlying the mines and underlying the water supply catchments are heterogeneous and the associated flow processes are complex. There is no comprehensive baseline information that describes system attributes and natural pre- and post-levels of



groundwater system connectivity in mined areas. There is also no historical longwall mining domain where long-term groundwater recovery to equilibrium conditions has been monitored. Some indication of likely attributes and seasonal trends can be obtained from adjacent 'control' areas where there has never been any mining or groundwater abstraction.

WaterNSW is particularly seeking quantitative performance indicators that are tolerable in respect of:

- Water leakage from reservoirs;
- Water losses from catchments;
- Water quality;
- Ecological impacts.

Losses from regional and superficial aquifers could be added to this list of indicators to provide a more holistic appreciation of impacts. Many of the groundwater modelling assessments completed for ongoing longwall mining provide predictions for water level impacts to different groundwater systems. These should not be confused with determining appropriate impact limits.

The *NSW Aquifer Interference Policy* (NOW, 2012) provides a framework for assessing the impacts of aquifer interference activities (such as mining) on water resources. Included in this policy document are quantitative criteria to assess 'minimal impact considerations' for aquifer interference activities on highly productive and less productive groundwater sources. The Sydney Basin – Central groundwater source (covering the Woronora Special Area and the Metropolitan mine) is a less productive groundwater source. The Sydney Basin – Nepean groundwater source (covering most of the Metropolitan Special Area and the Dendrobium Mine and smaller coal mines) is a highly productive groundwater source. The criteria proposed for "Porous and Fractured Rock Water Sources" under highly productive and less productive groundwater sources are a useful starting point to assess acceptable impacts to water table, water pressure and water quality attributes. The criteria are provided in Table 5.6 below.

**Table 5.6: Proposed Impact Criteria for Porous and Fracture Rock Water Sources**

Water Table	Water Pressure	Water Quality
<p>Less than or equal to 10% cumulative variation in the water table, allowing for typical climatic "post-water sharing plan" variations, 40 m from any:</p> <p>(a) high priority groundwater dependent ecosystem; or (b) high priority culturally significant site; listed in the schedule of the relevant water sharing plan. A maximum of a 2 m decline cumulatively at any water supply work.</p>	<p>A cumulative pressure head decline of not more than a 2 m decline, at any water supply work.</p>	<p>Any change in the groundwater quality should not lower the beneficial use category of the groundwater source beyond 40 m from the activity.</p>
<p>If more than 10% cumulative variation in the water table, allowing for typical climatic "post water sharing plan" variations, 40 m from any:</p> <p>(a) high priority groundwater dependent ecosystem; or (b) high priority culturally significant site; listed in the schedule of the relevant water sharing plan if appropriate studies demonstrate to the Minister's satisfaction that the variation will not prevent the long-term viability of the dependent ecosystem or significant site. If more than a 2 m decline cumulatively at any water supply work then make good provisions should apply.</p>	<p>If the predicted pressure head decline is greater than requirement 1. above, then appropriate studies are required to demonstrate to the Minister's satisfaction that the decline will not prevent the long-term viability of the affected water supply works unless make good provisions apply.</p>	<p>If condition 1 is not met then appropriate studies will need to demonstrate to the Minister's satisfaction that the change in groundwater quality will not prevent the long-term viability of the dependent ecosystem, significant site or affected water supply works.</p>



For the whole of the Special Areas, it is not possible for the groundwater components of the water cycle (both for regional baseline and regional cumulative mining impact scenarios) to be accurately quantified at this time. In fact it is unlikely that absolute quantification of groundwater impacts will ever be derived as it is not possible to directly measure impacts such as leakage rates and loss volumes through direct measurement. Instead there is going to have to be continued strong reliance on numerical modelling that is based on constantly revised conceptual models, improved parameterisation, and recalibrated numerical models. Verification of numerical models using observed piezometric and water level hydrographic data, and mine water fluxes should continue to be the primary proof of groundwater impacts.

Groundwater models are based on available geological and hydrogeological data and cannot accurately replicate all the physical attributes of the three dimensional areas that are modelled for each mine development. They are at best important management tools to predict the possible impacts associated with a particular mine development. Numerical models should be constantly updated and improved once site specific data becomes available to verify the initial predictions. Some model elements where there is a paucity of data include:

- Leakage from river bed and dam storages (diffusivity parameters);
- Natural permeability changes associated with facies changes (particularly aquitard characteristics);
- Enhanced permeability changes across multiple geological layers during and post mining;
- Storativity estimates.

It is also important that conceptual models upon which numerical models are built, and any changes over time be fully elaborated and justified in technical reports.

Increased transparency is required around model improvements, sensitivities of model parameters and model uncertainty. Improved reporting of water balances that identify all inflows and outflows from the different groundwater systems, important surface water features and each of the dam storages is also essential.

With respect to groundwater, a couple of existing impact thresholds are worth restating:

1. For superficial aquifers associated with upland swamps, most current TARPS suggest there should be no change from the natural variability exhibited in either the baseline period monitoring for that swamp or a comparable control swamp with similar hydrology and hydrogeological characteristics.
2. The Dam Safety Committee prescribes a limit of 1 ML/d limit on the volume of water lost by leakage from each WaterNSW storage.

Attempting to set performance criteria on baseflow losses from surficial and regional aquifers is difficult as they are relatively small and difficult to measure.

## 5.3 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 both water levels/piezometric pressures and water quality. This requirement applies to both mining impacted areas and control sites.

Prior to 2000, groundwater monitoring networks associated with coal mining activities were few and sparse. Project networks have been established over the last decade for new mining



developments that mainly comprise VWP installations above and adjacent to longwall panels, and shallow monitoring bores within upland swamps. Also if surface water-groundwater connectivity is expected and impacts are likely, then paired surface water gauging locations and shallow monitoring bores are sometimes established. Consequently on at least a local scale there are now reasonable networks to assess latest groundwater and baseflow trends however on a regional scale it is not possible to integrate data. Importantly however, current data cannot estimate 'pre-mining' attributes and is insufficient to distinguish natural seasonal variability of the different groundwater systems across the Metropolitan and Woronora Special Areas.

Longer term monitoring of groundwater levels/pressures is also essential to ensure that there are accurate long term predictions and modelling of impacts. Monitoring networks need to continue and data needs to be collected after mining until levels stabilise around a new equilibrium. Minimum timeframes are expected to be decades but attaining equilibrium could take much longer.

Mining impacts are mostly assessed against a small period of (local) pre-longwall mining piezometric data and shallow upland swamp water level data (usually less than 12 months). There is rarely any additional stream gauge or regional sandstone aquifer monitoring. This short 'baseline' monitoring period is not ideal as VWPs are equilibrating immediately after completion, and climatic and historical mining trends cannot be recognised in such a short period of record.

Piezometric/water level data is the primary data set used to assess mining induced impacts and the connectivity of different groundwater systems. This data set is the most important as the first indications of impacts to a groundwater system are always pressure/water level related. Geochemical, selected isotope data and tracer techniques have been used more recently as secondary proof to assist in describing the attributes and connectivity of these different systems. More use could be made of these secondary proof techniques (such as carbon 14 and chlorine 36 dating) to determine natural attributes and to assess mining induced impacts such as changed groundwater flow processes.

The following sections discuss the monitoring shortcomings for each of the different groundwater systems.

### 5.3.1 Superficial Aquifers

The superficial aquifers within colluvial and alluvial sediments and the contribution these superficial aquifers make to swamp ecosystems, stream flow and catchment yield are important in a number of ways.

Monitoring of shallow water levels in upland swamps is necessary to determine whether swamps are perched or connected to the regional sandstone aquifers and to understand the frequency and duration of natural wetting and drying cycles. Monitoring of outflow volumes and their duration assists with assessing baseflow contributions from these superficial aquifers. Wetting and drying cycles can vary substantially between swamps so baseline monitoring programs of several years in advance of mining is essential if natural climatic variations are to be distinguished from mining induced changes. Control site monitoring is also important and is underway for swamps overlying and remote from Peabody's Metropolitan mine activities. While control sites are useful to provide a good indication of natural variability, they are not absolute controls as individual upland swamps react differently to rainfall events.

Shallow monitoring bore networks are usually only installed months in advance of mining activities and often only within superficial aquifers (i.e. not nested with shallow bedrock piezometers). Paired monitoring bores (i.e. shallow colluvial monitoring bores together with shallow sandstone



monitoring bores) are only operational for some swamps associated with the Metropolitan mine in the Woronora catchment.

The early installation of paired monitoring bores and gauging stations that monitor the colluvial and sandstone aquifers and associated baseflow discharges to permanent streams is essential if the pre-mining behaviour and post-mining changes to superficial aquifers are to be understood.

### 5.3.2 Regional Aquifers

Monitoring of the important aquifers within the Hawkesbury Sandstone has been a relatively recent addition to the suite of groundwater data. There is little historical monitoring data of this key groundwater system within the Metropolitan and Woronora Special Areas. Monitoring occurs via both open monitoring bores and VWPs, but the latter predominates.

Long term and vertical monitoring of water levels within this aquifer system is essential to assess:

- The natural connectivity of shallow and deeper aquifers within the regional sandstone aquifer;
- The natural and mining-induced connectivity of baseflow discharges and streamflow;
- Hydraulic gradients and water quality attributes;
- Whether (and how far) the fractured zone induced by subsidence might propagate into this regional aquifer;
- Whether there is increased rainfall recharge to this system during, and post, mining; and
- Whether there is a permanent loss of head and water resource potential during and post mining.

It is particularly important to have shallow monitoring bores in this regional aquifer in close proximity to upland swamp monitoring (to assess whether these superficial aquifers are connected-gaining/losing or disconnected-losing). Similarly shallow monitoring bores in areas of permanent streams can assist in quantifying baseflow discharge volumes and determining where, when, and how the stream changes from connected-gaining to connected-losing (or disconnected-losing).

The early installation of monitoring bores and gauging stations that monitor the Hawkesbury Sandstone and associated baseflow discharges to permanent streams is essential. Additional isotopic sampling and periodic monitoring (in addition to tritium monitoring) would be useful to characterise the vertical variability of groundwater within the regional aquifer.

### 5.3.3 Deeper Groundwater Systems

Pore pressure measurements in these groundwater systems in the deeper Triassic and Permian sedimentary rocks are typically monitored with VWPs. There are relatively few open boreholes where representative water quality samples can be obtained from individual strata, which greatly limits the geochemical assessment of mining effects within these strata.

Depressurisation, permeability and connectivity trends associated with low permeability aquifers and aquitards can take months and years (and potentially decades) to eventuate and fully comprehend. The fact that VWPs often fail on installation or when horizontal shearing occurs during longwall mining, and these installations rarely have a life greater than a decade, severely limits this type of monitoring to assess long term impacts to (and potential recovery of) deeper groundwater systems. As the groundwater levels cannot be independently verified in a grouted VWP installation, it is important that sufficient screened "open hole" boreholes (if able to be



completed in low permeability and potentially gaseous formations) are available to confirm the accuracy of VWP arrays.

Earlier installation of VWPs and replacement of bundled VWPs when installations fail are important considerations to better assess long term groundwater trends. Monitoring of deep groundwater quality and fingerprinting the water using environmental and radio-isotopes would be extremely useful before, during and after mining, however little sampling and analysis is currently carried out prior to mining. It is appreciated that there are significant institutional impediments to requiring monitoring for sufficient length of time to confirm that recoveries in surface water and groundwater regimes occur as predicted. It is further understood that monitoring obtaining representative water samples is difficult and may be impossible from the low permeability aquitard units.

### 5.3.4 Other Knowledge Gaps

Further investigation of the groundwater flow processes (and subsequent changes with mining) within the fractured and constrained zones would greatly benefit our understanding of mine water inflows, and losses to and from streams and storages.

In particular these knowledge gaps include:

- Insufficient understanding is currently available on the seasonality of the superficial water tables in pre-and post-mining catchments;
- A comprehensive understanding of the difference in regional aquifer recharge behaviour between unmined and mined catchments is key to improving the analytical predictions of surface water flow losses and hydrogeological effects from mining;
- Improved understanding of the function of aquitards and their hydrogeological characteristics within the Narrabeen Group rock strata, before, during and after mining;
- Improved knowledge of the height of connective fracturing (HoCF) and the type and extent of movements and associated fracturing in various formations;
- Geomorphic and volumetric analysis of the proportion of stream flow that returns as downstream baseflow versus the proportion that is lost to groundwater.

Numerical groundwater models will continue to be important tools to predict and assess real world trends in the different groundwater systems. However, it should be remembered that they are only water management tools and do not accurately represent all of the sub-surface geology, groundwater processes and associated impacts. It is important in future reporting of numerical modelling and predictive results that:

- There is careful selection and justification of an appropriate modelling code;
- The numerical model construction is soundly based on the hydrogeological conceptualisation;
- Any changes to the conceptual model and associated changes to the numerical model are clearly articulated and justified;
- The conceptual model accurately reflects the changes in hydraulic characteristics of the rock mass above, and adjacent to, the extraction zone;
- The sensitivities of the different aquifer parameters are clearly identified;
- All relevant parameters (e.g. permeability, transmissivity), assumptions (e.g. saturation depths, fracture heights and connectivity) and conceptualisations (e.g. lithological interpretations) are clearly presented, preferably by means of exported layers that can be visualized within a GIS framework;



- Uncertainty analysis of the modelling must be clearly presented, and should be directed specifically to provide clarity on the level of confidence that unacceptable risk-based thresholds will not be exceeded;
- An adequate range of model outputs to show the predicted outcomes, such as water table contour plots for each main horizons (both aquifers and aquitards) at suitable time slices and pressure cross-sectional plots at steady state and under transient conditions for future longwall panel scenarios;
- Additional information is provided on horizontal and vertical flow rates for the relevant groundwater systems;
- Improved water balances for each model run are provided (against a pre-mining baseline) so that it is clear what the predicted inflows and outflows are for each of the relevant groundwater systems and groundwater receptors, for example:
  - Hawkesbury Sandstone recharge (rainfall), discharge (evapotranspiration, baseflow, deeper losses), and change in storage;
  - Narrabeen Group recharge (from rainfall, Hawkesbury Sandstone, dam storages), discharge (evapotranspiration, baseflow and deeper losses), and change in storage;
  - Illawarra Coal Measures recharge (from Narrabeen Group strata, deeper strata), discharges (pumped mine water), and change in storage.



## 6 Surface Water

Information on the surface water related environmental consequences of underground extraction in terms of surface water quantity, quality and swamps is provided in the following sections. The information in this section is based on the Literature Review summaries provided in Appendix C and F as well information provided in Section 3.6.

### 6.1 Environmental Consequences of Underground Extractions

#### 6.1.1 Surface Water Quantity

As described in Appendix C, direct impacts of subsidence on watercourses can include changes to stream bed and bank profiles, cracking of a watercourse bed and the creation or destruction of ponds. These effects have the potential to impact on the flow regime and leakage losses via subsurface cracking. As demonstrated through swamp substrate monitoring in many of the parts of the plateaux and hillsides, this cracking and subsequent subsurface flow diversion (increased groundwater recharge) occurs over a much wider part of the catchment than just the valley-bottom channels where they are most easily observed. Further details of the various consequences, based on the reviews in Appendix C, are provided below.

##### **Volume of Surface Flow in Streams**

The *Southern Coalfield Strategic Review* (2008) suggested that the following types of losses might plausibly occur due to subsidence caused by longwall mining:

- **Once-only losses to fill the shallow non draining subsurface fracture network associated with both tensile and shear failure.** These losses were assessed to have negligible impact on stream flows after initial filling of the storage created by the new fracture network.
- **Losses into a shear fracture network associated with the constrained zone at intermediate depths.** Dilation occurs on shear surfaces on bedding planes in the constrained zone, creating voids that can be filled by water as a once-only event. However, given the right combination of circumstances, shear surfaces could form a conduit for lateral water flow which may or may not report to the same catchment.
- **Sustained leakage losses into a mine:** While this is known to have occurred in the Southern Coalfield on isolated occasions it has generally been associated with a shallow depth of cover and/or the presence of anomalous conduits like fractured rock associated with igneous intrusions (Byrnes, 1999).

A number of studies assessed the environmental consequences of longwall mining on the volume of surface water flow in overlying streams.

Stout (2003) measured the consequences of longwall mining on headwater streams in northern West Virginia. While all streams were found to be impacted near their sources, the streams re-emerged downstream, with most reappearing gradually along the downstream gradient. Stream flow width returned to reference conditions in four of six longwall mined streams in catchments greater than 32 ha in area.

Jankowski (2009) describes the Sydney Catchment Authority's (SCA, now WaterNSW) understanding of how surface flow in subsidence-impacted streams is diverted to subsurface routes and surface water-groundwater connectivity is enhanced as a result of fracturing riverbeds and rockbars. Increased surface fracturing also allows a greater proportion of catchment rainfall to



infiltrate and recharge fractured aquifers, reducing runoff available for recharging streams and water storages.

Jankowski & Knights (2010) analysed streamflow records to identify reductions and losses in the Waratah Rivulet catchment, which the SCA believed had been impacted by subsidence from the Metropolitan Mine's longwalls beneath it. Analysis of flow monitoring records indicated that surface flow losses were occurring between the flow monitoring stations located upstream and downstream of the mining affected area. The authors acknowledged that it was not possible on the available evidence to ascertain whether all lost water re-emerges further downstream or whether there is temporary or permanent water loss from the catchment. Losses from the shallow (upper Hawkesbury Sandstone aquifer) to the deeper regional aquifer (lower Hawkesbury Sandstone aquifer) were not able to be monitored or accessed. Reduction in streamflow depends on surface fracturing and the hydraulic conductivity (or bed conductance) of the stream and therefore the interchange between surface flow, shallow aquifer and the deeper regional aquifer at the Rivulet. Another factor is the relative location of the creek to the regional aquifer (described as 'losing' when the creek bed lies above the regional water table and 'gaining' when it is below the water table and receiving groundwater inflows).

Krogh (2012) found that a number of rivers and streams on the Woronora Plateau have been impacted by longwall mining including Cataract River, Georges River, Waratah Rivulet, Wongawilli Creek, Native Dog Creek, Lizard Creek and Wallandoola Creek. In many of the affected streams pool levels have declined or drained completely and widespread iron staining has occurred.

The *Dendrobium Watercourse Impact Monitoring, Management and Contingency Plan* (WIMMCP) (Illawarra Coal, 2015b) documents impacts on Donalds Castle Creek. An area of fracturing up to 0.015 m wide and 2 m long with a maximum uplift of 0.040 m and flow diversion was observed at the basal step of Swamp 5, in the upper section of Donalds Castle Creek. Flow was inferred in this report to be returned to the surface approximately 10 m downstream at the bottom of the basal step. Subsequent evidence presented in the End of Panel 11 surface water report (HydroSimulations, 2016b) indicates that flow from the two headwater tributaries and their associated valley-fill swamps have been further impacted (see also Krogh, 2015).

HydroSimulations (2016b) also notes the severity of impacts in another creek to the east, identified as Watercourse WC21. Over a distance, the surface water flows in this creek cease and the cracked pools are drained dry except immediately after rainfall. A subsequent report by the State Government (DP&E, 2015) confirms that the level of impact at this location are above prediction, but notes that there is no specific performance measure in the project approval which prohibits such impacts.

As reported in HydroSimulations (2016b), McMahon (2015b) makes the point that flow gauging is unable to allow a conclusion that water re-emerges downstream, and is similarly unable to allow a conclusion that it does not re-emerge. While the loss of flow observed in the streams is significant enough to be discernible on hydrographs for those streams, any loss of flow is not discernible at the downstream gauges. This may be due to gauging accuracy and the small magnitude of loss compared to total flow at the downstream gauging stations (HydroSimulations, 2016b).

Table 6.1 provides a summary of the recorded impacts and consequences of longwall mining on the volume of surface flow in streams in the Special Areas.



**Table 6.1: Summary of Some Recorded Impacts and Consequences – Volume of Surface Flow in Streams**

Physical Subsidence Effects and Impacts	Environmental Consequences
<ul style="list-style-type: none"> <li>Ground deformation effects</li> </ul>	<ul style="list-style-type: none"> <li>Enhances surface water-groundwater interaction due to the enlargement of existing fractures, development of new fractures and the separation of bedding planes.<sup>1</sup></li> </ul>
<ul style="list-style-type: none"> <li>Fracturing across the catchment</li> </ul>	<ul style="list-style-type: none"> <li>Impacts on wider catchment area resulting in increased subsurface recharge/reduced runoff and increased aquifer storage/declined groundwater levels.<sup>1</sup></li> </ul>
<ul style="list-style-type: none"> <li>Fracturing of streambeds</li> </ul>	<ul style="list-style-type: none"> <li>Surface flow losses to sub-surface routes of up to 2 ML/day in the Waratah Rivulet during low flows (&lt;8 ML/day).<sup>1</sup></li> </ul>
<ul style="list-style-type: none"> <li>Fracturing of streambeds</li> </ul>	<ul style="list-style-type: none"> <li>Loss of surface flows in WC21 (tributary of Wongawilli Creek) above the mined panels for a length of 600 m, with the stream bed incapable of containing significant flows for more than a few days<sup>2</sup></li> </ul>
<ul style="list-style-type: none"> <li>Fracturing of streambeds</li> </ul>	<ul style="list-style-type: none"> <li>Mining of Dendrobium LW9 has reduced the outflow from catchments WC21_S1 and WWL by approximately 13% during the specified mined period<sup>3</sup></li> <li>Mining of LW 10 has reduced the outflow from catchments DC_S2 and WC21_S1 by approximately 10% during the specified mined period<sup>3</sup></li> </ul>

Sources:

<sup>1</sup> Jankowski and Knights (2010)

<sup>2</sup> NSW DP&E (2015)

<sup>3</sup> McMahon (2015b)

**Volume of Water in Pools**

Galvin (2005) related environmental consequences experienced by two rockbars in Waratah Rivulet caused by specific subsidence impacts due to Metropolitan Mine longwalls 9, 10, 11 and 12. While the rockpool behind rock bar WRS1 maintained its pre-mining water level, surface cracking was observed at rock bar WRS3, resulting in surface flow being diverted into the sub-surface fracture network upstream of WRS3, water ceasing to flow over the rock bar and the water level in the pond behind the rock bar to drop to very low levels in periods of low natural water runoff. Notwithstanding the consequences observed at WRS3, Galvin stated that there has been no indication of surface water loss into the mine to date; existing monitoring flow systems give no indication that subsurface flow is not reporting back into the Waratah Rivulet sub-catchment and surface water flow into the pond behind WRS3 is not inconsistent with sub-surface flow reporting back to the Waratah Rivulet further downstream of the WRS3 rock bar. Subsequent work suggests that the void space created within the rock fabric between an extracted seam and the subsided surface is in the order of 1 - 3 GL per 300 m wide longwall (Parsons Brinkerhoff, 2015; Tammetta, 2016).

The *Southern Coalfield Strategic Review* (NSW Government, 2008) found that the losses into a shear fracture network along shear planes commonly associated with bedding planes in the surficial zone can lead to draining of rock pools behind rock bars and consequent partial or complete disconnection of these key components of a healthy stream habitat, particularly during low stream flows. The shear fracture network extends to around 15 m in depth, or perhaps some greater depth depending upon local conditions. Increasing confinement at depth would be expected to reduce flow pathway apertures and the transmission potential of re-directed surface waters. Similarly, increasing confinement beneath valley sides would be expected to impede transmission along lateral pathways although there is little if any direct evidence to confirm this hypothesis. If these conditions of confinement prevail, then loss of flow from a surface drainage is likely to return to the system at some point downstream. Inspections conducted by the Enquiry Panel suggest this distance can vary from as little as 20 m for specific rock bars to more than 200 m.



Table 6.1 provides a summary of the recorded impacts and consequences of longwall mining on the volume of pools in the Special Areas.

**Table 6.2: Summary of Some Recorded Impacts and Consequences – Volume of Water in Pools**

Physical Subsidence Effects and Impacts	Environmental Consequences
<b>WRS1 - LW9 (Metropolitan Mine)</b> <ul style="list-style-type: none"> <li>▪ 130 m from WRS1</li> <li>▪ Valley closure 100 mm</li> <li>▪ Horiz disp 200 mm</li> <li>▪ Subsidence 10-25 mm</li> <li>▪ Upsidence 60 mm</li> <li>▪ Surface fracture to 6.5-7.5 m deep</li> <li>▪ Bed separation 37 mm</li> </ul>	<ul style="list-style-type: none"> <li>▪ Rock pool in Waratah Rivulet behind WRS1 maintained pre-mining level<sup>1</sup></li> </ul>
<b>WRS1 - LW10 (Metropolitan Mine)</b> <ul style="list-style-type: none"> <li>▪ upsidence 150 mm</li> <li>▪ valley closure of 180 mm over 30 m interval</li> <li>▪ Groundwater levels unchanged from the previous longwall</li> </ul>	<ul style="list-style-type: none"> <li>▪ Rock pool in Waratah Rivulet behind WRS1 maintained pre-mining level<sup>1</sup></li> </ul>
<b>WRS1 – 3 more LWs (Metropolitan Mine)</b>	<ul style="list-style-type: none"> <li>▪ Rock pool in Waratah Rivulet behind WRS1 maintained pre-mining level<sup>1</sup></li> </ul>
<b>WRS3 - LW10 (Metropolitan Mine)</b> <ul style="list-style-type: none"> <li>▪ 270 m from WRS3</li> <li>▪ valley closure of 60 mm over 40 m interval</li> </ul>	<ul style="list-style-type: none"> <li>▪ Surface cracking in Waratah Rivulet observed<sup>1</sup></li> </ul>
<b>WRS3 - LW11 (Metropolitan Mine)</b> <ul style="list-style-type: none"> <li>▪ upsidence 60 mm</li> <li>▪ valley closure of 180 mm over 30 m interval</li> </ul>	<ul style="list-style-type: none"> <li>▪ 4 to 4.5 ML/d of surface flow diverted into the sub-surface fracture network upstream of rock bar WRS3 in Waratah Rivulet since Nov 2004<sup>1</sup></li> <li>▪ Water has ceased to flow over the rock bar</li> <li>▪ Water level in the pond behind the rock bar dropped to very low levels in periods of low natural water runoff</li> </ul>
<b>WRS3 - LW12 (Metropolitan Mine)</b>	<ul style="list-style-type: none"> <li>▪ Very low likelihood that water is currently being lost or will be lost from Waratah Rivulet on an ongoing basis to the catchment when LW12 is extracted<sup>1</sup></li> <li>▪ No indication of surface water loss into the mine to date</li> <li>▪ No indication that subsurface flow is not reporting back into the Waratah Rivulet sub-catchment</li> <li>▪ Surface water flow into the pond behind WRS3 is consistent with sub-surface flow reporting to Waratah Rivulet further downstream of WRS3</li> </ul>
<b>Dendrobium Mine</b>	<ul style="list-style-type: none"> <li>▪ Pool levels declined or completely drained over a distance of over 600 m<sup>3</sup></li> <li>▪ Loss of flow in a tributary of Wongawilli Creek (WC21) except immediately after rainfall for distance of over 600 m<sup>3</sup></li> <li>▪ Widespread iron staining<sup>2</sup></li> </ul>

Sources:

<sup>1</sup> Galvin (2005)

<sup>2</sup> Krogh (2012)

<sup>3</sup> Cardno (2016)

**Catchment Yield**

A number of different approaches have been adopted to assess the impact of mining on catchment yield.



Parsons Brinkerhoff (2008d) analysed rainfall and flow records for the Waratah Rivulet from 2007-2008 for the then Sydney Catchment Authority to estimate losses to catchment yield. Rainfall data from four rain gauges and flow data for three gauging stations were obtained. One of the gauging stations was located upstream of the subsidence impacted area and two of the stations were located downstream of the subsidence impacted area. Two methodologies of analysis were used, resulting in an estimated reduction in surface flow for this section of the Rivulet of 15 to 30%.

More recently Gilbert & Associates (2015) re-calibrated the AWBM models for Waratah Rivulet and Woronora River (see Section 3.7.5) in order to assess compliance with the relevant performance measure set out in the conditions of approval for Metropolitan Coal Longwalls 20-22 and 23-27, namely: *Negligible reduction in the quantity of water resources reaching the Woronora Reservoir.*

The analysis by Gilbert & Associates indicated that there was no statistical difference between the flow reaching the reservoir as a result of mining compared to pre-mining conditions.

HydroSimulations (2016b) assessed the impacts of mining on flow in a number of small catchments draining from the area subject to mining in Dendrobium 3B. The assessment was undertaken by comparing the observed flow with the modelled flow using AWBM rainfall-runoff models. The analysis provided the estimates of reduction in catchment yield set out in Table 6.3.

**Table 6.3: Assessed Reduction in Catchment Yield in Dendrobium Area 3**

Catchment	Monitoring Site	Catchment Area (ha)	Record Prior to Mining (years) <sup>1</sup>	Yield Reduction (%)
Donalds Castle Creek	DC2	108	1.0	20%
Donalds Castle Creek	DC13	164	na	15%
Wongawilli Creek	WC21	243	1.2	11%

Source: *HydroSimulations (2016b)*

A subsequent report by HydroSimulations (2016c) provide the following discussion in relation to apparent water loss as a result of mining:

*McMahon (2015b) makes the point that flow gauging is unable to allow a conclusion that water re-emerges downstream, and is similarly unable to allow the conclusion that it does not re-emerge. McMahon's point is that while the loss of water observed in the streams such as WC21, DC13S1 is significant enough to be discernible on hydrographs for those streams (HydroSimulations, 2016b), any loss of flow is not discernible at the downstream gauges (WWL and DCU). This is because of gauging accuracy and the small magnitude of loss compared to the total flow at the downstream gauging stations.*

It should also be noted that the assessment of loss of yield set out in Table 6.3 is entirely dependent on the adequacy of the calibration of the AWBM models for the affected catchments. As discussed in Section 3.7.5.2, the short period of flow data prior to mining and the adopted method of calibration do not provide a sufficiently robust basis for assessing loss of flow.

### **Summary**

Table 6.4, adapted from the *Southern Coalfield Strategic Review* (NSW Government, 2008), summarises the relevant consequences on surface water quantity (and quality). Further details of the various consequences, based on the reviews in Appendix C, are provided below.



**Table 6.4: Summary of Subsidence Impacts and Potential Consequences for Watercourses**

Physical Subsidence Effects and Impacts	Potential Consequences
<ul style="list-style-type: none"> <li>Tensile cracking of stream rock bars;</li> <li>Tensile/shear movement of joint and bedding planes in the stream bed</li> <li>Localised uplift and buckling of strata in the stream bed (e.g. lifting/ mobilising of stream bed rock plates)</li> </ul>	<ul style="list-style-type: none"> <li>Loss of surface water flow into subsurface flow path</li> <li>Loss of standing pools/connectivity</li> <li>Additional groundwater inflows, commonly carrying ferrous iron from freshly broken rock</li> <li>Adverse water quality, impacts e.g. iron bacterial mats</li> <li>Localised adverse visual impacts</li> <li>Aquatic ecology loss (connectivity)</li> <li>Reduction in Sydney's water supply yields not currently confirmed whether by significant volumes</li> </ul>
<ul style="list-style-type: none"> <li>Tilting of stream beds (both dynamic/ incremental and final outcome)</li> </ul>	<ul style="list-style-type: none"> <li>Stream bank and bed erosion where gradient increased</li> <li>New/enlarged pools where gradient decreases</li> <li>Migration of flow channels</li> <li>Aquatic ecology loss (connectivity)</li> <li>Reduction in Sydney's water supply yields</li> </ul>
<ul style="list-style-type: none"> <li>Gas releases from near surface strata</li> </ul>	<ul style="list-style-type: none"> <li>Temporary gas releases to the water column, with water quality impacts</li> <li>(Rarely) riparian vegetation dieback</li> <li>Appears to have no significant long term impact on water quality</li> <li>Diffuse emissions of methane may be occurring across the landscape, increasing greenhouse emissions by unknown volumes.</li> </ul>

Source: based on NSW Government, 2008

**Mining in the Vicinity of Large Water Bodies**

Singh and Jakeman (1999) discuss historical worldwide experience in coal mining in the vicinity of large water bodies as well as the impacts of coal extraction under Cataract Reservoir. Recommended depths of cover between the seam to be mined and the waterbody to prevent ingress of water into the mine are provided.

**Table 6.5: Summary of Some Recorded Impacts and Consequences – Mining in the Vicinity of Large Water Bodies**

Physical Subsidence Effects and Impacts	Environmental Consequences
<ul style="list-style-type: none"> <li>Fracturing of sea bed (overseas experience)</li> </ul>	<ul style="list-style-type: none"> <li>At 125 m to 140 m, 51% of mines experienced wet conditions (UK)</li> <li>Required depths to top of seam below the sea bed to prevent wet conditions:               <ul style="list-style-type: none"> <li>160-760 m (Canada)</li> <li>140 m (Chile)</li> <li>330 m (Japan)</li> </ul> </li> </ul>
<ul style="list-style-type: none"> <li>Potential fracturing of base of Cataract Reservoir due to:               <ul style="list-style-type: none"> <li>first 8 faces - 105 m wide face with 70 m wide rib pillars</li> <li>subsequent face - 115 m with 65 m x 100 m wide rib pillars</li> <li>Depths 325 m to 445 m</li> </ul> </li> </ul>	<ul style="list-style-type: none"> <li>Caving zone extended up from 40 m</li> <li>Zone of linked fractures extended up to 85 m above the Bulli Seam</li> <li>Strata response to mining operations under Cataract Reservoir has been very small</li> </ul>

Source: Singh and Jakeman (1999)



## 6.1.2 Surface Water Quality

The following section is based on the Literature Review summaries contained in Appendix C.

Impacts on surface water quality can be caused by surface water infiltrating the sub-surface, due to mining induced subsidence and consequent fracturing, and re-emerging with a different chemistry due to water-rock interactions. The water may pick up iron, manganese, aluminium, sodium, calcium, barium, chloride and sulphate. Carbonates may be mobilised to give bicarbonate ions. These changes are more noticeable during low flows (NSW Government 2014).

The University of Wollongong (2007) documented localised changes in stream water chemistry brought about by water-rock interactions along new flow pathways. This process targets any available carbonate or sulphide minerals in the sandstones and other strata. Candidate carbonate minerals include siderite, witherite, strontianite and less frequently calcite, which respectively contribute the cations iron, barium, strontium and calcium together with the bicarbonate anion to the groundwater and eventually to the surface stream flow. Dissolution of iron oxy-hydroxides like limonite, goethite and haematite provides a mechanism for increasing the presence of iron in surface water and groundwater. Marcasite (iron sulphide) may also contribute to elevated iron, sulphate and increased acidity through oxidative dissolution.

These iron minerals are common to the Hawkesbury Sandstone and their influence on water quality is reflected in the characteristic bright orange discolouration of groundwater emanating from some cracked stream beds and rock bars. This discolouration is often accompanied by the downstream growth of bacterially-mediated iron mats and blooms in rock pools which in turn lead to a reduction in dissolved oxygen in the stream flow and related eco toxic impacts (University of Wollongong, 2007).

Ecoengineers (2007) found that subsidence may enhance groundwater storage and transmission characteristics of the Bringelly Shale and the underlying interface with the Hawkesbury Sandstone. Exposure of shale to new water/rock chemical interactions could lead to elevated iron and manganese probably resulting from reductive dissolution. Unlike oxidative dissolution of marcasite, there appears to be an absence of sulphates and acidity. Migration of the groundwater from elevated areas to the fractured regime associated with valley sides and floors is believed to have initiated several ferruginous springs associated with the Cataract and Georges Rivers.

Stout (2003) assessed the impacts of longwall mining on headwater streams in northern West Virginia. When compared to reference streams longwall mined streams were found to be similar in terms of pH and hardness, but significantly different in terms of alkalinity, conductivity, and dissolved oxygen. Higher electrical conductivity and oxygen demand were found to be indicative of somewhat degraded conditions in longwall mined headwater streams.

Galvin (2005) concludes that changes in water quality due to mining have been sporadic, localised in nature and have had no detectable influence on water quality at the Woronora Water Filtration Plant. There is field evidence that water quality impacts associated with the sub-surface flow through fresh fracture networks ameliorate over a 5 to 10 year period.

Jankowski (2010) describes a section of the Waratah Rivulet where subsidence and cracking of streambeds and rockbars due to longwall mining has occurred, causing surface water to be redirected into subsurface fracture systems, mix with groundwater and partially reappear downstream. The salinity upstream of the mined area was found to have low EC values ranging from 200 and 280  $\mu\text{S}/\text{cm}$ . Salinity increases along the Rivulet as more water re-emerges from the subsurface, with EC values between 260 and 340  $\mu\text{S}/\text{cm}$ . The pH upstream is slightly acidic, with a range of 6.5-7.1, increasing to pH of 7.7 where subsurface water dominates surface flow.



Concentrations of iron and manganese initially rise in surface flow as groundwater discharges from the subsurface. However, a few hundred metres downstream dissolved metal concentrations decrease as Iron and Manganese oxides and hydroxides are precipitated causing the development of thick mats of iron / manganese-oxides / hydroxides and the growth of large quantities of oxidising bacteria (Jankowski, 2010).

Monitoring carried out by Metropolitan Coal for 2014 and 2015 Annual Reports found:

- fluctuations in pH values at the Woronora River sampling sites between pH 8.5 in June 2014 and pH 3.7 in August 2014;
- three samples with elevated dissolved iron concentrations in the Eastern Tributary in April, May and October 2014;
- the trend of increasing pH and EC at the downstream sampling sites on Tributary B prior to the start of the reporting period appear to have plateaued. Dissolved manganese at these sites appears to be trending upward relative to historical concentrations but still remains relatively low
- negligible reduction to the quality of water resources reaching the Woronora Reservoir.

The Dendrobium End of Panel Reports (Illawarra Coal, 2013, 2014, 2015, 2016) also document localised impact on water quality associated with the catchment being mined under.

Notwithstanding the localised short-term impacts on water quality on local watercourses identified in this Literature Review, it was also found that there is no discernible impact on water quality in the reservoirs due to mining (Metropolitan Coal, 2015a and Figure 3.20 to Figure 3.22). Fell (2014) found that although the impact of underground long-wall mining in the catchment could lead to small changes in the levels of impurities in water entering WaterNSW's dams, these changes could be adequately addressed by Sydney Water's treatment plants. Evidence to date did not suggest a sufficiently large change in soluble organic concentrations to be of concern to WaterNSW values. Water quality issues in the Special Areas can largely be managed through existing treatment works, although an upgrade to infrastructure would be required to sustain this capability.

A summary of the impacts and consequences of subsidence on surface water quality is provided in Table 6.6.

**Table 6.6: Summary of Impacts and Consequences of Subsidence on Surface Water Quality**

Physical Subsidence Effects and Impacts	Potential Consequences
<ul style="list-style-type: none"> <li>▪ Tensile cracking of stream rock bars;</li> <li>▪ Tensile/shear movement of joint and bedding planes in the stream bed;</li> <li>▪ Localised uplift and buckling of strata in the stream bed (e.g. lifting/mobilising of stream bed rock plates.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Localised changes in stream water chemistry due to water-rock interactions along new flow pathways to subsidence;</li> <li>▪ Increases in iron, manganese, aluminium, sodium, calcium, barium, chloride and sulphate in surface water;</li> <li>▪ Increases in iron, barium, strontium and calcium together with the bicarbonate anion in surface water;</li> <li>▪ Mobilisation of carbonates to give bicarbonate ions;</li> <li>▪ Orange discolouration of surface water due to dissolved iron;</li> <li>▪ Growth of bacterially-mediated iron mats and blooms in rock pools;</li> <li>▪ Reduction in dissolved oxygen and related eco toxic impacts;</li> <li>▪ Increases in alkalinity and salinity;</li> <li>▪ Consequences are likely to be sporadic, localised in nature and have had no detectable influence on water quality in downstream reservoirs;</li> <li>▪ Water quality consequences associated with the sub-surface flow through fresh fracture networks ameliorate over a 5 to 10 year period.</li> </ul>



In summary, although some consequences on water quality within the watercourses in the study are documented in the literature, these impacts are likely to be short term, sporadic and localised. Provided the existing management and mitigation measures are maintained, negligible water quality impacts are likely to be experienced at the downstream WaterNSW Reservoirs. Any consequences on water quality at the reservoirs would be treatable by the existing Sydney Water treatment plants.

### 6.1.3 Upland Swamps

Upland swamps comprise about 4.8% of the catchment area draining to the reservoirs within the Special Areas. As described in Section 3.6.4 upland swamps in the Special Areas can be considered in four categories depending on their position in the landscape, soils, contributing catchment area and vegetation:

- Headwater swamps occur in the headwaters or elevated sections of the Woronora Plateau, where they usually occupy broad, shallow, trough-shaped valleys on first-order and sometimes second-order drainage lines;
- Valley-side swamps 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;
- Valley in-fill swamps are less common than headwater swamps and occur on relatively flat sections of more deeply incised second and third order watercourses;
- Hanging swamps occur mainly in the Blue Mountains and Newnes Plateau, but have also been identified in the Bargo and Cataract gorges on the Woronora Plateau;

Despite an increase in monitoring by mining companies in recent years, the hydrology of upland swamps remains poorly understood and little is known about the fate of water that is apparently lost from some headwater swamps as a result of mining induced subsidence. Much of the monitoring is confined to measurement of the piezometric water levels within a swamp substrates and observation as to whether there is a change in behaviour as a result of mining beneath the swamp compared to pre-mining conditions or to nearby 'reference' swamps not impacted by mining. Whilst impacts on superficial aquifers can be clearly demonstrated by such monitoring, the fate of the water diverted from the swamp substrates cannot be confirmed. Knowledge of underlying bedrock aquifer water tables and changes in downstream overland flow discharges is required to demonstrate whether or not such water is 'lost' from the overall catchment water resource.

The *Southern Coalfield Strategic Review* (2008) provided a useful summary of the issues relating to the potential impacts of mining on swamps:

*Different swamp types, geometries and locations are also likely to affect the extent of any adverse impacts, in relation to issues such as swamp drainage and resultant vegetation changes due to water losses and changes to water storage characteristics. For example, it seems reasonable to infer that valley infill swamps are simply organic/sandy sediment-draped stream valleys with a rocky substrate if those streams are located in upland environments. A number of such swamps are known to have rock bars and the swamps themselves may therefore fill pre-existing pools. It seems likely that these rock bars and pools in the rocky substrate will respond to subsidence effects in a manner similar to those in streams which are filled with water, rather than sediment.*



*Tensile and shear cracking, together with localised upsidence and buckling of the surface strata, would be anticipated beneath at least some valley infill swamps. In turn, it is reasonable to infer that such cracking is likely to lead to drainage of water from the swamp into the fracture network in the stream bed below. Thus, it is possible that water tables may drop within valley infill swamps, leading to the potential for damage by fire, surface vegetation changes or scouring erosion by high flow events. It can be suggested that scouring may also be caused or increased by slope changes in the swamp as the result of subsidence.*

*Interactions between subsidence effects and impacts such as vertical displacement, strata fracturing, buckling and uplift (possibly leading to water loss) have potential consequences for swamps.*

*The issue of, and mechanisms associated with, swamp impacts from mining-induced subsidence is an extremely complex one, for which there is no simple generic explanation. It appears that there is a possibility that undermining of valley infill swamps has or will cause drainage, water table drop and consequent degradation to swamp water quality and associated vegetation.*

*The consideration of potential impacts becomes one of site specific characterisation, together with site specific determination of the significance of each individual swamp.'*

Table 6.7 summarises the potential subsidence impacts and consequences for swamps. The consequences of water loss due to subsidence on the vegetation communities and ecology are well recognised. However, there is no understanding of the fate of water lost from swamps as a consequence of mining induced subsidence. Unlike in rock-bed creeks, direct observation of any cracking is not observable and can only be inferred by the reduction in piezometric water level and the drying of the organic soils within the swamp. The subsequent pathway followed by water lost from the base of a swamp is dependent on the geometry of fracturing in the surface fracturing zone.

**Table 6.7: Summary of Subsidence Impacts and Consequences for Swamps in the Southern Coalfield**

Physical Subsidence Impacts	Primary Consequences	Secondary Consequences
<b>Valley infill swamps</b>		
<ul style="list-style-type: none"> <li>Tensile cracking, tensile/ shear movement of joint and bedding planes, and buckling and localised upsidence in the stream bed below the swamp</li> </ul>	<ul style="list-style-type: none"> <li>Draining of swamps, leading to:               <ul style="list-style-type: none"> <li>drying and potential erosion and scouring of dry swamps</li> <li>loss of standing pools within swamps</li> <li>vulnerability to fire damage of dry swamps</li> <li>change to swamp vegetation communities</li> <li>adverse water quality impacts, e.g. iron bacterial matting</li> </ul> </li> <li>Loss of stream baseflow</li> </ul>	<ul style="list-style-type: none"> <li>Loss of swamp ecology (terrestrial and aquatic)</li> <li>Loss of flow leads to the full range of downstream consequences</li> </ul>
<b>Headwater swamps</b>		
<ul style="list-style-type: none"> <li>Tensile cracking and tensile/ shear movement of joint and bedding planes in the rocks below the swamp</li> </ul>	<ul style="list-style-type: none"> <li>Potential drop in perched water tables, leading to draining of swamps</li> <li>Impacts are likely to be similar in character but less extensive and significant than for valley infill swamps</li> </ul>	<ul style="list-style-type: none"> <li>Loss of swamp ecology (terrestrial and aquatic)</li> <li>Loss of flow leads to the full range of downstream consequences</li> </ul>

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



As discussed in Section 5.3.2 subsidence can cause fracturing within the surface fracturing zone which typically is thought to extend to depths of 15-20 m and can contain fractures less than 1 mm to more than 50 mm wide. Figure 4.13 (based on Parsons Brinkerhoff, 2015) indicates that the surface fracturing zone is likely to experience increased horizontal and vertical permeability as well as increased porosity. However, in the constrained zone, the change in vertical permeability and porosity is likely to be small while the horizontal permeability is likely to increase by an order of magnitude compared to pre-mining conditions.

These effects suggest that any water lost from a swamp as a result of cracking of the bedrock is likely to migrate laterally at a significantly greater rate than vertically. McMahon (2015) reviewed the work by Krogh (2015) and noted that there is no evidence to support the conclusion that reduced flow from Dendrobium Swamp 1b as a result of mining is evident in the Donalds Castle Creek tributary, but rather that it is possible that some or all of the flow identified as lost at the swamp outlet may resurface downstream. However, the proportion of any lost flow that reports to the regional aquifer or to deeper groundwater systems has not been defined.

Evans and Peck (2014) noted that the potential consequences of subsidence to headwater swamps located away from the valley floor include:

- Differential settlement leading to change in the bed level relative to any drainage outlet (if one exists) and:
  - Increased water storage capacity of the swamp if the subsidence occurs up-slope of any drainage outlet;
  - Decreased water storage capacity if the subsidence occurs at the outlet;
  - Change in flow pathways through the swamp due to changes in ground level (tilt);. Any changes in flow pathways have the potential to concentrate surface flow and lead to erosion.

Notwithstanding these possible effects, because the surface slope of the headwater swamps in the Russell Vale Extension Project is of the order of 10% (10 m in 100 m), subsidence of the order of a few metres is unlikely to significantly impact on the water storage characteristics or flow pathways of these swamps.

- Cracking due to tensile or compressive strains. The impact of any cracking will depend significantly on nature of the cracking (depth and any sub-surface shearing) and the location of any cracking with respect to the local topography of a headwater swamp:
  - Cracking towards the up-slope edge of a swamp has the potential to re-direct surface runoff from the contributing catchment;
  - Cracking within the body of the swamp or towards the down-slope boundary has the potential to drain any seasonal perched water table;
  - Cracking towards the sides of the swamp is unlikely to have a significant impact on any runoff contribution from up-slope or the balance of incident rainfall.

In addition, for valley in-fill swamps located on major water courses there is potential to be subject to cracking of the basement rock due to upsidence in the same manner as observed in exposed rock sections of creek following mining (e.g. Waratah Rivulet).

As noted in the *Bulli Seam Operations PAC Report* (PAC, July 2010):

*“Consequences of these impacts depend upon a wide variety of factors such as how much water is lost, over what period, whether “self-healing” occurs and to what degree, and whether there are severe rainfall events or fire events. Depending on these factors and their*



*interactions, a swamp could show no evidence of change, or be severely damaged over a relatively short space of time."*

One of the main difficulties for predicting (and avoiding) subsidence effects on swamps is that the precise location of any bedrock cracking cannot be determined in advance. In his review of the subsidence assessments in the preferred project report for the Russell Vale Extension Project, Hebblewhite (2013) noted that:

*"In discussing strains and tilts, it is worth emphasising the point made by SCT that it is simply not possible to predict exact locations of maximum or peak strains, and hence potential crack locations, for example. Regions where such strains might occur can be identified, but it is never going to be possible to predict in advance the actual location of actual cracks in the rock mass."*

The majority of monitoring of swamps has focussed on monitoring water levels on shallow piezometers within the swamp itself. The swamp monitoring for Metropolitan Mine (2015a) includes the useful addition of monitoring of water levels in the sandstone bedrock at 10 m beneath the swamp and, in some instances, also monitoring groundwater in the sandstone at 4 m depth. This monitoring provides useful information regarding the hydraulic gradient leading to groundwater flow into or away from the swamp. Similar to some of the groundwater monitoring in the sandstone below swamps in the Metropolitan Mine area, Ross (2009) suggests that the water table in swamps in the Kangaloon area is perched with the regional water table in the underlying sandstone being some 4 to 5 m below the swamps.

As noted by Pells et al (2014) *"Astonishingly, there is no adequate hydrological balance for any of the upland swamps on the Woronora Plateau."* While a full water balance that accounts for all sources and losses of water is of general scientific interest, it is beyond the routine monitoring that mines are required to show whether a swamp has been impacted or not. Notwithstanding, the understanding of the hydrology of headwater swamps has been further advanced by the work of Krogh (2015) – which is currently ongoing and the subsequent ongoing research (e.g. Glamore and Rayner, 2016). As described in 3.7.7.2 and Appendix F, Krogh has monitored swamp piezometric levels, soil moisture, rainfall and pan evaporation at a swamp located outside the area scheduled for mining, one in a location scheduled to be mined in a few years and one in a swamp that was undermined shortly after monitoring commenced.

Krogh's work shows that the observed impact at Dendrobium Swamp 1B which was undermined by Longwall 9 in April 2013 has been a decline in perched water levels which have had a significant impact on soil/peat moisture levels in Swamp 1B (20-40%) as compared to other nearby swamps (70-85%). A preliminary water balance analysis indicated an unexplained shortfall of approximately 0.3-0.4 ML/day of surface drainage from the swamp. A review of Krogh's work by McMahon (2015b) noted issues with the equations used in the model, incorrect units and coefficients used in calculations, and incorrect estimates used in calculations (for example for evaporation) which cast doubt on the magnitude of the calculated loss of discharge to the surface drainage system.

One of the main difficulties in attempts to quantify the magnitude of any loss of water from a swamp is that, in general, the period of monitoring before mining is relatively short and does not capture the range of swamp behaviour due to climate variation. An example of this is shown on photographs of Dendrobium Swamp 1b in Appendix F. The photographs show the swamp extensive drying of vegetation in 2010 prior to the start of mining in early 2013.

The swamp monitoring data for the Russell Vale Extension Project was derived from swamps that were previously undermined, most of it by mining in the Bulli and Balgownie seams in the period from the late 19<sup>th</sup> century through to 1982. The review by Evans & Peck (2014) found that the



majority of headwater swamps that have been subject to subsidence from previous mining have maintained a perched groundwater system. Whether the maintenance of a water table within the swamp is due to limited subsidence (not measured at the time) or to some 'self-sealing' is unknown.

A study prepared for the Commonwealth of Australia (2014b) evaluated mitigation and remediation techniques for peat swamps on the Woronora Plateau impacted by underground mining. The report was based on an extensive international literature review and liaison with industry and international experts and coalmining companies. The report concludes that:

- Information on subsidence impacts, and remediation of these impacts, has focused on exposed bedrock channels, with no remediation examples of undermined upland peat swamps.
- There are no proven mitigation strategies other than alterations to mining layout. The time delay between mining and observation of surface impacts—in particular, ecological impacts—suggests that existing industry mitigation strategies, such as TARPs, are not suitable. Engineering solutions such as the creation of stress relief slots are untried for peat swamps, but likely to be ecologically damaging to implement.
- International peat swamp remediation techniques are not applicable because these swamps and peatlands are not impacted by uncontrolled vertical seepage.

## 6.2 Impact Limits

As for groundwater (Section 4.1.1), while surface water may be impacted by longwall mining, the severity of the impact and what is tolerable water resource loss (to both surface water and groundwater) are key questions for this Review. Quantification of criteria to apply to surface water, catchment yield and water quality are important considerations for WaterNSW.

WaterNSW would like to identify quantitative performance indicators that are tolerable in respect of:

- Water leakage from reservoirs;
- Water losses from catchments;
- Water quality; and
- Ecological impacts.

Further discussion on issues relating to surface water related performance indicators is provided below.

### 6.2.1 Water Quantity

The key difficulty with setting limits on an acceptable loss of water attributable to the impacts of mining is one of measurement accuracy. Can any limited volume be measured or modelled with sufficient accuracy to provide a mechanism for verifying that any established limit is not being exceeded?

#### **Mining in the Vicinity of Water Storages**

Impact limits appropriate to mining under water storages could be in the form of recommended depths of mining below the reservoirs. Overseas experience indicates limits in the range of 125 – 760 m. Under Cataract Reservoir mining depths of 325 m to 445 m have been adopted and the corresponding strata response has been very small.



In the Special Areas, WaterNSW has adopted a limit of 1 ML/day on the volume of water lost from each storage. In the context of the total water resource reporting to the reservoirs, 1 ML/day from each storage equates to 1,825 ML/year which is trivial in the context of the overall water resource reporting to the dams and weirs in the Special Areas (average of 396,000 ML/year – see Table 3.15) and other 'losses' such as spills and evaporation (Table 3.15). The loss of 1,825 ML/year would be far less than the margin of error contained in the estimates of the total resource and would not be measurable.

## **Surface Water in Streams and Pools**

A number of studies have reported losses of surface flow in streams reporting to the WaterNSW reservoirs and depletion of water levels in pools. In addition to any loss of flow, the ecological value of pools is also important.

However, due to limitations of gauging accuracy, limited length of record before mining commences, the limitations of the rainfall-runoff models and the complexity of surface water and groundwater interactions, there is no current certainty regarding how much surface water is actually diverted from streams, pools, swamps and the broader catchment and how much may be resurfacing further down the catchment. In reality, there is likely to be a large variety of responses, controlled largely by the density, position and orientation of mining induced cracking within the upper bedrock aquifer, as well as natural permeability, topography, climate and other influences.

As noted earlier, McMahon (2015b) makes the point that existing flow gauging is unable to allow a conclusion that water re-emerges downstream, and is similarly unable to allow a conclusion that it does not re-emerge. While the loss of flow observed in the streams is significant enough to be discernible on hydrographs for those streams, any loss of flow is not discernible at the downstream gauges. This is because of gauging accuracy and the small magnitude of loss compared to total flow at the downstream gauging stations.

The concept of setting subsidence limits dependent on stream order according to the Strahler system is well established in the Hunter Valley and its wider application was suggested by the commissioners of the *Southern Coalfield Strategic Review* (NSW Government, 2008). While the Strahler system is easy to use and has value in terms of catchment classification, it is not necessarily an adequate indicator of flow and the potential reduction or diversion of flow from the catchments in the Special Areas. An alternative would be to classify potentially impacted streams in terms of catchment area, proportion of the catchment covered by upland swamps and/or estimated catchment yield.

## **6.2.2 Water Quality**

Various studies have identified localised changes in stream water chemistry due to water-rock interactions along new flow pathways to subsidence, including increases in iron, manganese, aluminium, strontium, sodium, calcium, barium, chloride, sulphate, alkalinity and salinity as well as reductions in dissolved oxygen. Increased iron concentrations in the surface water can lead to orange discolouration of surface water due to dissolved iron and growth of bacterially-mediated iron mats and blooms in rock pools.

However the consequences of these changes are likely to be sporadic, localised in nature and have had no detectable influence on water quality in downstream reservoirs. Water quality consequences associated with the sub-surface flow through fresh fracture networks ameliorate over a 5 to 10 year period.



The water quality in the reservoirs is highly variable over time and is likely to be influenced by management of water level in the storage and the level from which supply is drawn more than changes in water quality due to the impacts of mining. Fell (2014) considers that any consequences for the water supply to Sydney as a result of mining or coal seam gas extraction can be managed through existing treatment works.

### 6.2.3 Swamps

There are few identified examples of performance measures or TARPs set on the basis of volumetric water losses from swamps, which reflects the lack of knowledge about swamp water balances and the fate of water which may be diverted due to subsidence.

Water lost from swamps is presumed to drain into the underlying sandstone. The subsequent fate of this water is often unknown, but it may be reasonably presumed that it will either appear as seepage lower in the landscape or drains to the deeper regional aquifer. The diversion of this water may have implications for downstream ecological receptors and to whether it is “lost” from WaterNSW storages. It could be argued that because a drier swamp will have less water available for evapotranspiration, such swamps may actually contribute more water to the groundwater and surface water resources than wetter swamps.

The current state of knowledge regarding swamp hydrology does not permit any limits to be set in terms of any hypothesised net ‘loss’ of water. This is not to take away from the ecological consequences, which are the key consideration for upland swamps.

## 6.3 Gaps in Existing Knowledge

A common theme throughout Section 3.7 and Sections 6.1 and 6.2 is that the water resources and hydrological processes are poorly understood in sufficient detail to allow a cause and effect relationship to be quantified between mine subsidence effects and the 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 responsible for water supply to have a good understanding of the available resource and the variability from year to year. However at smaller spatial and time scales, that are more likely to reflect any consequences of mining, there is a paucity of detailed understanding of a number of key processes, as summarised in the sections below.

### 6.3.1 Baseflow

Baseflow following significant flow events 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 largely focussed 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 level measurement and the rating for very low flows;
  - continuously monitor salinity as a tracer in accordance with the recommendation from SKM and 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 will 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 catchments would help to clarify the overall magnitude of baseflow to the reservoirs.

### 6.3.2 Near Surface Hydraulic Gradients

Loss of water from swamps and water courses has been observed. However there is paucity of firm evidence regarding the fate of this water which is dependent on the hydraulic gradient in the shallow bedrock and relative magnitude in any changes in hydraulic conductivity.

Metropolitan Coal has contributed to an understanding of the relative piezometric levels in swamps and shallow groundwater in the sandstone beneath the swamp. The evidence from the monitoring undertaken to date is that hydraulic gradients leading to flow both towards and away from swamps have been observed. Further monitoring in other swamps that are currently monitored for swamp piezometric levels would assist in understanding the interactions between swamps and the any shallow groundwater system.

Further understanding of the fate of water lost from swamps and cracked creek beds could be gained by the installation of a line of piezometers down slope of an impacted area in order to determine the magnitude of any change in the hydraulic gradient.

### 6.3.3 Near Surface Hydraulic Conductivity

An effect of mine induced subsidence is considered to be tensile fracturing within the 'surface zone'. Information on the depth to which cracking occurs below the surface and the 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 the surface water system.

The models postulated by Pells and Pells (2012b) (shown in Figure 4.11) and Parsons Brinkerhoff (2015) (shown in Figure 4.13) differ slightly in their representation of the changes that occur to the hydraulic conductivity in the surface fracture zone and constrained zone as summarised in Table 6.8.

**Table 6.8: Postulated Changes in Hydraulic Conductivity Resulting from Subsidence**

Location of Change	Flow Direction	Change in Hydraulic Conductivity	
		Pells and Pells (2012b)	Parsons Brinkerhoff (2015)
Top of surface fracture zone	Horizontal	x 100	x 100?
	Vertical	na	x 10
Bottom of surface fracture zone	Horizontal	x 4	x 20
	Vertical	na	No change?
Constrained zone	Horizontal	x 10	x 20
	Vertical	x 4	No change?



Given that the hydraulic gradient will usually be 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. The other unknown factor is what is the effect of down-slope rock that has not been impacted by subsidence. Hypothetically, if the un-impacted rock acted like a dam, and there was sufficient volume of water up-slope, the water could be directed towards the surface. However, such a mechanism is purely conjecture.

### 6.3.4 Hydrology of Headwater Swamps

The work of Krogh (2015) has considerably enhanced the insight into the hydrologic regimes in swamps that are, or are not, impacted by mining. As noted by McMahon (2015), the analysis of Krogh's monitoring data in terms of the water balance of the swamp requires further work. A key missing element is an understanding of how the actual evapotranspiration rate changes as the swamp soils dry out. Over the years much work has been undertaken to understand the relationship between soil moisture and evapotranspiration loss from forests. In addition to detailed monitoring of soil moisture at different levels within the root zone, lysimeters were used to measure the rate of water loss by evapotranspiration.

The other missing element from Krogh's work is monitoring of groundwater levels beneath the swamp in order to understand the changes in hydraulic gradient that occur as a result of subsidence.

### 6.3.5 Measurement and Modelling

Issues of concern to WaterNSW fall into two broad categories – maintenance of water supply (and quality), and the preservation of the ecological functioning of the catchments.

In relation to water supply, the key issues relate to the magnitude of any loss of supply to the reservoirs. The problem relates to two issues that are common to monitoring and modelling:

- Is the monitoring system capable of detecting change at a time and space 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 process that may change as a result of mining; and can the parameters needed for such a model be determined with sufficient spatial discrimination?

Based on the preliminary analysis of available literature, the current catchment models (such as Sacramento and AWBM) are appropriate for modelling catchment hydrology and are likely to be able to discriminate any significant change in flow at a reservoir catchment scale. However, they are not capable of representing the detailed hydrologic processes that occur at a local catchment scale (say 100 ha including a headwater swamp). Detailed modelling at this scale has been undertaken by forest hydrologists. However such modelling is expensive in terms of collecting sufficient data to adequately characterise the heterogeneity of the physical system and monitoring to flow processes with sufficient accuracy.



**Advisian**

WorleyParsons Group



## 7 Biodiversity

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### 7.1 Impacts and Consequences of Coal Mining

#### 7.1.1 Introduction

Potential impacts on the region's biodiversity from longwall mining-related subsidence can result in changes to the underlying regolith, physical features (cliffs, rock overhangs etc.), groundwater and surface water resources. Changes to the environment and the comparatively more subtle changes, 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 influences both from inside and outside the ecosystem and, importantly, have different system-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.

The casual factors impacting on biodiversity are derived from the groundwater and surface water impact/consequence assessments as presented in the previous Sections 5 and 6, as well as other impacts identified in the literature. Because the ecosystems are water dependent (from rainfall, surface flow or groundwater), the identified groundwater and surface water impacts and consequences, by dependency, essentially become the core threats to biodiversity. The hierarchical sequence from impact to consequence/secondary consequence does not follow a step-wise pattern nor is it unidirectional with many ecosystems functioning interdependently with positive and negative feedbacks. .

The biodiversity of the Special Areas, comprising all living things and the environments in which they live, is complex and the term 'biodiversity' is not restricted to just the number of plants and animals in a specific area. The contemporary understanding recognises genetic diversity, ecosystem diversity, the range of ecosystem processes across landscapes and the environmental services they provide.

The focus on biodiversity in this section is directed towards upland swamps and streams given their regional significance and for their role in regulating and maintaining water quality and quantity - protecting water quantity and quality both being key principles of WaterNSW. An additional key Water NSW principle and one relevant to biodiversity is the maintenance and protection of the ecological integrity of the Special Areas. The ecological integrity encompasses more than swamps and streams and includes the broader landscape with its diverse and complex habitat features.

#### 7.1.2 Impacts and Consequences on Terrestrial Biodiversity

##### 7.1.2.1 Reported Impacts on Terrestrial Biodiversity

Reported impacts on habitat features in the Southern Coalfield as a result of longwall mining principally relate to upland swamps, streams and to a lesser degree other features such as cliff lines (e.g. Biosis Research, 2007; Total Environment Centre, 2007; NSW Department of Planning, 2008; Krogh, 2012 and Pells *et al.*, 2014). These impacts have been reported as the physical and hydrological changes to the upland swamps and streams, as well as rock fall along cliffs, have been observed. These features are also more generally targeted for study and ongoing monitoring due



to their environmental significance and predicted likelihood of impact. In both the Southern and Western Coalfield there are little to no known records of direct impacts on biodiversity associated with the terrestrial ecosystems on slopes and ridgetops (refer Biosis Research, 2007; NSW Minerals Council, 2007; NSW Department of Planning, 2008 and Centennial Coal, 2012). There is, however, evidence of short-term terrestrial vegetation dieback as a result of temporary gas releases from near surface strata in the Upper Cataract River gorge (Biosis Research, 2007 and NSW Department of Planning, 2008) and dieback of riparian vegetation on the Waratah Rivulet/Eastern Tributary (Eco Logical, 2015).

MSEC (2007c) reasons that mining induced ground movements at a point on the surface do not automatically result in adverse environmental impacts at that point. Where ground movement results in subsidence effects (e.g. cracking) the effect may alter the social/aesthetic value of an area, however it does not in all cases result in environmental impacts. For example, in relation to surface bedrock and soil cracking, Biosis Research (2007) notes that while landscape alteration has occurred there is little to no evidence that vegetation or fauna habitats have been altered as a result such that terrestrial ecological functioning has been significantly impacted.

Addressing terrestrial biodiversity in its entirety is unrealistic and this section aims to focus on ecosystems of significance and/or that are likely to be threatened by longwall mining-related impacts. Therefore, an inferred evaluation of broad habitat features to the threats of longwall mining is outlined in Table 7.1.

**Table 7.1: Key Habitat Features and Potential Impacts from Longwall Mining**

Habitat	Potentially Impacted	Reasoning
<b>Broad Vegetation Group (BVG)</b>		
Shale Sandstone Transition Forest	Yes	Occurs along western boundary of Metropolitan SA mostly outside mining lease areas, also as pockets within this SA. Includes Shale Sandstone Transitional Forest EEC
Elevated Mittagong Sandstone Woodland-Heath	No	Outside mining lease areas and therefore area of impact, inferred from NPWS (2003) vegetation group description
Scrubs on Sandy Alluvium	Yes	Includes scrubs of the upland swamps and some riparian zones are covered under rainforests and upland swamps
Tall Open Forests on Enriched Soils	Yes	Occurs across a range of topographies and is widespread in the Special Areas. This vegetation group Includes the O'Hares Creek Shale Forest EEC
Rainforests and Tall Moist Eucalypt Forests	Yes	Occurs in the Special Areas, mostly in the higher rainfall areas to the east and along upper drainage lines. There is a risk of mining related impacts in these areas
Exposed Sandstone Woodlands and Heath	Yes	Dry woodlands occur on the sandstone plateau areas. Their dependency on groundwater is unknown, but would be related to the depth to water table and the extent of any fracture systems that allow roots to reach the water table.
Sandstone Gully Forests	Yes	Occurs in the Special Areas along drainage lines where there is a risk of mining related impacts
Upland Swamp Complex	Yes	Occurs in the Special Areas, has high ecological significance and is known to be impacted by longwall mining
<b>Endangered Populations and Ecological Communities</b>		
Woronora Plateau population of <i>Callitris endlicheri</i>	No	Population currently restricted to single outcrop of sandstone ~2 ha in area. Threats from underground mining not identified in the NSW Scientific Committee (2016e) listing
Coastal Upland Swamp	Yes	As above for Upland Swamp Complex
Southern Sydney Sheltered Forest	Yes	Occurs within Special Areas. No reported impacts, likelihood of impacts uncertain, though possible



Habitat	Potentially Impacted	Reasoning
O'Hares Creek Shale Forest	Yes	Restricted occurrence - known community lies between Cataract Reservoir and Appin Road (OEH, 2016c)
Robertson Rainforest	No	Outside mining lease areas and therefore area of impact, inferred from OEH (2016e) EEC profile description
Robertson Basalt Tall Open-forest	No	Outside mining lease areas and therefore area of impact, inferred from OEH (2016d) EEC profile description
Shale Sandstone Transitional Forest	Yes	The Transitional Shale Dry Ironbark Forest occurs in the Metropolitan SA, inferred from OEH (2016f) EEC profile description
Cumberland Plain Woodland	No	Outside mining lease areas and therefore area of impact, inferred from OEH (2016a) EEC profile description
<b>Priority Fauna Habitat (as per DECC 2007b)</b>		
Upland swamps	Yes	As above for Upland Swamp Complex & Coastal Upland Swamp EEC
Grassy Box Woodlands	Yes	Locality of habitat is in pockets on the western boundary of Woronora Special Area, small patches inside current Appin mining lease area, inferred from DECC (2007b)
<b>Other Habitat Features</b>		
Cliffs, rock benches, rock overhangs & elevated sandstone ledges	Yes	Many of the significant cliff lines are located in the river gorges. Reported cliff falls in the Upper Cataract gorge, Tower Colliery (now Appin West) (NSW Department of Planning, 2008) and Dendrobium Area 2 and 3A (Krogh, 2012) associated with steep topography around the river valleys (NSW Department of Planning, 2008)
Riparian habitats	Yes	Impacts likely from subsidence-related changes in stream gradients, increased scouring of stream banks, changes to stream alignments, cracking and/or change in stream water levels (MSEC, 2008a)

**Note:** For the purpose of this report riparian habitats is discussed in Section 7.1.3 relating to aquatic biodiversity and the Upland Swamp Complex, Coastal Upland Swamp EEC and Upland Swamp Priority Fauna Habitat is discussed broadly as 'upland swamps' in Section 7.1.4.

**7.1.2.2 Potential Impacts and Possible Consequences**

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 may present in the future with adverse potential consequences. Impacts and their related, possible consequences are outlined in Table 7.2. Impacts and consequences presented in this table have been compiled with reference to the groundwater and surface water sections of this report and from a number of other sources (e.g. Pokorný *et al.*, Everett *et al.*, 1998; Biosis Research, 2007; DECC, 2007b; NSW Department of Planning, 2008; Serov *et al.*, 2012; NSW National Parks & Wildlife Service, 2016 and NSW Scientific Committee, 2016a).

**Table 7.2: Potential Impacts on Terrestrial Biodiversity and Possible Consequences of such Impacts**

Impacts on Terrestrial Biodiversity*	Consequences
<p><b>Subsidence</b> Cliff falls and instability of cliffs and overhangs</p>	<ul style="list-style-type: none"> <li>▪ Loss of habitat for fauna species utilising the cliffs for resources</li> <li>▪ Cliff line species such as <i>Epacris hamiltonii</i> and <i>Apatophyllum constable</i> that rely on surface or subsurface water may be affected by accelerated cliff collapse. Loss of roosts for bats and nest sites for cliff-nesting birds</li> <li>▪ Cliffs, rock benches, rock overhangs and elevated sandstone ledges also provide shelter and nesting sites for threatened, protected and regionally significant species such as snakes, geckos, insectivorous bats, Brown Antechinus, Rockwarblers and the Superb Lyrebird</li> <li>▪ Loss of habitat for the adult Red-crowned Toadlet</li> </ul>



Impacts on Terrestrial Biodiversity*	Consequences
<b>Surface bedrock &amp; soil cracking</b> On ridgetops where sandstone is outcropping at the surface	<ul style="list-style-type: none"> <li>▪ Rock fractures can act as pitfalls for small ground fauna</li> </ul>
<b>Impact on regional groundwater aquifer</b> Falling water levels in plateau areas and change in groundwater storage in plateau areas leading to loss of or changed terrestrial ecosystems that are partially groundwater dependent	<ul style="list-style-type: none"> <li>▪ Applicable to Scrubs on Sandy Alluvium, Tall Open Forests on Enriched Soils, Rainforests and Tall Moist Eucalypt Forests &amp; Sandstone Gully Forests BVGs               <ul style="list-style-type: none"> <li>- Consequences heightened during periods of extended drought or climate change</li> <li>- Change in species composition or vegetation structure following a likely long lag period and possibly after several seral stages until climax community reached</li> <li>- Modification of habitat features and resources for fauna/flora</li> <li>- Alteration of nutrient &amp; water cycles; and energy flow paths (e.g. dissipation of solar energy via water cycle). May change community fire-susceptibility and recovery; resilience to drought, disease &amp; insect attack</li> <li>- Increased susceptibility to fire can threaten the habitat of the Red-crowned Toadlet and other fauna species</li> </ul> </li> </ul>
<b>Gases emissions</b> Gas diffusing upwards through cracks occurring in the strata and emitted from the surface	<ul style="list-style-type: none"> <li>▪ Localised plant death as anaerobic conditions are created within the soil</li> </ul>

### 7.1.2.3 Factors influencing impacts and consequences

There are many factors that can influence the duration, intensity and probability of impact and their related consequences, such as:

- **Degree of impact** - intensity and duration of impact e.g. groundwater depth and storage fluctuation (difference between natural variation and post-mining variation);
- **Ecosystem recovery potential** - propensity of the ecosystem to recover following impact or the system to 'self-heal';
- **Ecosystem resilience** - resilience of vegetation community and dependent biota to groundwater flux;
- **Groundwater dependency** - ecosystem type and dependency on groundwater for reproduction or survival;
- **Past disturbance history** - in particular, fire and the condition of the vegetation following a fire or significant historical-disturbance event. This may influence the ecosystem's susceptibility to additional stresses; and
- **Future short and long-term climatic conditions** - extreme climatic events, such as drought and long-term shifts in climate through 'climate change' effects.

## 7.1.3 Impacts and Consequences on Aquatic Biodiversity

### 7.1.3.1 Reported Impacts on Streams and Aquatic Biodiversity

Underground mining has adversely impacted a number of streams in the Southern Coalfield with reviews by numerous authors (e.g. Everett *et al.*, 1998; Holla and Barclay, 2000b; Waddington Kay & Associates, 2002; Galvin and Associates, 2005; Biosis Research, 2007; Krogh, 2007; Total Environment Centre, 2007; NSW Department of Planning, 2008; Bio-Analysis Pty Ltd, 2009; Pells *et al.*, 2014; Metropolitan Coal, 2015 and WaterNSW, 2016). The streams in the Southern Coalfield reported to be impacted by underground mining are given in Table 7.3.



**Table 7.3: Reported Impacts on Streams and Aquatic Biodiversity**

Stream ID	Impacts and Consequences
<b>Waratah Rivulet</b> 4 <sup>th</sup> order stream lying between the downstream edge of Flat Rock Swamp and the full supply level of the Woronora Reservoir (Metropolitan Colliery)	<ul style="list-style-type: none"> <li>▪ Predicted: upsidence-related impacts with flow diverted into subsurface network; decrease in water quality &amp; loss of ecological integrity; site-specific ponding, erosion instability of cliffs &amp; overhangs</li> <li>▪ Actual: fracturing of bedrock in a number of areas above LW 11 panel, drainage of pools, ferruginous springs and iron bacterial matting, riparian vegetation dieback</li> </ul>
<b>Eastern Tributary</b> 3rd order stream lying between main gate of LW 26 and full supply level of Woronora Reservoir (Metropolitan Colliery)	<ul style="list-style-type: none"> <li>▪ Iron staining, increase in the numbers of prong-gilled mayflies compared to control sites-possibly due to mining, riparian vegetation dieback</li> </ul>
<b>Tributary B</b> (Metropolitan Colliery)	<ul style="list-style-type: none"> <li>▪ Minor cracking of the stream substratum, iron staining, significant change in structure of aquatic macroinvertebrate assemblages due to changes in contributions of prong-gilled mayflies, long-horned caddisfly and shrimp</li> </ul>
<b>Dendrobium Area 3B WC21</b> (1st & 2nd order tributary of Wongawilli Creek (Dendrobium Colliery)	<ul style="list-style-type: none"> <li>▪ Of total mine-related impacts observed in the area, 52% have been attributed to watercourses - accounting for 46 occurrences. Most impacts fall within the scale and significance predicted in the Illawarra Coal's Area 3B Subsidence Management Plan (SMP)</li> <li>▪ Impacts to WC21 are greater than predicted and are considered significant. They include significant rock fracturing, reduction in water levels in pools, an absence of surface flows and fracturing of the rock bars. Since undermining of LW 9 and 10, complete loss of flow observed in area overlying mined panels</li> </ul>
<b>Watercourse SC10</b> Sandy Creek (Dendrobium Colliery)	<ul style="list-style-type: none"> <li>▪ Exceeded level of impacts predicted in SMP for Area 3A</li> <li>▪ Creek completely dry over entire length, frequent evidence of cracking &amp; iron-staining in stream bed, no evidence of re-emergence of diverted stream water</li> <li>▪ In times of low-flow the majority, if not all, water is diverted into the dilated strata below &amp; is affecting the quality &amp; quantity of water</li> </ul>
<b>Watercourse WC17</b> Wongawilli Creek (Dendrobium Colliery)	<ul style="list-style-type: none"> <li>▪ Exceeded level of impacts predicted in SMP for Area 3A</li> <li>▪ Similar level of environmental consequence as SC10C</li> <li>▪ In times of low-flow the majority, if not all, water is diverted into the dilated strata below &amp; is affecting the quality &amp; quantity of water</li> </ul>
<b>Areas outside Special Areas</b>	
<b>Cataract River</b> downstream of Broughtons Pass Weir	<ul style="list-style-type: none"> <li>▪ Riverbed cracking and river drying, water re-emerging downstream with altered water quality, and reported loss of aquatic life</li> </ul>
<b>Upper Cataract River Gorge</b> , Tower Colliery (now Appin West)	<ul style="list-style-type: none"> <li>▪ River bed cracking</li> </ul>
<b>Upper Georges River</b> near Marhnyes Hole (Westcliff Colliery)	<ul style="list-style-type: none"> <li>▪ River bed cracking, river draining from pools, significant loss of flow in the Upper Georges River</li> </ul>
<b>Bargo River</b> above longwalls of Tahmoor Colliery	<ul style="list-style-type: none"> <li>▪ Riverbed cracking</li> </ul>
<b>Cataract River Gorge</b>	<ul style="list-style-type: none"> <li>▪ Gas affected vegetation. Four small areas of riparian vegetation were affected by gas emissions resulting in the loss of approximately 90 young trees, shrubs and groundcover species. Regeneration effective at the cessation of gas emissions</li> </ul>

**7.1.3.2 Potential Impacts and Possible Consequences for Aquatic Biodiversity**

Impacts and consequences presented in Table 7.4 have been compiled with reference to the groundwater and surface water sections of this report and to a number of sources including (Galvin and Associates, 2005; Biosis Research, 2007; DECC, 2007b; FloraSearch and Western Research Institute, 2008; Hose, 2008; NSW Department of Planning, 2008; Hose, 2009; Serov *et al.*, 2012; Serov, 2013; Cenwest Environmental Services, 2016 and NSW National Parks & Wildlife Service, 2016).



**Table 7.4: Potential Impacts and Possible Consequences of Longwall Mining on Aquatic Biodiversity**

Impacts on Aquatic Biodiversity	Possible Consequences
<p><b>Upsidence induced bedrock fracturing leading to change in stream flow pattern and flow rate</b></p> <ul style="list-style-type: none"> <li>▪ Re-direction of surface water into the strata below</li> <li>▪ Reduced or interrupted flows</li> <li>▪ Draining of pools</li> <li>▪ Reduced volume of water in pools</li> <li>▪ Change from permanent to intermittent flows</li> <li>▪ Reduction in flow volume</li> <li>▪ Changes in flood behaviour</li> <li>▪ Changes in groundwater and surface water levels</li> <li>▪ Changed surface water – groundwater interactions</li> <li>▪ Stream becomes a losing stream</li> <li>▪ Increase groundwater discharge</li> <li>▪ Loss of stream connectivity</li> </ul>	<ul style="list-style-type: none"> <li>▪ Draining or drying of pools causing the reduction or loss of refugia for aquatic species during periods of low flow</li> <li>▪ Loss or reduction of available watering and feeding resources for terrestrial fauna species and change in their distribution</li> <li>▪ Loss or reduction of critical habitat for threatened, protected and regionally significant terrestrial fauna species. (e.g. amphibians, the Eastern Snake-necked Turtle, Platypus, Water Rat, and the Large-footed Myotis bat)</li> <li>▪ Disruption of fish passage - migratory fish, such as Macquarie Perch, living in impoundments need to migrate upstream to spawn. Flow changes could lead to fish declines or complete loss</li> <li>▪ Change in fish assemblages, population size or distribution</li> <li>▪ Disruption of the downstream dispersal ('diel drift') of macroinvertebrate larvae in the water column</li> <li>▪ Loss or alteration of habitat for submerged and emergent aquatic plants; desiccation of macrophytes</li> <li>▪ Alteration of flow can affect periphyton cover (algal biomass). High algal biomass can result in fish kills, particularly during low flow scenarios. During sunlight hours, algae consume carbon dioxide from the water and can increase pH leading to sensitive stream organisms being affected</li> <li>▪ Alteration to stream connectivity and the consequent transfer of nutrients, organic carbon, sediment, as well as the partitioning of organisms within stream habitats</li> <li>▪ Interruption of the breeding cycle for some amphibian species by reducing or affecting the quality of breeding habitat</li> </ul> <p>Consequences common to all impacts</p> <ul style="list-style-type: none"> <li>▪ Alteration or loss of habitat for aquatic invertebrates including stygofauna</li> <li>▪ Change in species assemblages of aquatic invertebrates</li> <li>▪ Loss of riparian vegetation or changes to vegetation composition</li> </ul>
<p><b>Subsidence/upsidence induced stream bed alteration</b></p> <ul style="list-style-type: none"> <li>▪ Differential subsidence movements resulting in additional pools being formed or existing pools made deeper</li> <li>▪ Increase or decrease in stream gradient leading to an increase or decrease in ponding</li> <li>▪ Increase in stream gradient and the increase in stream power contributing to erosion or scouring of river bed and banks</li> <li>▪ Decrease in stream gradient contributing to sediment accumulation and possibly changing flow paths</li> <li>▪ Creation or alteration of riffle: pool sequences (lower reaches)</li> <li>▪ Changes in stream geometry or channel features</li> <li>▪ Change in flow pattern in stream channel</li> <li>▪ Fracturing of the stream bed rock stratum</li> <li>▪ Fracturing of rock bars</li> </ul>	<ul style="list-style-type: none"> <li>▪ Connectivity of aquifers causing mixing of stygofauna communities, risk of reducing aquifer condition and groundwater quality</li> <li>▪ Alteration of flow can affect periphyton cover (algal biomass). Increase flow or stream power can decrease algal biomass</li> <li>▪ Increase of sediment loading in stream alters stream substratum (deposition and accumulation affecting fauna and flora aquatic habitat) and suspended sediments affecting water quality</li> <li>▪ See above for consequences common to all impacts (particularly changes to riparian vegetation)</li> </ul>



Impacts on Aquatic Biodiversity	Possible Consequences
<p><b>Alteration of the subterranean/hyporheic zone</b></p> <ul style="list-style-type: none"> <li>Streambed lowering</li> <li>Reduction in groundwater levels and baseflow discharging to perennial streams</li> <li>Dewatering for longwall mining can result in depressurisation of the aquifer leading to compression or compaction and restricted pathways and reduced pore size<sup>9</sup></li> </ul>	<ul style="list-style-type: none"> <li>Groundwater drainage from upstream area depriving groundwater fauna elsewhere</li> <li>Loss of habitat for stygofauna due to aquifer no longer being saturated and compression and compaction restricting their movement and habitat value<sup>10</sup></li> <li>See above for consequences common to all impacts</li> </ul>
<p><b>Change in water quality</b></p> <ul style="list-style-type: none"> <li>Change in water quality parameters such as EC, dissolved oxygen, pH, temperature, turbidity, oxygen reduction potential and alkalinity</li> <li>Loss of biota that contribute to maintaining water quality, e.g. stygofauna</li> <li>Increase in mobilisation of sediments or suspended sediments in the water column from overland and stream bed and bank erosion</li> <li>Altered hydro-chemical interaction between surface and groundwater</li> <li>Introduction of iron and manganese from weathered rock</li> <li>Contamination of the groundwater and hyporheic zone</li> <li>Presence of iron oxidising bacterial mats</li> <li>Gas emissions into the water column. The gas is typically methane and not readily soluble in water, therefore only impacting the immediate area</li> </ul>	<ul style="list-style-type: none"> <li>Loss of native fauna and flora due to iron toxicity and other water quality parameters               <ul style="list-style-type: none"> <li>Change or loss of stygofauna community</li> </ul> </li> <li>Suspended sediments and accumulating sediment on the stream bed - smothering of benthic habitat and biota and reduced light available for aquatic plants</li> <li>Growth of thick mats of iron bacteria               <ul style="list-style-type: none"> <li>Bacterially-catalysed oxidation of iron consumes dissolved oxygen from the water column</li> <li>Clogs streams</li> <li>Reduces available food for aquatic organisms</li> <li>Smothering of benthos from the precipitation of released iron and associated iron-oxidising bacteria</li> <li>Change in the percent cover of algae on the streambed</li> </ul> </li> <li>Gas release               <ul style="list-style-type: none"> <li>Small scale disturbance of the substratum where the release occurs with localised impacts on aquatic biota</li> </ul> </li> <li>Loss of susceptible riparian vegetation in immediate area and death of newly recruiting vegetation</li> <li>Loss or alteration of riparian vegetation or the submerged and emergent aquatic plants               <ul style="list-style-type: none"> <li>Sensitivity to chemical changes or smothering by sediment or bacterial mats</li> <li>Change in relative abundance or cover in plant communities</li> </ul> </li> </ul>

**7.1.3.3 Factors influencing impacts and consequences**

Key factors that influence impacts and consequences to the aquatic environment are:

- Degree of impact** - severity of bedrock deformation;
- Stream flow** - an already reduced flow rate due to drought conditions or an upstream impoundment will increase the impact of water loss through cracking; and impacts on the flows of ephemeral creeks are likely to be greater than those on permanent creeks;
- Stream gradient** - the steeper the gradient the more likely sediments transported by water flow will be moved downstream; thus, keeping bedrock cracks open and the potential loss of flows to the subsurface to continue;
- Type of stream bed substrate** - the quality (e.g. sediment size) and quantity of bed substrate influences the potential for crack filling;

<sup>9</sup> See Section 3.8.5.3 and for further reading refer Appendix D: Biodiversity, reference numbers D3.4, D3.5 and D3.6.

<sup>10</sup> As above footnote



- **Geology and geomorphic character of the stream** - either bedrock controlled (formed in erosion resistant Hawkesbury Sandstone) or unconfined channel morphology (alluvial streams formed in weathered and erodible Wianamatta Shale);
- **Catchment area** - catchment area will influence the impacts of altered flow;
- **Change in the reliability of baseflows** - many species of surface aquatic macroinvertebrates and aquatic invertebrates rely on base flows for reproduction, habitat for larvae, refuge during periods of extreme high or low flows, and a supply of nutrients from upwelling zones.
- **Persistence of iron springs** - length of time iron springs persist in the future as they have been known to last for decades;
- **Characteristics of instream pools** - geomorphic character, size and depth, substratum material, rate of water level decline and in-pool drying frequency;
- **Ecosystem recovery potential** - ability of system to self-heal, which depends on many other factors listed in this section;
- **Natural variation** - e.g. there is significant natural variation across areas and between years in regards to the presence and absence of adult amphibians and breeding events in response to seasonal variation;
- **Past disturbance history** - disturbances such as bed and bank erosion, gullyng and fire can influence ecosystem and geomorphic resilience;
- **Future short and long-term climatic conditions** - extreme climatic events, such as drought and long-term shifts in climate through 'climate change' effects;
- **Groundwater dependency** - species and ecosystems have varying degrees of dependency on groundwater. Some are obligate users, while others are facultative or opportunistic; and
- **Aquatic macroinvertebrate recolonisation** - ability of macroinvertebrates to drift to new unimpacted environments (flowing waters) or to recolonise from refugia to rehydrated pools.

## 7.1.4 Impacts and Consequences on Upland Swamp Ecosystems

### 7.1.4.1 Reported Impacts on Upland Swamps

A number of upland swamps in the Special Areas have been impacted by mining practices and, as for aquatic environments, have been reported widely (e.g. Tomkins and Humphreys, 2006; Krogh, 2007; NSW Department of Planning, 2008; Krogh, 2012; Commonwealth of Australia, 2014b; Metropolitan Coal, 2014; Pells *et al.*, 2014; Bower, 2015; Cenwest Environmental Services, 2015; Krogh, 2015 and WaterNSW, 2016). Some of the swamp impact-histories illustrate how a primary impact can change the resilience of the swamps rendering them susceptible to progressive impacts (Tomkins and Humphreys, 2006 and Krogh, 2007). Despite the recognised vulnerability of hanging swamps to subsidence-related impacts (Pells *et al.*, 2014 and Commonwealth of Australia, 2014b), no adverse impacts on hanging swamps (known to occur in the Bargo and Cataract Gorges that lie outside the Special Areas) have been reported in the literature reviewed. Further, no known mapping or reporting of hanging swamps have been undertaken for the Special Areas.

Interestingly, impacts to swamps are not universally recognised and suggestions have been made in the literature to argue that there is no evidence of longwall mining related impacts to these systems. Biosis Research (2007) in their submission to the NSW Minerals Council argue that 'there is little evidence of impact to upland swamps as a result of longwall mining' with 'few, if any, impacts associated with mining having been reported'. The foundation for their argument is based on the following, summarised, justifications for exhibited scouring and erosion at some sites:



- Upland swamps are continually evolving with scour channels developing and infilling and have occurred in the pre-mining history (see Section 3.6.4 for overview of these processes);
- Changes in swamp character appear to be related to episodic fire events which may lead to other physical changes within the swamp;
- There is little difference between the current state of swamps that do and do not overlie mining operations;
- There is no significant difference in surface water between the swamps that have and have not been subject to mining related surface deformation;
- Some swamps are predisposed to gullyng;
- Swamps dry through drought and other mechanisms;
- Disturbance to the cover vegetation may be through fire or mechanical means; and
- Intense rainfall and associated flow events prior to the re-establishment of cover vegetation over exposed soil can cause erosion.

The upland swamps in the Southern Coalfield reported to be impacted by underground mining are provided in Table 7.5. To date no impacts to hanging swamps have been reported in the Southern Coalfield nor have there been any known long-term ecological impact studies on any swamp.

**Table 7.5 Upland Swamps Reported to be Impacted by Longwall Mining**

Swamp ID	Swamp Type	Impacts and Consequences
Swamp 20 (Metropolitan Colliery)	Headwater	<ul style="list-style-type: none"> <li>▪ Fracturing of bedrock</li> <li>▪ Change in perched water table</li> </ul>
Flat Rock Swamp on Waratah Rivulet (Metropolitan Colliery northern end; Darkes Forest Colliery at southern end)	In valley	<ul style="list-style-type: none"> <li>▪ Pre-mining erosion evident (fires/rainfall events likely triggers); mining likely contributor to gullyng and swamp draining</li> </ul>
Dendrobium 1b Dendrobium Area 3B (Dendrobium Colliery)	Headwater	<ul style="list-style-type: none"> <li>▪ Fracturing of bedrock in a number of areas above LW panel with consequent impacts to perched aquifer and soil moisture levels, and loss of flow to the Donalds Castle Creek tributary downstream of Swamp 1b</li> </ul>
Swamp 1 Dendrobium Area 2 (Dendrobium Colliery)	Headwater	<ul style="list-style-type: none"> <li>▪ Fracturing of bedrock</li> </ul>
Dendrobium 1a, 5, 12, 15b Dendrobium Area 3A (Dendrobium Colliery)	Headwater	<ul style="list-style-type: none"> <li>▪ Swamps 12 &amp; 15b – impacts have exceeded the level predicted in the SMP for Area 3A</li> <li>▪ Impact on shallow groundwater levels</li> <li>▪ Swamp very dry with no evidence of wet patches or springiness</li> <li>▪ Additional fracturing in bedrock of Swamps 15b &amp; 12</li> <li>▪ Monitoring results of shallow Hawkesbury sandstone aquifers adjacent to swamps or perched aquifers within swamps suggest Dendrobium mine has impacted each one it has directly undermined or where the swamp was located on the surface immediately adjacent to the extracted panel (Swamp 15b)</li> </ul>
Drillhole Swamp on Flying Fox Creek (Elouera Colliery)	In valley	<ul style="list-style-type: none"> <li>▪ Subsidence related cracking in bedrock downstream of swamp. Significant surface impacts including construction of small dam which failed &amp; triggered gully erosion and swamp draining</li> </ul>
Swamp 18, 19 (Elouera Colliery)	In valley	<ul style="list-style-type: none"> <li>▪ Pre-mining erosion. Drained, further eroded and subsidence related bedrock cracking in creek downstream of swamp. Little investigative work undertaken on Swamp 19, however considering proximity to S18 &amp; similar mining history, impacts likely to be caused by subsidence-related cracking</li> </ul>



In addition, Evans & Peck (2014) reviewed the water level behaviour of swamps in the ‘Wonga East’ areas for the proposed Russell Vale Extension that had been undermined between the late 19<sup>th</sup> Century and 1982. Although the subsidence was only inferred from analysis of the mine maps, only one swamp exhibited water level decline following rainfall that might indicate drainage from the base of the swamp.

**7.1.4.2 Potential Impacts and Possible Consequences**

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. Many swamp ecosystems have evolved to tolerate shifts in natural disturbances; however, if the disturbance is great enough to exceed an internal threshold, then the system will, in time, readjust geomorphically or through vegetative successional change with all the attending feedback mechanisms to self-heal or to change to an ‘alternate stable state’<sup>11</sup>.

The causal agents affecting the ecological and geomorphic integrity of swamps and their dependent organisms are outlined below in Table 7.6. Similar to the terrestrial and aquatic biodiversity sections above, the impacts and consequence table have been compiled with reference to the groundwater and surface water sections of this report and to a number of sources including (Pokorný *et al.*; Beadle and Costin, 1952; Hope *et al.*, 2009; Baird and Burgin, 2010; Benson and Baird, 2012; Krogh, 2012; Serov *et al.*, 2012; Commonwealth of Australia, 2014a; IESC, 2014a; Bower, 2015; Cenwest Environmental Services, 2016 and NSW Scientific Committee, 2016c, a).

**Table 7.6 Potential Impacts on Upland Swamps and the Possible Consequences of such Impacts**

Impacts on Upland Swamps	Primary Consequences	Secondary Consequence
<p><b>Impact on regional groundwater aquifer</b> Falling water levels in plateau areas; change in groundwater storage in plateau areas leading to loss of hillside springs and reduced groundwater resource potential</p>	<p><b>Loss or alteration of headwater and valley-side swamps</b></p> <ul style="list-style-type: none"> <li>▪ Drying of areas once wet from localised groundwater seeps</li> <li>▪ Peat desiccation, oxidation and peat subsidence where it occurs around seepage areas</li> <li>▪ Reduced perched groundwater availability below seep</li> <li>▪ Surface erosion may occur on steep slopes following substrate drying and reduction in vegetative cover</li> <li>▪ Increased risk of fire</li> </ul>	<ul style="list-style-type: none"> <li>▪ Reduced vegetation community diversity leading to more homogeneous structure and composition (previously wet areas around seeps resembling vegetation distal to seep zone)</li> <li>▪ Consequences common to valley-side, headwater and valley-infill swamps:               <ul style="list-style-type: none"> <li>- Alteration of vegetation structure and composition due to swamp drying</li> <li>- Alteration of vegetation structure and composition due to fire</li> <li>- Colonisation of swamp by terrestrial species</li> <li>- Loss of geomorphic stability and increased potential for gully incision mobilisation of peat and sediments, and complete collapse of swamp</li> </ul> </li> </ul>

<sup>11</sup> **Alternate stable state:** ecosystems with alternate stable states may shift discontinuously from one stable state (e.g. change in population or community composition) to another as environmental parameters cross a threshold. An example could be a sedgeland (stable over ecological time) changing to an open forest (stable over ecological time)



Impacts on Upland Swamps	Primary Consequences	Secondary Consequence
		<ul style="list-style-type: none"> <li>- Loss of potential habitat for key groundwater dependent ecosystems and species e.g. stygofauna (resulting in terminal losses of specific suites of organisms), the Giant Dragonfly &amp; burrowing crayfish (resulting in local losses and cumulative impacts on metapopulations)</li> <li>- Changes in hydraulic conductivity and a loss of recharge potential (peat loses some of its absorption capacity)</li> <li>- Disruption of feedback mechanisms (e.g. organic matter accumulation, above and below ground vegetative growth, sediment trapping, water storage capacity of substrate, nutrient cycles, hydraulic conductivity of peat)</li> <li>- Loss of habitat for opportunistic threatened faunal species such as frogs (Giant Burrowing Frog, Red-crowned Toadlet and Littlejohn's Tree Frog resulting in localised loss or populations)</li> </ul>
<p><b>Impact on regional groundwater aquifer</b> Increased recharge across plateau; changed surface water-groundwater interactions; potential stream losses and increased groundwater discharge; loss of groundwater discharge</p>	<p><b>Loss or alteration of <u>valley in-fill swamps</u></b></p> <ul style="list-style-type: none"> <li>▪ Swamp drying</li> <li>▪ Peat desiccation and oxidation</li> <li>▪ Peat breakdown and the release of methane and dissolved organic carbons, and loss of thermal insulation</li> <li>▪ Reduced perched groundwater availability below discharge area</li> <li>▪ Surface erosion may occur following substrate drying and reduction in vegetative cover</li> <li>▪ Reduced sediment storage and peat drying resulting in decreased water-holding capacity and change in water quality               <ul style="list-style-type: none"> <li>- Reduced baseflow from swamps to downstream creeks</li> <li>- Flashier flooding during storm events resulting in alteration of flow to downstream reaches</li> <li>- Increased concentrations of low pH and high iron groundwater to streams</li> </ul> </li> <li>▪ Increase number of cease to flow days</li> <li>▪ Increased risk of fire</li> </ul>	<ul style="list-style-type: none"> <li>▪ Impacts can cause consequences to downstream aquatic environments (see Section 7.1.3 for impacts and consequences)</li> <li>▪ Impact on threatened species in downstream habitats reliant on base flows from streams for water permanency. such as Macquarie Perch and Giant Burrowing Frog</li> <li>▪ See above for consequences common to headwater, valley-side and valley infill swamps</li> </ul>



Impacts on Upland Swamps	Primary Consequences	Secondary Consequence
<p><b>Impact on regional groundwater aquifer</b> As above for headwater swamps</p>	<p><b>Loss or alteration of <u>hanging swamps</u></b></p> <ul style="list-style-type: none"> <li>▪ Drying of areas once dependent on localised groundwater seeps</li> </ul>	<ul style="list-style-type: none"> <li>▪ Loss of habitat for groundwater dependent vegetation favouring these swamp types</li> <li>▪ Loss of habitat for stygofauna due to aquifer no longer being saturated and compression and compaction restricting their movement and habitat value</li> <li>▪ Loss of habitat for opportunistic faunal species such as frogs and impacts on metapopulations of these species</li> </ul>
<p><b>Impact on <u>local superficial aquifer</u></b> Falling water levels and loss of water storage;</p>	<p><b>Loss or alteration of <u>headwater and valley-side swamps</u></b></p> <ul style="list-style-type: none"> <li>▪ Large wetting and drying cycles</li> <li>▪ Loss or alteration of valley infill swamps</li> <li>▪ Increased tendency for the catchment valley to dry up faster post rainfall periods</li> </ul>	<ul style="list-style-type: none"> <li>▪ See above for consequences common to headwater and valley infill swamps</li> </ul>
<p><b>Impact on surface water quality and quantity</b> Tensile cracking of rock bars; tensile/ shear movement of joint and bedding planes in rocks below the swamp; and buckling and localised upsidence in the stream bed below valley in-fill swamps</p>	<p><b>Loss or alteration of <u>headwater and valley-side swamps</u></b></p> <ul style="list-style-type: none"> <li>▪ Potential drop in perched water tables</li> <li>▪ Swamp drying</li> <li>▪ Large wetting and drying cycles</li> <li>▪ Increased susceptibility to fire</li> </ul>	<ul style="list-style-type: none"> <li>▪ Alteration of vegetation structure and composition due to swamp drying</li> <li>▪ Alteration of vegetation structure and composition due to fire</li> <li>▪ Colonisation of swamp by terrestrial species</li> <li>▪ Loss of habitat for opportunistic threatened faunal species such as frogs (Giant Burrowing Frog, Red-crowned Toadlet and Littlejohn's Tree Frog resulting in localised loss or populations</li> <li>▪ Reduced baseflow and consequences to downstream reaches (see Section 7.1.3 Aquatic Biodiversity)</li> </ul>
<p><b>Impact on surface water quality and quantity</b> As above for headwater swamps</p>	<p><b>Loss or alteration of <u>valley infill swamps</u></b></p> <ul style="list-style-type: none"> <li>▪ Change in surface flow pathways due to tilt</li> <li>▪ Differential swamp elevation due to subsidence leading to localised redistribution of surface water</li> <li>▪ Swamp drying</li> <li>▪ Increased potential for erosion and scouring of dry swamps</li> <li>▪ Increased tendency for the catchment valley to dry up faster post rainfall periods</li> <li>▪ Change in surface flow pathways due to tilt</li> <li>▪ Loss of standing pools</li> <li>▪ Change in water quality with peat degradation and compounds such as iron and manganese</li> <li>▪ Consequences similar to valley-side and headwater swamps, but more extensive and significant</li> </ul>	<ul style="list-style-type: none"> <li>▪ Alteration of nutrient &amp; water cycles; and energy flow paths (e.g. dissipation of solar energy via water cycle)</li> <li>▪ Loss of native fauna and flora due to iron toxicity and other water quality parameters</li> <li>▪ Alteration of vegetation structure and composition due to fire</li> <li>▪ Colonisation of swamp by terrestrial species</li> <li>▪ Loss of habitat for opportunistic threatened faunal species such as frogs (Giant Burrowing Frog, Red-crowned Toadlet and Littlejohn's Tree Frog resulting in localised loss or populations</li> <li>▪ Reduced baseflow and consequences to downstream reaches (see Section 7.1.3 Aquatic Biodiversity)</li> </ul>



Impacts on Upland Swamps	Primary Consequences	Secondary Consequence
Impact on <u>cliff lines</u>	Loss or alteration of <u>hanging swamps</u> <sup>12</sup> <ul style="list-style-type: none"> <li>Mechanical alteration through cliff collapse or rock fall</li> <li>Erosion of sediment within fractures that provide substrate to vegetation</li> </ul>	<ul style="list-style-type: none"> <li>Loss of habitat for swamp vegetation and faunal species</li> <li>Loss of habitat for the adult Red-crowned Toadlet</li> </ul>

### 7.1.4.3 Factors influencing Impacts and Consequences

Key factors that influence impacts and consequences to upland swamps include:

- **Degree of impact** - intensity and duration;
- **Ecosystem recovery potential** - ability of system to self-heal, which depends on many other factors listed in this section;
- **Ecosystem type and dependency on groundwater** - the greater the degree of groundwater dependency the greater the likely consequence;
- **Community resilience** - resilience of vegetation to groundwater change;
- **Degree of groundwater depth fluctuation** - change between before and after undermining;
- **Past disturbance history** - most particularly the 2001/2 fire and the status of the vegetation and the susceptibility to additional stresses;
- **Subsequent disturbances** - the intensity and intervening time-period between each successive disturbance (e.g. fires and storm events);
- **Prevailing climate** - future short and long-term climatic conditions;
- **Fire history** - fire as an influence to vegetation succession, geomorphic thresholds and the trigger for erosion (frequency and intensity);
- **Time** - some impacts may have direct and immediate consequences (e.g. bedrock cracking and swamp drying), which is measurable through piezometric or soil moisture data. However, some consequences, for example, change in vegetation composition and structure may require a considerable lag period before change is measurable or observed (references). Coupled with this is change that may occur simultaneously such as vegetation succession following fire;
- **Species survival and reproduction** - ability of the eggs of zooplankton to survive drying and the specific means of dormancy breakage and hatching. Multiple generations in the egg and plant seed bank and complexity of environmental cues for dormancy breakage also contribute to the ecosystem's ability to recover after a drying event;
- **Level and type of disturbance** - disturbances are a source of spatial heterogeneity for many communities as they open up spaces that can be colonised by other individuals and species; thereby maintaining biodiversity. The disturbance can include those that are externally generated (e.g. fire, storms, droughts), and those that are intrinsically generated (e.g. tree fall from hillside); and
- **Swamp rehabilitation and remediation** - the success or otherwise of rehabilitation and remediation techniques for swamps over appropriate time-scales to maintain their ecological, hydrological and geomorphic integrity.<sup>13</sup>

<sup>12</sup> Hanging swamps, refer Appendix D: Biodiversity, reference numbers D4.1 and D4.8

<sup>13</sup> Evaluation of mitigation and remediation techniques for swamps, refer Appendix D: Biodiversity, reference number D4.9.



## 7.2 Impact Limits

Adopting impact limits directly to ecosystems and 'living things' has the risk of attributing levels of accuracy or quantification to systems that are highly variable in time and space, are influenced by factors within and outside the system, and respond to impacts with a degree of uncertainty and unpredictability; thus, it has the potential to increase the error of interpretation or the interpretation becomes meaningless.

It also depends on what ecological or geomorphic attribute the impact limit is set for. Is it for an ecosystem, a threatened species, habitat for fauna, vegetative assemblage, peat integrity, or water storage/quality? Setting impact limits for species requires the maintenance of suitable habitat, such that swamp drying and the loss of a perched water table in a swamp would not result in the loss of obligate groundwater dependent species<sup>14</sup> from that particular habitat, but it may not result in the loss of facultative plant or animal species<sup>15</sup>. Further, the loss of a perched water table will have greater consequences on ecosystems in permanently saturated ecosystems than periodically saturated.

In addition, another example of when the exceedance of an impact limit can give different outcomes and different value judgements of what is significant and what is acceptable is presented in the following scenario: a quantified water quality parameter in a stream has exceeded its impact limit in a given period of time. The outcomes could be the complete loss of a unique assemblage of stygofauna in the hyporheic zone; the temporary change or removal of aquatic macroinvertebrates (until the next 'fresh' following rain or recolonization of biota); the temporary and partial alteration of riparian vegetation; unknown impacts on native fish; unknown long-term consequences and unknown recovery periods. A slight adjustment of the impact limit may not capture consequences to less sensitive biota, but may still be enough to decimate stygofauna populations. The questions then arise as to 'what is an acceptable consequence and what is significant enough to protect?

Guiding principles for setting impact limits are that they should:

- Be set against the expected natural variation of the ecosystem in time (before impact) and space (within and between ecosystems);
- Be measurable and statistically robust;
- Be formulated in recognition of the hydrological, geomorphic and ecological integrity of the ecosystem – not just components within these systems; and
- Be set to reflect cumulative impacts at the scales of time (reflecting lag responses), space and 'within-system' cumulative hierarchical consequences within a point location (e.g. loss of perched water table that triggers an alteration of vegetation assemblage, peat breakdown, change in biochemical reactions, alteration of substrate biota, decrease in clay eluviation<sup>16</sup>).

### 7.2.1 Terrestrial Biodiversity

The summary of documented impacts and impact limits are:

- Subsidence and the effects of cliff falls etc.

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<sup>14</sup> Species with total and continuous dependence on groundwater.

<sup>15</sup> Species that are not totally reliant on groundwater for their survival. Dependence on groundwater for facultative groundwater dependent *ecosystems* can range from opportunistic to being highly dependent.

<sup>16</sup> Eluviation is the transport of soil material from upper layers of soil to lower levels by downward precipitation of water across soil horizons (or sedimentary layers)



- Impact limit derived from Pells *et al* (2014) No pillar recovery or longwall extraction, within a depth of nominally 500 m, other than mine access entries, should occur in areas defined by 45° in front of the toe line, to 45° behind the crest line, for at least:
  - i. cliff lines greater than 50 m high;
  - ii. any cliff lines that include overhang caves that may have Aboriginal significance;
  - iii. any cliff lines that include hanging swamps or similar ecological and groundwater features.
- Surface bedrock and soil cracking
  - No known impact limit in literature.
- Impact on regional groundwater aquifer
  - Groundwater dependent vegetation (phreatophytes) depend on the subsurface presence of groundwater, often accessed via the capillary fringe where most trees take up groundwater. As water is removed by transpiration it is continually replenished from the water table through capillary rise. Phreatophytes include both deep and /or shallow rooted forests and woodlands. Groundwater dependence varies with species, seasonal variation and the environment in which they live. A drop in groundwater level as a result of subsidence could impact on these ecosystems;
  - Derived from the NSW Aquifer Interference Policy: terrestrial groundwater dependent ecosystems (GDE), the minimal impact on the water table in porous rock water sources is: *less than or equal to 10% cumulative variation in the water table, allowing for typical climatic variations, 40 m from any high priority GDE.* For water pressure the minimal impact is: *a cumulative pressure head decline of not more than a 2 m decline, at any water supply work.* High priority status may be given to terrestrial GDEs if they are recognised as being an Endangered Ecological Community or are the preferred habitat for threatened species or have other significance.

## 7.2.2 Aquatic Biodiversity

The summary of documented impacts and impact limits are:

- Change in stream flow and flow rate;
- Stream bed alteration;
- Change in water quality; and
- Alteration of the subterranean/hyporheic zone.

The first three impacts can be measured and impact limits set against natural variation with adequate before-impact data collection. The latter impact is likely to be inferred from the other impacts due to the relative difficulty in measuring suitable parameters, such as stygofauna and subterranean water quality (refer Serov *et al.*, 2012).

The Metropolitan Colliery Water Management Plan the water quality performance indicator is triggered: *if any water quality parameter should exceed the baseline period mean concentration plus two standard deviations for two consecutive months.* While other studies rely on guidelines or limits provided in the ANZECC and ARM CANZ guidelines<sup>17</sup> for the protection of aquatic ecosystems.

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<sup>17</sup> ANZECC and ARM CANZ (2000) – Australia and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand (2000) *Australian and New Zealand Water Quality Guidelines for Fresh and Marine Water Quality*



## 7.2.3 Upland Swamps

The summary of impacts and impact limits are the change in regional groundwater and the local superficial aquifer, and the change in surface water quantity and quality. Fundamentally the impact limits are:

- The alteration of the perched water table (for swamps with this characteristic) outside expected natural variation for that upland swamp:
  - Measured by swamp piezometers;
  - An impact limit or performance indicator adopted by Metropolitan Coal (Metropolitan Coal, 2015) in their *Longwalls 23-27 Biodiversity Management Plan* is: if there is a statistically significant change in swamp substrate groundwater levels (i.e. the seven-day moving average data lie outside the 5<sup>th</sup> and 95<sup>th</sup> percentiles established for the full length of record).
- Peat and/or swamp substrate drying outside expected natural variation for that upland swamp measured by, for example, soil moisture meters.

The impact on hanging swamps located on cliff lines are as above for terrestrial biodiversity.

## 7.3 Gaps in Existing Knowledge

Data gaps that limit our knowledge of impacts and consequences, and the predictability or probability of impacts, to each situation are infinite and for this reason there is a need for the scope to be delimited. However, knowledge in key areas is critical for impacts to be reported and quantified as well as consequences to be better understood and ultimately predicted. General data gaps include:

- Much of the data, analysis and reporting of impacts pertaining to longwall mining is in the grey-literature 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 in the public domain.
- There is a lack of a comprehensive, centralised data retrieval document that records, characterises, maps and quantifies mining-related impacts to the natural environment across the Special Areas.

### 7.3.1 Terrestrial Biodiversity

The dependency of the broad vegetation groups or site-specific vegetation communities on the regional groundwater is unknown, as is their resilience to withstand change. It is also expected that it would be highly variable across the diversity of regional landscapes, leading to a major constraint in surveying and monitoring these attributes. The practice would likely have a high resource requirement for, perhaps, little gain given the low recorded impacts to date.

### 7.3.2 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.



### 7.3.3 Upland Swamps

Knowledge gaps for the upland swamp ecosystems include:

- Understanding cumulative impacts across spatial and temporal scales and the hierarchical culmination of consequences (see Section 7.2.3);
- Hydrological balance of upland swamps with adequate baseline pre-mining 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 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?



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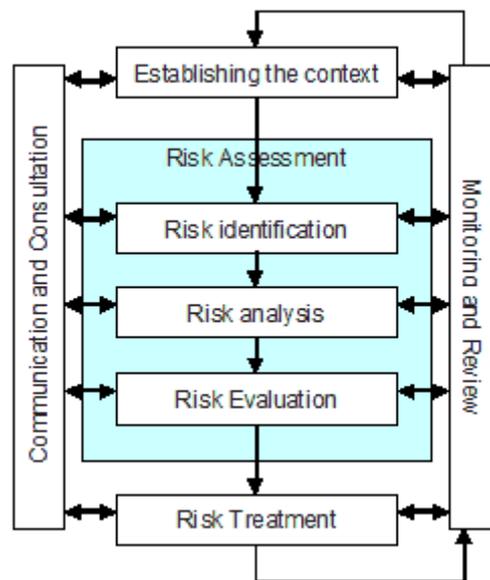


## 8 Risk Assessment Methodologies

Appendix E contains a review of risk related documents relevant to this Review. The documents include both Policy and Guideline documents and Risk Assessment reports for mining specific applications/projects.

All of the reviewed policy and framework documents refer to *ISO 31000: 2009 Risk Management Principles and Guidelines* (or its predecessor standards).

The standard risk management framework includes a standard risk management process, which is shown graphically in Figure 8.1.



**Figure 8.1: Standard Risk Management Process**

A number of the documents reviewed in Appendix E are more appropriate to the development and assessment of dam infrastructure and are not particularly relevant to the impacts on catchments due to underground mining. These policies focus on very low likelihood - very high consequence risks of dam failure and subsequent loss of life associated with flooding. They do not address high likelihood, but generally low or moderate consequence risks like impacts on reservoir yield or water quality issues. They also do not consider how risks may change over time.

The risk assessments on previous mining applications were all considered consistent with the requirements of ISO 31000: 2009. It is recommended that the following aspects of the specific risk assessments reviewed in Appendix E be considered by WaterNSW:

- Use of an event tree template (similar to that used in Broadleaf (2015)) to assist in the initial identification of risks relevant to the individual mining application. This also provides a graphical presentation and clearly indicates risks that have been excluded from further assessment. A sample event tree analysis is provided in Figure 8.2 below.

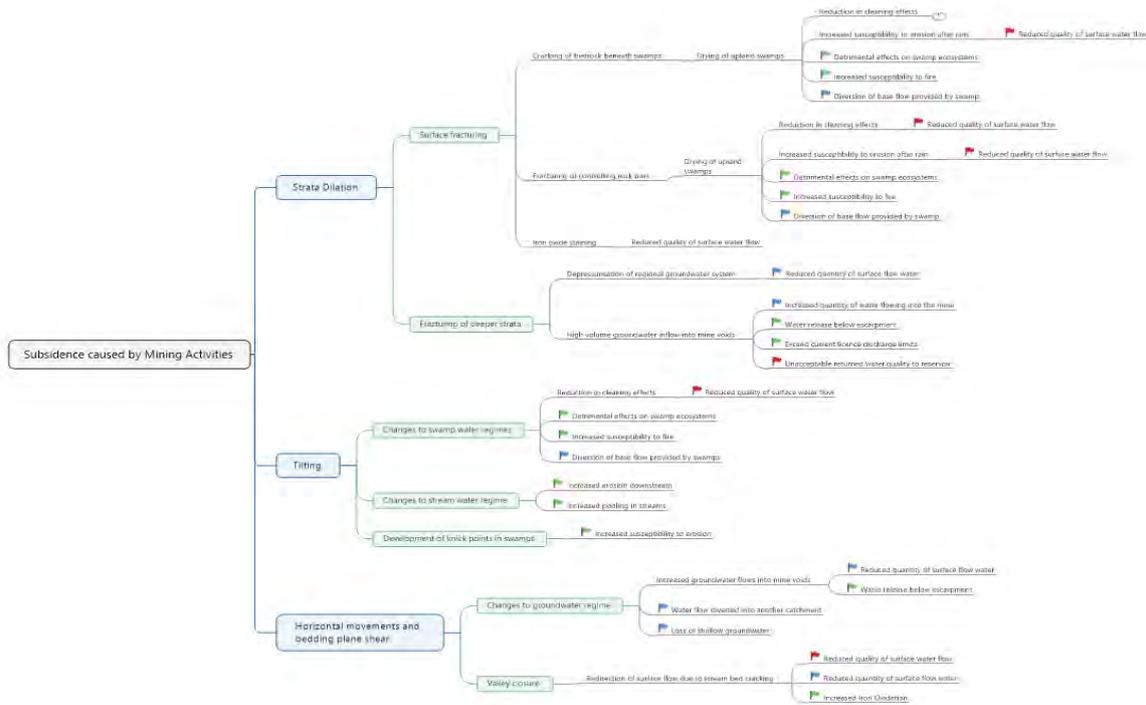


Figure 8.2: Sample Event Tree Analysis

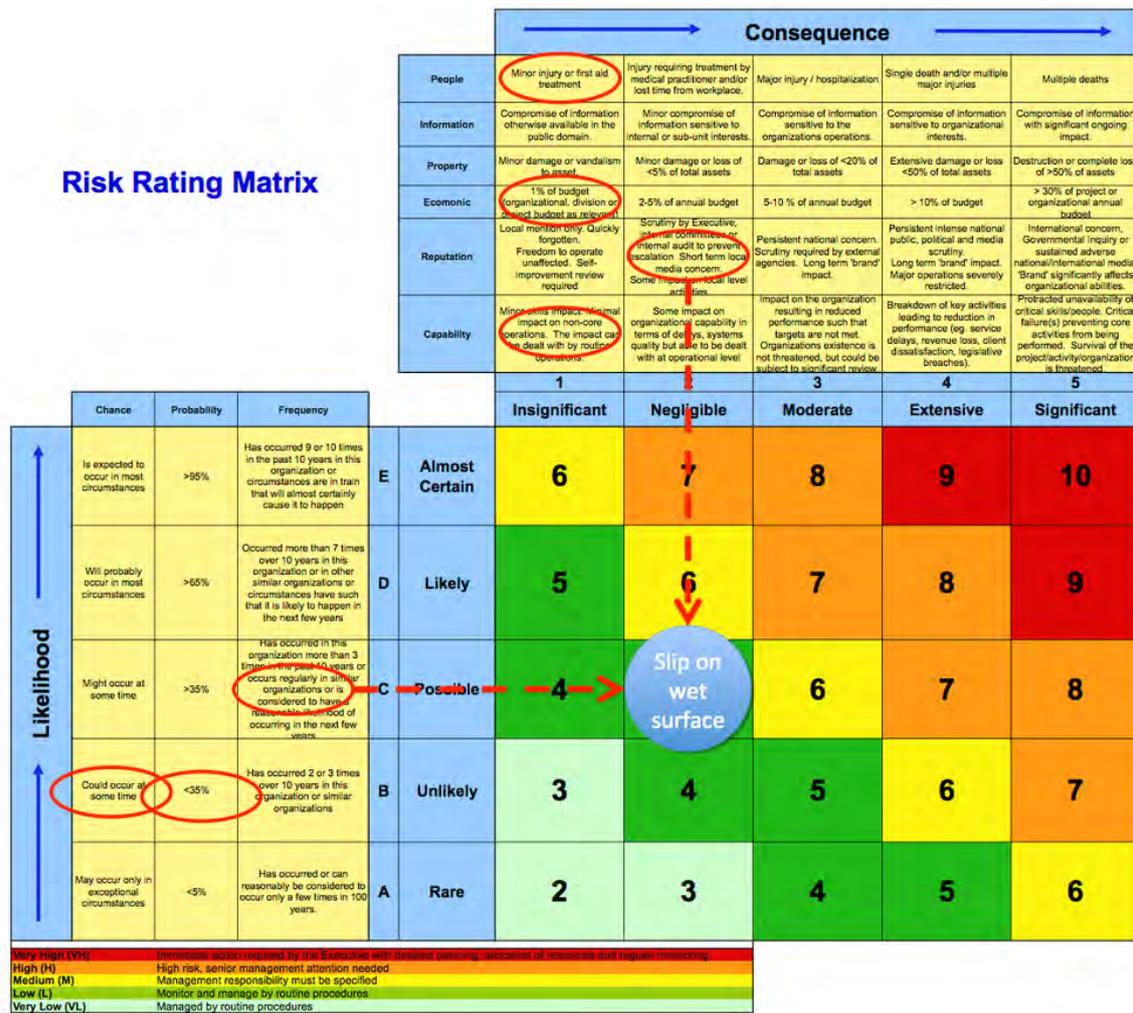
- Development of a more detailed consequence table (similar to that used by Galvin (2005)) separately addressing water quality, water quantity, ecological risk etc. The ranges for each level of consequence will need to be agreed with WaterNSW e.g. what loss of water yield is considered as a moderate consequence. A sample risk consequence table is provided in Table 8.1.

Table 8.1: Sample Consequence Table

Water NSW - Mining Application - Risk Assessment Tool				
Consequence Ranking Table				
Ranking		Water Quality	Water Yield	Ecological Integrity
1	High	Filtration Plant can't meet BWSC > 75% time	< 80%	No surface flow and ponds empty for months at a time. Most current stream fauna and flora
2	Moderately High	Quality decrease at filtration plant but plant meets BWSC > 95% time	80 - 90%	No surface flow for weeks at a time. Some current stream fauna and
3	Moderate	Quality decrease down to dam but no impact at filtration plant	90 - 97%	No surface flow for days at a time, but ponds hold water. Some current stream flora and Fauna lost permanently
4	Minor	Quality decrease in stream but no impact at dam	97 - 99%	Periods of reduced surface flow, but pond levels unchanged. Current stream flora and fauna
5	Negligible	No measurable change in stream	> 99%	No detectable change in stream



- Consideration of the change in risk consequence over time (similar to the approach in Galvin (2005)).
- Development of a standard likelihood table and risk matrix in accordance with the standard WaterNSW templates. All future risk assessments should use the same templates for consistency, particularly when assessing cumulative impacts. A sample risk assessment matrix is included as Figure 8.3.



**Figure 8.3: Sample Risk Assessment Matrix**

- Consideration of cumulative impacts of multiple mining applications within the one catchment area.
- Development of a consistent standard risk management framework for reviewing risk assessments and particularly when assessing cumulative impacts.
- Identification of appropriate mitigation strategies that can be implemented before and/or after the risk occurs.



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# Appendix A: Literature Review Summaries – Subsidence

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## **Appendix B:** **Literature Review Summaries – Groundwater**

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## **Appendix C:** **Literature Review Summaries – Surface Water**

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## **Appendix D: Literature Review Summaries – Biodiversity**

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# Appendix E: Literature Review Summaries - Risk Assessment

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# Appendix F: Review of Hydrology of Upland Swamps

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