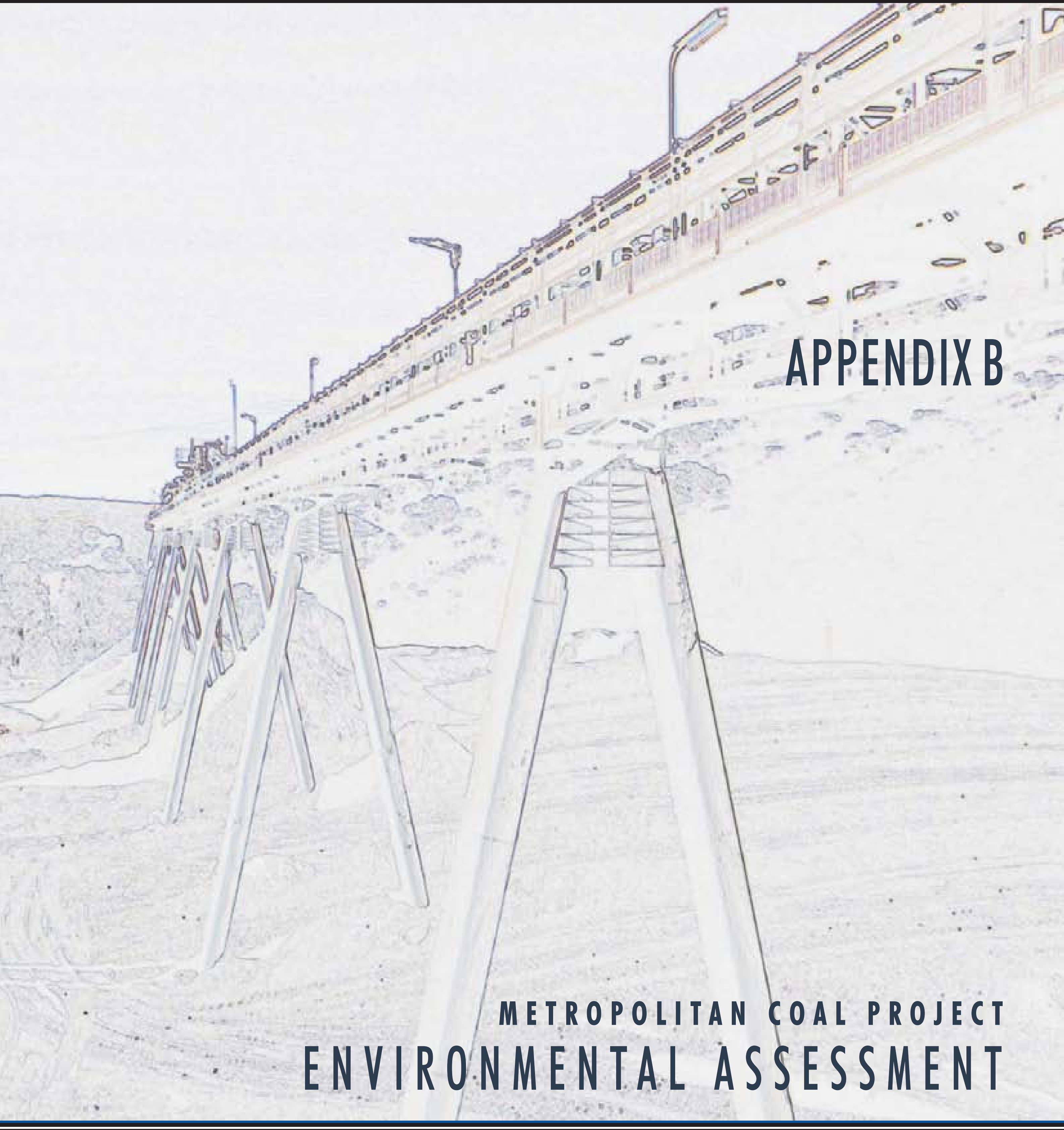


APPENDIX B

METROPOLITAN COAL PROJECT

ENVIRONMENTAL ASSESSMENT

METROPOLITAN COAL PROJECT
GROUNDWATER ASSESSMENT

A HYDROGEOLOGICAL ASSESSMENT IN SUPPORT OF METROPOLITAN COLLIERY LONGWALLS 20 TO 44 ENVIRONMENTAL ASSESSMENT

FOR

HELENSBURGH COAL PTY LTD

PO BOX 402

HELENSBURGH NSW 2508

By

Dr N. P. Merrick

Heritage Computing

Project Number: MET-06-02
Report HC2008/5
Date: August 2008

DOCUMENT REGISTER

REVISION	DESCRIPTION	DATE	AUTHOR
A	FIRST DRAFT	16 MAY 2008	NPM
B	SECOND DRAFT	10 JUNE 2008	NPM
C	THIRD DRAFT	17 JUNE 2008	NPM
D	FOURTH DRAFT	10 AUGUST 2008	NPM

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

LIST OF TABLES

LIST OF ATTACHMENTS

1.0 INTRODUCTION

This report has been prepared for Helensburgh Coal Pty Ltd (HCPL), a wholly owned subsidiary of Peabody Pacific Pty Ltd. The report provides a hydrogeological assessment of proposed Longwalls 20 to 44 at the Metropolitan Colliery (Figure 1).

The Metropolitan Colliery is located within the Southern Coalfield at a distance of approximately 30 kilometres (km) to the north of Wollongong in New South Wales (NSW), close to the Helensburgh township.

The proposed Metropolitan Coal Project (the Project) would involve the continuation of underground mining operations at the Metropolitan Colliery. The area of proposed underground mining is situated to the north of the current longwall mining areas (Longwalls 14 to 19A; Figure 1). The Project would extend the life of the Metropolitan Colliery by approximately 25 years.

Existing surface and underground facilities at the Metropolitan Colliery (e.g. conveyors, ventilation equipment and service infrastructure) would be used to service the Project. However, some new facilities and/or upgrades to existing infrastructure would be required to support the ongoing mining activities and the proposed increase in mine production. A description of the Project is provided in Section 2 of the Main Report of the Environmental Assessment (EA).

1.1 SCOPE OF WORK

The key tasks for this assessment are:

- review of relevant hydrogeological data and description of the hydrogeological setting including historical workings, Darkes Forest and North Cliff workings;
- description of a conceptual groundwater model;
- development of a groundwater model (including set-up and calibration) and simulation of mining scenarios including sensitivity analysis;
- qualitative and quantitative assessment of the expected hydrogeological impacts resulting from the extraction of Longwalls 20 to 44, taking into consideration Mine Subsidence Engineering Consultants (MSEC) subsidence predictions;
- recommendations for a hydrogeological monitoring programme to monitor the potential effects of Longwalls 20 to 44 on the hydrogeological conditions of the area; and
- recommendations for management and mitigation measures should hydrogeological impacts be observed through the monitoring programmes.

In accordance with the NSW Government Department of Planning Director-General's Environmental Assessment Requirements (EARs) for the Project, this assessment is cognisant of the following groundwater-related technical and policy guidelines:

- National Water Quality Management Strategy Guidelines for Groundwater Protection in Australia (ARMCANZ/ANZECC);
- NSW State Groundwater Policy Framework Document (DLWC);
- NSW State Groundwater Quality Protection Policy (DLWC);
- NSW State Groundwater Quantity Management Policy (DLWC) Draft;
- NSW Groundwater Dependent Ecosystem Policy (DLWC);
- Murray-Darling Basin Groundwater Quality. Sampling Guidelines. Technical Report No 3 (MDBC); and
- Murray-Darling Basin Commission. Groundwater Flow Modelling Guideline (Aquaterra Consulting Pty Ltd).

The specific EARs for the water components of the assessment are:

- a detailed assessment of the potential impacts of the project on the quantity, quality and long-term integrity of the surface and ground water resources in the project area, paying particular attention to the Waratah Rivulet and Lake Woronora;
- a site water balance; and
- a detailed description of the measures that would be implemented on site to minimise the water use of the project.

The surface water components of the assessment are provided separately in the surface water assessment (Appendix C of the Environmental Assessment).

Further to the above, the EARs require the findings and recommendations of the Southern Coalfield Inquiry to be considered. The independent report to the NSW Ministers for Planning and Primary Industries titled "Impacts of underground coal mining on natural features in the Southern Coalfield: strategic review" was finalised in July 2008. Where relevant, the recommendations have been incorporated within this document.

1.2 Proposed Mine Development

The Project would extend the life of the Metropolitan Colliery by approximately 25 years. The main activities associated with development of the Project would include:

- continued development of underground mining operations within existing HCPL coal lease (and associated sub-lease) and two new Mining Lease Application (MLA) areas (MLA 1 and MLA 2) (Figure 1);
- upgrades of the existing mining and materials handling systems (e.g. longwall machinery and conveyors) to facilitate an increased run of mine (ROM) coal production rate (up to approximately 3.2 million tonnes per annum [Mtpa]);
- upgrades and/or extension of the existing supporting infrastructure systems (e.g. underground access, water management, ventilation and electrical systems) as required;
- upgrades of the coal handling and preparation plant (CHPP) to facilitate increased production of washed coal (approximately 2.8 Mtpa);
- continued transport of coal reject to the Glenlee Washery;
- construction of a coal reject paste backfill plant and associated coal reject stockpile, pumping, pipeline and underground delivery systems to facilitate the underground emplacement of coal reject materials as an integrated component of the longwall mining operation[1];
- continued transport of product coal by road to Coalcliff Coke Works and Corrimal Coke Works;
- train loading and train movements associated with the transport of product coal to Port Kembla Coal Terminal 24 hours per day and seven days per week; and
- other associated minor infrastructure, plant, equipment and activities.

A description of the Project is provided in Section 2 of the Main Report of the Environmental Assessment (EA).

[1] In the event that the quantity of coal rejects is greater than anticipated or commissioning of the underground goaf injection technique is delayed, emplacement may take place into the old underground workings via Ventilation Shaft No.1.

2.0 HYDROGEOLOGICAL SETTING

2.1 Rainfall and Evaporation

The area experiences a wet temperate climate. Rainfall at Darkes Forest, the closest Bureau of Meteorology rainfall gauge with reliable long term statistics, has averaged some 1,420 mm per year. Potential (pan) evaporation (based on the station at the Nowra Naval Base) is some 1,150 mm per year. The average monthly rainfall and potential evaporation statistics from these stations are summarised in Table 1 below.

Table 1 Monthly Average Rainfall and Evaporation (mm)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Average Rainfall*	135	157	154	125	135	140	99	93	75	94	104	107
Average Evaporation**	195	161	146	120	96	87	96	127	150	177	183	214

Source: Gilbert and Associates (2008)
* Darkes Forest Record 1894 – 2006.
** Nowra RAN Air Station Record 1969 – 1997.

Rainfall intensity and the regularity of rainfall are particular features of the area and have a significant bearing on the moisture levels in catchment soils and on the hydrological response of the local catchments.

Fluctuations in the groundwater table result from temporal changes in rainfall recharge to aquifers. Typically, changes in the groundwater elevation reflect the deviation between the long term monthly (or yearly) average, and the actual rainfall, usually described as the Residual Mass Curve (RMC).

The groundwater levels recorded during periods of rising RMC are expected to rise while those recorded during periods of declining RMC are expected to decline. A plot of RMC since 1940 is shown on Figure 2 (from Gilbert and Associates, 2008).

2.2 Topography and Drainage

There is significant topographic relief in the catchment and a relatively high drainage density. Surface elevations vary from approximately 180 m to 365 m AHD[2] with ridgelines typically rising between 50 and 100 m above the drainage floor.

The topography consists of 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 (Geosensing Solutions, 2008).

[2] Australian Height Datum

2.3 LAND USE

The proposed longwalls are situated predominantly within the Woronora Special Area, which is owned and administered by the Sydney Catchment Authority (SCA). The Woronora Special Area is largely undeveloped and covered by bushland.

2.4 UPLAND SWAMPS

The following description of upland swamps on the Woronora Plateau has been sourced from FloraSearch and Western Research Institute (2008).

Upland swamps on the Woronora Plateau occur in small headwater valleys that are characteristically sediment choked and swampy (Young, 1986). The presence of the upland swamps is related to their topographic position, the lithology of the bedrock and the hydrological balance on the plateau (ibid.), as described below.

Topographically, upland swamps occur mainly on the eastern, higher parts of the Woronora Plateau. They generally occupy gently-sloping and trough-shaped valleys, but some extend from the valley-floor upwards onto quite steep slopes or occupy benches on the valley sides (ibid.). The swamps are most extensive and most numerous where the plateau is least dissected (ibid.). In the more dissected catchments (e.g. the Woronora River catchment), the swamps are confined largely to the headwater tributaries (ibid.).

The upland swamps are restricted to valleys cut in the Hawkesbury Sandstone (Young, 1986). Regional groundwater flow within the Hawkesbury Sandstone is largely horizontal, as vertical permeability is low. The Hawkesbury Sandstone provides a low permeability base on which the swamp sediments and organic matter rest.

Swamps on the Woronora Plateau are not attributed to the presence of claystone underlying the sandstone, as is the case for the hanging swamps of the Blue Mountains. The Hawkesbury Sandstone is also the predominant source of sediment for the upland swamps; erosion of the sandstone on the plateau surface supplies largely medium-coarse sand to the valleys in which the swamps lie. Due to the gentle gradients, only the largest of the dells are able to maintain an open channel and even these have only short channels near the downstream end, and sometimes a series of discontinuous elongated pools in the valley axes further upstream. The sandy sediment accumulation in the swamps traps rainfall infiltration, seepage and low-flow runoff.

The eastern part of the Woronora Plateau has a favourable climate for upland swamp formation. The rainfall saturates the accumulating swamp material and cannot drain away quickly enough due to low floor slope, low permeability base, and average rainfall generally higher than average evaporation.

Partially decayed organic matter accumulates in the sediments, further increasing their water-holding capacity (Young, 1986). In most years the central axes of the swamps are saturated, though the margins may dry out periodically (Keith, 1994; Keith et al., 2006).

There is a spectrum of upland swamp types that differ according to the hydrological processes that are dominant. Broadly, upland swamps can be classified as headwater upland swamps or in-valley upland swamps, as illustrated in Figure 3 and as described below.

Headwater upland swamps (Figure 3a) occur in the headwaters or elevated sections of the topography on the plateau where the land surface is fairly flat. They are essentially rain-fed systems in which rainfall exceeds evaporation continuously. The water levels within the swamps fluctuate seasonally with climatic conditions, as rain adds to soil moisture and evapotranspiration slowly removes moisture from storage. Excess rainfall produces a permanent perched water table within the sediments that is independent of the natural regional water table in the underlying Hawkesbury Sandstone. During rain events, some stream flow and runoff along indistinct braided channels will infiltrate through the swamp sediments. The growth of dense vegetation and the low land gradient prevent the formation of an open channel that would otherwise transport water and sediments. In some headwater upland swamps, there could be minor groundwater seepage from the outcropping sandstone at the edges of the swamp.

In-valley upland swamps (also called in-stream or valley floor swamps) occur along well defined drainage lines in the more deeply incised valleys, and are less common than headwater upland swamps on the eastern Woronora Plateau. They occupy relatively flat sections of streams within deeper valleys and are thought to be formed by deposition of sediments behind barriers such as piles of logs at choke points in the stream (Tomkins and Humphreys, 2006), or terminate at 'steps' in the underlying substrate where the gradient suddenly becomes steeper (Earth Tech, 2003). In-valley upland swamps (Figure 3b) have multiple sources of water. Primarily, they are sustained by stream flow along distinct channels, supplemented by rain infiltration. Given the incised nature of the axial stream, they are more likely to receive groundwater seepage from the sandstone walls at the edges of the swamp. In most cases the hydrology of the swamp is independent of the deeper regional water table in the underlying Hawkesbury Sandstone, but there might be occasions when the regional water table intersects the swamp sediments. In the latter case, depending on the relative elevations of the perched and regional water tables, groundwater could supplement swamp moisture or swamp moisture could drain towards the underlying aquifer.

In the proximity of Longwalls 20 to 44, there are a number of upland swamps as shown on Drawing No. MSEC285-07 in Appendix A (subsidence assessment) and is based on vegetation mapping by Bangalay Botanical Surveys [2008] in Appendix E (baseline flora survey) of the Environmental Assessment).

2.5 GROUNDWATER DEPENDENT ECOSYSTEMS

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

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

The Project is located within the Sydney Basin sedimentary rock groundwater system.

The NSW State Groundwater Dependent Ecosystems Policy (DLWC, 2002) also recognises the four Australian groundwater dependent ecosystems types by Hatton and Evans (1998) that can be found in NSW, namely:

- Terrestrial vegetation;
- Base flows in streams;
- Aquifer and cave ecosystems; and
- Wetlands.

The groundwater dependent ecosystems which are known or likely to occur within the Project area are described in Appendix C (surface water assessment), Appendix D (aquatic ecology assessment), Appendix E (baseline flora survey) and Appendix F (terrestrial vertebrate fauna survey) of the Environmental Assessment.

The potential impacts of the Project on groundwater dependent ecosystems that may occur within the Project area are described in Appendix C (surface water assessment), Appendix D (aquatic ecology assessment) and Appendix G (terrestrial flora and fauna impact assessment) of the Environmental Assessment.

2.6 Stratigraphy and Lithology

The Southern Coalfield lies in the southern part of the Sydney Basin (Moffitt, 2000), which is infilled with sedimentary rocks of Permian age (<270 million years ago) and of Triassic age (<225 million years ago). Immediately overlying the Bulli Coal unit of the Illawarra Coal Measures are sandstones and claystones of the Narrabeen Group (Figure 4). At the top of the sequence in the area of interest is the Hawkesbury Sandstone (Figure 5).

A summary of the lithology as described in Geosensing Solutions (2008) is provided below. A geological cross section of the Project area is shown on Figure 6. A number of boreholes have been drilled in the Project area as shown on Figure 7. Geosensing Solutions (2008) also reports on the characteristics of the Project area.

Hawkesbury Sandstone - outcrops over the Project area and consists of thickly bedded or massive quartzose sandstone (with grey shale lenses up to several metres thick). The maximum geological thickness is about 170 m.

Narrabeen Group - sequence of about 230 m is developed below the Hawkesbury Sandstone and above the Illawarra Coal Measures. The Narrabeen Group is overlain by the Hawkesbury Sandstone and does not outcrop within the Project area.

Newport Formation - the uppermost stratum of the Narrabeen Group and consists of interbedded grey shales and sandstones.

Garie Formation - consists of cream to brown, massive, characteristically oolitic claystone.

Bald Hill Claystone - consists of brownish-red coloured “chocolate shale”, a physically weak but lithologically stable unit. The “chocolate shale” is an easily recognised marker horizon. The Bald Hill Claystone has a near constant thickness over a large portion of the Southern Coalfield.

Bulgo Sandstone - consists of strong, thickly bedded, medium to coarse-grained lithic sandstone with occasional beds of conglomerate or shale. Thickens northerly from 160 m to 195 m, averaging 175 m thick.

Stanwell Park Claystone - consists of greenish-grey mudstones and sandstones.

Wombarra Claystone - has similar properties to the Stanwell Park Claystone.

Coal Cliff Sandstone - consists of basal shales and mudstones that are contiguous with the underlying Bulli Coal Seam.

Illawarra Coal Measures - consist of interbedded shales, mudstones, lithic sandstones and coals of which ten named seams occur in the area.

Bulli Coal - the uppermost coal unit in the Illawarra Coal Measures. It has been worked extensively in the northern portion of the Southern Coalfield, from outcrop mines on the coastal margins to inland mines. The Bulli Coal is currently mined at Metropolitan Colliery and will continue to be mined as part of the Project.

2.7 STRUCTURAL GEOLOGY

Geological structures that are known either to exist in underground workings or are inferred from current geological data that may extend into the Project area have been identified for further investigation through surface mapping. These include (Geosensing Solutions, 2008):

- Metropolitan Fault (also known as Pit Bottom Fault).
- Powell Fault.
- Main West Fault.
- Freeway Fault.
- Long Hole Fault.
- Madden Fault Zone.

In addition to the known structures exposed in the underground workings, other structures are inferred from the review of existing data. These include (Geosensing Solutions, 2008):

- AMEG Fault
- Mini Sosie Fault

In general, individual structural features located on the floor of the Bulli Coal Seam have not been identified at surface despite focused searches over the years, nor have individual surface features been successfully projected and proven at the Bulli Coal Seam horizon.

Tertiary age igneous intrusions in the form of sills and dykes post date the sedimentary strata in the area. Igneous dykes are present as generally thin (less than 1m) altered clays at outcrop. No igneous sills are known in the strata over the coal measures (Geosensing Solutions, 2008).

No diatremes have been identified in the Project area (Geosensing Solutions, 2008).

2.8 HYDROGEOLOGY

Apart from coal seam aquifers at depths of greater than 400 m (Figure 8), the recognised aquifers in the stratigraphic sequence at the Metropolitan Colliery are the Hawkesbury Sandstone and the sandstones of the Narrabeen Group. Whilst of very low permeability, the Hawkesbury Sandstone has the relatively higher permeability (refer to Section 3.4) compared to other units and is therefore capable of higher groundwater yields.

The Hawkesbury Sandstone outcrops over the area of interest in the form of the Woronora Plateau, as shown in Figure 5, and is subject to weathering processes. Secondary porosity in the form of fractures dominates over primary porosity. Due to alternation of sheet and massive facies, groundwater flow is primarily horizontal with minor vertical leakage. Surface water fed perched water tables (i.e. hydraulically disconnected from the regional aquifer) can be expected adjacent to cliff faces and within upland swamps.

Vertical continuity with the underlying Narrabeen Group aquifer is interrupted by a major aquitard, the Bald Hill Claystone. The thickness of the Bald Hill Claystone is consistent and continuous across the Project area (Figure 6) (Geosensing Solutions, 2008). This unit will retard vertical groundwater flow downwards from the Hawkesbury Sandstone. This is consistent with SCA's findings in the Upper Nepean (Kangaloon) Borefield Project Environmental Assessment (KBR, 2008) which states:

"At depth, the Bald Hill Claystone also stops the vertical flow of groundwater because it, too, acts as an effective confining layer."

The base of the Narrabeen Group, at the top of the Bulli Seam, is marked by the Wombarra Claystone. This unit is an aquitard that will limit vertical flow into mine workings. The Coal Cliff Sandstone lies between the two where it is developed.

The only recognised economic aquifer in the area is the Hawkesbury Sandstone. The water quality in the Hawkesbury Sandstone is quite good beneath the Woronora Plateau and the Illawarra Plateau, but it deteriorates rapidly towards the northern limits of the Southern Coalfield (as shown in Figure 9). In the vicinity of the Metropolitan Colliery, the salinity is generally in the range 1000-3000 mg/L (refer to Section 2.12).

The Metropolitan Colliery lies within the *Hawkesbury Sandstone – South-East* groundwater flow system (GFS) as defined by Grey and Ross (2003). This GFS tracks the Metropolitan Water Supply Catchment Area that includes the Nepean, Avon, Cordeaux, Cataract and Woronora Reservoirs. Very little groundwater development has been permitted due to its status as a protected area. Only 82 bores are registered throughout the whole area of the GFS for stock and domestic use with total entitlements of 55 ML/year. This contrasts with a sustainable yield estimate of 58,000 ML/year (Grey and Ross, 2003). There are no high yield bores (>6 L/s) identified within the GFS.

The Hawkesbury Sandstone is in general a low-yield aquifer of good quality. It is well developed for commercial production in the Mangrove Mountain area north of Sydney and partially developed in the Blue Mountains west of Sydney. It is currently the subject of investigations by the SCA in the Southern Highlands at Kangaloon-Robertson and at Leonay-Wallacia. High yields (~30 L/s) have been found in both areas where the sandstone is heavily fractured. The Hawkesbury Sandstone in the Southern Coalfield would be expected to be as productive as the Mangrove Mountain and Blue Mountains aquifers, but water supply protection prevents its development.

The Narrabeen Group is a much poorer aquifer than the Hawkesbury Sandstone, and there is no known use of the aquifer in the Southern Coalfield. The low permeability of the Narrabeen Group lithologies is substantiated by the common experience of "dry mines" in the Southern Coalfield.

2.9 GROUNDWATER BORE CENSUS

According to the Natural Resources Atlas (http://test.nratlas.nsw.gov.au) there are seven registered bores in the vicinity of the Metropolitan Colliery. Their locations are shown on Figure 7, and bore details are summarised in Table 2.

None of the bores have reported survey levels; therefore groundwater elevations are estimated from approximate ground levels.

Table 2. Known registered bores in the vicinity of the Metropolitan Colliery

BORE	GW18337	GW18338	GW18339	GW107489	GW27422	GW48548	GW62719
Easting (AMG)	307100	307260	307340	309526	318900	311305	312850
Northing (AMG)	6210975	6210200	6210275	6213805	6215935	6211615	6214025
Elevation (mAHD)	310-320	370-375	c.373	c.230	c.200	c.330	c.310
Year of Construction	1945	1946	1946	2003	1967	c.1978	1986
Hole Depth (m)	123.4	67.6	56.3	28	480	76.5	152.4
Depth to Water (m)	-	-	3.0	-	21.3	-	61.0
Water Level (mAHD)	-	-	c.370	-	c.179	-	c.250
Yield (L/s)	-	-	1.1	-	0.63	-	0.06
Licensed Use	Domestic Irrigation	-	Domestic General	Monitoring	Domestic General	Domestic	Domestic Stock
Lithology	Clay to 1.8m; sandstone to end.	-	(0-500 mg/L)	Sandstone	Full log; coal at 416m depth.	No log; backfilled 76.5 - 115m	Full log; tested 67-73m.

NB: GW27422 is not shown on Figure 7 (the location is approximately 5 km north-east of GW62719).

2.10 GROUNDWATER MONITORING

Environmental Earth Sciences (EES) NSW is contracted by HCPL to undertake monthly groundwater sampling and water level monitoring, in accordance with the Environmental Monitoring Programs established for Longwalls 14-17 and Longwalls 18-19A, respectively. Data is stored and written reports are submitted every six months and following completion of each Longwall panel.

Details of the current monitoring program are summarised in Table 3 (EES, 2008). The locations of the monitoring sites are shown on Figure 7.

There are 12 groundwater bores drilled to a depth of approximately 20 m, as well as three bores in upland swamps augured to the point of refusal. All bores are monitored with data loggers (15 minute intervals).

Table 3. Current Monitoring Program [from EES, 2008]

PARAMETERS	MONITORING SITE	FREQUENCY
• Groundwater Level.	• WRGW-1 to WRGW-6. • UTGW-1 to UTGW-3. • FGGW-1 to FGGW-3.	• Continuous (15 minute intervals), with data downloaded monthly.
• Electrical Conductivity (EC). Total Dissolved Solids (TDS). • pH. • Turbidity. • Ca. Mg. Na. F. K. Cl. • SO_4. HCO_3. • NO_2. N_{tot}. NH_4-N. NO_3. • P_{tot}. PO_4. • Ba. Sr. Mn. Fe. Zn. Co. Al. Al_{tot}. Ba_{tot}. Co_{tot}. Fe_{tot}. Mn_{tot}. Sr_{tot}. Zn_{tot}.	• WRGW-1 to WRGW-6. • UTGW-1 to UTGW-3. • FGGW-1 to FGGW-3.	• Monthly and during and/or after large rainfall events.
• Upland swamp water level.	• SWAMP-1 to SWAMP-3.	• Continuously (15 minute intervals), with downloads conducted regularly.

The SCA has also conducted quarterly groundwater sampling at sites WRGW-1 to WRGW-6, UTGW-1 to UTGW-3 and FGGW-1 to FGGW-3 from March 2007 to January 2008. Details of the SCA monitoring program are summarised in Table 4 (SCA, 2007b).

Table 4. SCA Monitoring Program [from SCA, 2007b]

PARAMETERS	MONITORING SITE	FREQUENCY
• EC. TDS. • pH. • Redox potential. • Temperature. • Dissolved Oxygen (DO). • CO_2. • Turbidity. • Ca. Mg. Na. K. Cl. • Hydroxide as $CaCO_3$. Carbonate as $CaCO_3$. Bicarbonate as $CaCO_3$. Alkalinity as $CaCO_3$. • Sulphate. Sulphide. • Silica. • Al (dissolved). Ba (dissolved). Co (dissolved). Fe (dissolved). Mn (dissolved). Ni (dissolved). Sr (dissolved). Zn (dissolved). • Fe (total). Mn (total). Al (total). • Methane	• WRGW-1 to WRGW-6; • UTGW-1 to UTGW-3; and • FGGW-1 to FGGW-3.	• Quarterly.

In addition to the above, pool levels are generally monitored daily (all pools) and at 15 minute intervals (Pool A and Pool F) at surface water locations discussed in Gilbert & Associates (2008).

Deep groundwater monitoring to date has been conducted at Longwall 10 (LW10) goaf hole, which was drilled adjacent to Fire Road 9H from 19 February to 5 April 2007 (Figure 7). The bore reached a depth of 326.7 m from a collar elevation of 274.5 mAHD. As the floor of the Bulli Seam is at –188 mAHD (462.5 m below ground), the bore finished about 130 m above the goaf zone. At the time of drilling, mining was advancing along Longwall 14 about 700-900 m to the west, heading in a north-easterly direction.

Vibrating wire (VW) piezometers were installed at depths of 35, 70, 110, 135, 165, 205, 250 and 300 m below ground surface. Hydrostatic pressure heads have been recorded continuously since April 2007.

The data acquired in the LW10 goaf hole are documented in SCT Operations Pty Ltd (2007) and Waring *et al.* (2007), and the piezometric data were analysed in Merrick (2007). Further analysis of the LW10 goaf hole results are provided in Section 2.11.

Coal exploration borehole PM02 was drilled in December 2007 adjacent to Fire Road 9E (Figure 7). The bore reached a depth of 575.15 m from a collar elevation of 267.4 mAHD.

VW piezometers were installed at depths of 35, 100, 220, 250, 400, 435, 475 and 495 m below ground surface. Hydrostatic pressure heads have been recorded continuously since 19 December 2007.

The piezometric data acquired from PM02 are documented in SCT (2008). Further analysis of the Metropolitan Hole PM02 results is provided in Section 2.11.

2.11 BASELINE GROUNDWATER LEVEL DATA

2.11.1 Spatial Groundwater Level Data

Natural groundwater levels are sustained by rainfall infiltration and are controlled by ground surface topography and surface water elevations (Alkhatib and Merrick, 2006). A typical situation would be a local groundwater mound beneath hills with discharge to incised creeks and rivers. During short events of high surface flow, streams will lose water to the host aquifer, but during recession the aquifer will discharge water slowly back into the stream from bank storage.

Topographic relief will tend to drive vertical groundwater flow near the ground surface, but the alternation of aquifers and aquitards in this area will promote horizontal groundwater flow at the base of permeable units. Water will appear as seeps in cliff faces at the junction of formations with contrasting permeability.

Based on the available groundwater level data and to gain an impression of the regional water table pattern, a contour map of inferred groundwater level has been prepared for groundwater levels either measured at bores or equal to stream bed elevations and 10 m lower than measured perched levels in upland swamps (Figure 10).

Contour maps were also developed for alternative scenarios where (1) groundwater levels were assumed 5 m higher than stream bed elevations and (2) groundwater levels were assumed 10 m lower than stream bed elevations.

Apart from small changes in detail where groundwater measurements have been made, the overall patterns are insensitive to the assumption made as to the relative levels of surface water and groundwater where they interact. In all cases, the contour maps indicate that groundwater flow is toward the Woronora Reservoir.

As groundwater will flow perpendicular to the contours, the groundwater in the upper part of the Hawkesbury Sandstone will flow from the ridges to the natural surface drainages. There is a clear potential for groundwater discharge along Waratah Rivulet across the area already mined.

Of significance is that the direction of groundwater flow has not reversed as a result of mining of Longwall 10. The shallowest piezometer at the LW10 goaf hole has a total head that is well above the water level in Waratah Rivulet Pool A. The head difference is about 30 m. As the Waratah Rivulet is about 300 m distant, the horizontal hydraulic gradient is about 1:10 (or 0.1). This is a very high gradient that will maintain horizontal flow through the Hawkesbury Sandstone to the Waratah Rivulet. The magnitude of the flow is controlled by the horizontal hydraulic conductivity of the sandstone.

Note that there is compelling evidence at bore DDH34 at Dendrobium Colliery (Figure 11) that shows no change in water table elevation as longwall mining passes by, whereas a reduction in head of 13 m was measured at a piezometer 51 m deeper (Dendrobium Technical Services Staff, 2007). Although the shallow water table is unlikely to be perched, there is clear isolation between the shallow and deep aquifers. Certainly, the direction of flow at the Metropolitan Longwall 10 goaf hole has not been altered by mining, and the Waratah Rivulet will still be gaining baseflow from the aquifer.

Similarly, long-term pumping trials beneath Stockyard Swamp (Figure 12) and Butlers Swamp (Figure 13) at the planned Kangaloon Borefield near Robertson show no response in swamp perched water levels when the Hawkesbury Sandstone aquifer is depressurised (KBR, 2008). This illustrates the potential for hydraulic isolation of aquifers within the stratigraphic section when one formation is depressurized.

2.11.2 Temporal Groundwater Level Data

Month-averaged groundwater levels since February 2007 for the monitoring bores in Figure 7 (i.e. Waratah Rivulet, upland swamps, Forest Gully and the Unnamed Tributary) are shown in Figures 14-17.

In Figure 14, comparison is provided of groundwater levels at paired bores WRGW3 and WRGW4 with the water level in Pool F. As Pool F is about 50 m upstream of the two bores, and the water level at Pool F is 20 cm higher than the bore levels, the water level at Waratah Rivulet at the location of the bores will be very similar on average to the ambient groundwater level. It is expected that the water table will be higher (than the stream) after a wet event, and lower during a dry period. The average groundwater levels along Waratah Rivulet vary very little with time.

In Figure 15, the average perched groundwater levels at the upland swamp sites increased with time in early 2007 and have remained fairly stable since then. Note that the upland swamps are surface water fed and the perched groundwater is hydraulically disconnected from the regional aquifer. The water level in SWAMP3 increased by 3.1 m over 5 months in the first half of 2007.

Along Forest Gully the monitoring sites are placed above Longwalls 13 and 14. The groundwater levels behave differently between the three monitoring bores in Forest Gully (Figure 16). At FGGW3 levels are steady; at FGGW2 levels rose 1.2 m over 3 months in autumn 2007; and the response at FGGW1 (over Longwall 13) is atypical, with the average water level rising by 3 m in June 2007 in response to a period of heavy rainfall.

The monitoring bores along the Unnamed Tributary traverse Longwalls 13-16. Average water levels are steady except at UTGW2, where an average drop of 5.6 m was measured in June 2007 (Figure 17). This bore is above Longwall 14 close to the junction with Longwall 15, and seems to have responded to the passage of Longwall 14. In July 2007, the average water level recovered by 1.6 m in response to a period of heavy rainfall in June. However, the nearest monitored pool level (UTP1; Figure 17) which is 180 m downstream and directly above Longwall 14 has shown no drop in average water level.

The pool level at UTP2 is coincident with the groundwater level at UTGW3 (Figure 17). The sites are only 11 m apart, and the difference in average water levels is only 6 cm, with the average pool level always the higher of the two levels.

The anomalous responses at FGGW1 (Figure 16) and at UTGW2 (Figure 17) are examined in more detail in Figure 18 by comparing the month-averaged water levels with measurements logged every 15 minutes (from March to July 2007).

FGGW1 shows clear peaks that respond to rainfall events, followed by characteristic recessions as groundwater flows back to the adjacent stream (for example, the event at 25 April 2007 on Figure 18). The rise in water level at FGGW1 due to rainfall is typically 10 times higher than at FGGW2. This can be due to locally low rock porosity at FGGW1, but is more likely due to proximity to a rock pool that will raise the groundwater level to pool level.

The heavy rains from 8 June 2007 (Figure 18) are likely to have filled and sustained rock pools with water, as has been observed at monitored pools on Waratah Rivulet. The probable connection of FGGW1 with a rock pool would explain why high groundwater levels were sustained for some months from June 2007 (Figure 16).

UTGW2 shows a clear response to the rainfall event on 25 April 2007, but there is no corresponding rise for the 8 June 2007 rainfall event (Figure 18). At this time, in early June, the Longwall 14 mining front passed underneath. From late May to late June the water level at UTGW2 declined by about 8 m from its normal dry level. Full recovery to 235 mAHD occurred in early July 2007 following the heavy rains in June 2007 and this level has been sustained ever since (Figure 17). The substantial size of the decline (8 m) suggests that the water table here is perched, indicating a low-volume aquifer, and the water has drained downwards to a deeper regional water table; if the water table were regional at UTGW2, fracturing would not cause such a large decline in water level as the surrounding high-volume aquifer would replenish any losses. It is likely that cracking induced by subsidence from Longwall 14 increased the porosity of the low-permeability base upon which the water table at UTGW2 is perched. Water would drain downwards and infill this void space resulting in a temporary drop in the water table level. The cracks then closed/infilled either by the change in stress with the passage of the subsidence front, by water or by sediments mobilised by the heavy rains of June 2007. With the integrity of the low-permeability base restored, the June 2007 rains were able to replenish the perched aquifer to its normal water level within 4-6 weeks of the mining impact event.

The monitored rock pool UTP1 (180 m downstream of UTWG2) was undermined by Longwall 14 in late June 2007. Figure 19 shows no apparent mining impact on the pool at this time, but Gilbert and Associates (2008) show a definite effect 3-4 months later at a time of low flow in the creek.

Month-averaged depths to water since February 2007 for monitoring bores at Waratah Rivulet, upland swamps and the Unnamed Tributary and since March 2007 for Forest Gully are shown in Figures 20-23. Depths are measured from top of casing (typically about 0.5 m above ground level).

Where water levels are stable in time, depths to water are typically 1-5 m. Note that all monitoring sites are close to watercourses, and groundwater levels will be expected to be at shallow depths where the streams and the shallow aquifer are interacting. Greater depths to water are expected away from the watercourses towards the ridges. For example, the depth to water at the Longwall 10 goaf hole is about 25 m and the depth to water at exploration hole PM02 is about 26 m.

2.11.3 Piezometric Analysis

Longwall 10 Goaf Hole

Investigations undertaken as part of the Longwall 10 Goaf Hole by SCT Operations Pty Ltd (2007) included:

- Lithological logging;
- Geophysical logging (30-167 m depth) – natural gamma, caliper and density;
- Installation and monitoring of eight (8) vibrating wire piezometers;
- Falling head tests (during drilling);
- Packer tests;
- Core fracture analysis; and
- Core measurements of hydraulic conductivity.

Investigations by ANSTO (Waring et al., 2007) included:

- Geophysical logging (full depth) – prompt gamma neutron activation (PGNA), caliper and density;
- Packer tests at two intervals with probable fractures; and
- Geochemical analysis at two intervals with probable fractures.

At the Longwall 10 goaf hole, apart from Piezo135 in the Bald Hill Claystone, there is a systematic reduction in total head with depth (Figure 24). This means that there is a *potential* for downwards groundwater flow in response to a vertical hydraulic gradient. The *actual* flow magnitude depends on the vertical hydraulic conductivity of the strata. By comparison with groundwater heads at similar depths in hole PM02 (in the next section), it is clear that the potential for vertical flow has been enhanced by mining.

There is some doubt as to the validity of the early readings in Piezo135 and Piezo300, as they exhibit anomalous behaviour in the temporal plot of groundwater head in Figure 25. If the later readings are reliable, then the deepest piezometer suggests that pressure is dropping continuously in the lower Bulgo Sandstone. This is consistent with slow discharge of water downwards towards the mine. However, there is no loss of pressure and consequently no loss of water in all higher formations from the mid Bulgo Sandstone upwards.

On Figure 25 there are clear responses in Piezo35 and Piezo70 to high rainfall events in April and June 2007, and in February 2008, with smaller lagged responses in Piezo110 and Piezo165. There is no obvious event response in deeper piezometers, but slow rainfall recharge and decay is a likely explanation for the protracted rises and falls in deep piezometers (Figure 25).

An important observation to be made on the hydrostatic pressure heads (not shown here) is that all heads are positive. This means that the formations being monitored have not become unsaturated due to the mining of Longwall 10. The free-draining fractured zone that is to be expected above a goaf zone does not extend as high as 130 m above the goaf.

Metropolitan Hole PM02

Figure 26 shows how the total piezometric head varies with sampling depth in exploration hole PM02. Apart from a pronounced high water level in the shallowest piezometer, the other piezometers have little variation from each other and all cluster around the approximate elevation of Lake Woronora, which is about 500 m to the east. There is a clear lateral hydraulic gradient for shallow groundwater flow towards the lake. The water table encountered in the shallowest piezometer is about 25 m below ground.

Potential vertical groundwater flow directions are indicated on Figure 26, as a consequence of vertical hydraulic gradients. The amount of groundwater flow depends on the magnitude of the gradient and is mediated by the permeability of intervening strata. At most depths there is a mild propensity for downward groundwater flow. The only exceptions are:

- In the upper Bulgo Sandstone, which has a head of about 1.4 m higher than the Bald Hill Claystone; and
- In the upper Scarborough Sandstone, which has a head of about 12 m higher than the Stanwell Park Claystone.

These two exceptions suggest that the two claystone strata (Bald Hill and Stanwell Park) are acting as strong aquitards that confine the underlying sandstone formations (Bulgo and Scarborough) and put them under increased pressure. Very little water must be passing across the aquitard-aquifer interface, otherwise the heads would tend to equilibrate or follow the normal decline with depth.

Unlike the Longwall 10 Goaf Hole, there is no obvious event response to rainfall in any of the piezometers (Figure 27). Apart from the two shallowest piezometers, the groundwater pressures are continuing to decline six months after installation.

The observations of total head at PM02 (Figure 26) are in contrast with those at the Longwall 10 Goaf Hole (Figure 24). At that location, which was undermined before the piezometers were installed, there is a steady decline in head with depth apart from one reversal in the upper Bulgo Sandstone where the head is about 40 m higher than in the Bald Hill Claystone (Figure 25). Although the lowest piezometer was placed in the Bulgo Sandstone well above the Bulli Seam (by 160 m), the total drop in head across eight piezometers is about 170 m at the Longwall 10 Goaf Hole (Figure 25). This contrasts with a drop of about 80 m in PM02 over all eight piezometers.

2.12 Baseline Groundwater Chemistry Data

Table 5 summarises the chemical attributes of all monthly groundwater samples from March 2007 to February 2008 taken at the shallow monitoring sites shown in Figure 7 by EES and the SCA.

The groundwater is very fresh, as indicated by an average salinity (TDS) of 166 mg/L and an average electrical conductivity (EC) of 261 µS/cm. This is evidence of good stream-aquifer interaction. Although there are no deep groundwater samples available, the salinity of deeper waters is expected to be much higher in accordance with Figure 9. This indicates a separation of deeper groundwater from surface waters.

Table 5. Chemical Data Summary at Groundwater Monitoring Sites (March 2007 to February 2008)

ANALYTE	UNIT	MEDIAN	MINIMUM	MAXIMUM	AVERAGE
pH	-	6.3	4.0	8.2	6.3
TDS	mg/L	145.0	58.0	519.2	165.7
EC	µS/cm	230.0	95.0	683.0	261.2
Turbidity	NTU	50.0	0.1	1700.0	93.4
Fe	mg/L	0.5	0.01	16.0	3.2
Al	mg/L	0.1	0.01	0.6	0.1
Mn	mg/L	0.3	0.001	1.3	0.3
Na	mg/L	24.0	13.0	109.0	28.8
Ca	mg/L	15.0	0.7	90.0	20.2
K	mg/L	1.0	0.2	4.0	1.3
Mg	mg/L	5.6	2.1	16.0	6.7
NH_4-N	mg/L	0.1	0.1	0.3	0.1
Cl	mg/L	40.0	19.8	53.0	39.9
F	mg/L	0.1	0.1	0.2	0.1
SO4	mg/L	8.0	1.0	23.0	7.8
HCO_3	mg/L	72.0	1.0	330.0	100.0
PO_4	mg/L	0.1	0.1	0.5	0.1

Source: (HCPL and SCA, 2007b)

The groundwater data are also shown graphically in Attachment A.

3.0 CONCEPTUAL MODEL

A conceptual model of the hydrogeological regime has been developed based on the review of existing hydrogeological data as described in Section 2 including:

- Southern Coalfield geology mapping;
- surrounding and regional geological logs (Figure 7);
- relevant data from the DWE register on the Natural Resources Atlas (http://test.nratlas.nsw.gov.au);
- geological and hydrogeological assessments undertaken for Metropolitan Colliery and other Southern Coalfield mine operations;
- SCA's hydrogeological investigations and assessments undertaken for the Upper Nepean (Kangaloon) Borefield Project; and
- piezometric monitoring and geological information from the Longwall 10 Goaf Hole and PM02 Hole at Metropolitan Colliery.

In addition some elements of linkage to the surface flow and groundwater (baseflow) interaction mechanisms described in the surface water assessment by Gilbert and Associates (2008) (Appendix C of the Environmental Assessment) have been considered.

Based on the above, the data supports three separate groundwater systems:

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

The three separate groundwater systems are described further below and are illustrated in the conceptual model of the region in Figure 28.

Recharge to the groundwater system is from rainfall and from lateral groundwater flow at the boundaries of the study area. Although groundwater levels are sustained by rainfall infiltration, they are controlled by ground surface topography and surface water levels. A local groundwater mound develops beneath the sandstone hills with ultimate discharge to incised creeks and water bodies, and loss by evapotranspiration through vegetation where the water table is within a few metres of ground surface within upland swamps and outcropping sandstone.

During short events of high surface flow, streams can lose water to the sandstone aquifers that host the streams, but during recession the sandstone will discharge water slowly back into the stream from bank storage. Groundwater also discharges naturally to cliff faces and ultimately to the sea. In places where mining has occurred, groundwater discharge is expected to occur to the mined seam from above and below in proportion to local permeabilities.

Immediately above a mined coal seam, rocks will collapse into the void to form a caved zone and cause changes to aquifer permeability and porosity. As the mining proceeds, a fractured zone will develop above the caved zone and aquifer properties will change with time. The overlying rocks in the fractured zone will have a higher vertical permeability. Depending on the width of the longwall panels and the depth of mining, and an alternation of thick sandstone/claystone lithologies, there will be a constrained zone in the overburden that acts as a bridge. This will isolate shallow and deep aquifers. At the substantial depths of cover at Metropolitan Mine (Figure 8), there will not be connective cracking from the ground surface to the mined seam. Groundwater pressures will reduce towards atmospheric pressure at the base of the fractured zone.

A stream bed with an exposed rock base can experience cracking in response to subsidence to a depth of 10-20 metres. There will be no permanent loss of shallow water to a deep mine because there will be no continuity of fractures from the surface to the mine. There will be diversion of a portion of surface water flows through the rock fractures beneath the stream bed, which will move as underflow through the aquifer immediately beneath the stream, with emergence farther downstream.

Topographic relief will drive vertical groundwater flow near the ground surface, but at depth the alternation of aquifers and aquitards will promote horizontal groundwater flow at the base of permeable units. Along the escarpment to the east of Metropolitan Mine, water will appear as seeps in cliff faces at the junction of formations with contrasting permeability.

Thirteen (13) layers are conceptualised in Figure 29 for the purpose of numerical modeling. The three major sandstone formations (Hawkesbury, Bulgo and Scarborough) are split into multiple layers in recognition of natural or mining-induced vertical hydraulic gradients.

3.1 PERCHED GROUNDWATER SYSTEM

Figure 30 illustrates the relative groundwater levels between the LW10 goaf hole and Metropolitan Hole PM02. The surface water hydraulic gradient over this separation distance from Waratah Rivulet to Lake Woronora is about 1:110. In contrast, the water tables encountered in the shallowest piezometers at the two sites give an almost flat gradient of about 1:830. This suggests that the water tables are perched, as they are controlled more by depth below ground than by regional gradients.

Apart from shallow sandstone, perched water tables also occur in upland swamps.

3.2 Shallow Groundwater System

The shallow groundwater system is separate from the perched groundwater system. The groundwater levels in the mid Hawkesbury Sandstone at the two sites give a gradient of about 1:120 which is very similar to the natural surface water gradient. This suggests that the groundwater levels define a regional water table.

At both sites, there is a lateral hydraulic gradient towards the nearest surface water bodies (Waratah Rivulet and Lake Woronora). Although the Longwall 10 goaf hole has been undermined, the direction of shallow groundwater flow has not been reversed.

The contour map of the shallow water table in Figure 10 indicates the overall pattern of groundwater flow from the ridges to the drainage lines, irrespective of the fact that mining is progressing.

3.3 Deep Groundwater System

There is a hydraulic disconnect between the deep and shallow groundwater systems. This separation is driven by the low permeabilities of the Bald Hill Claystone and the Upper Bulgo Sandstone which lie beneath the Hawkesbury Sandstone that hosts shallow groundwater.

This is consistent with SCA's findings in the Upper Nepean (Kangaloon) Borefield Project Environmental Assessment (KBR, 2008) which states:

"At depth, the Bald Hill Claystone also stops the vertical flow of groundwater because it, too, acts as an effective confining layer."

Figure 30 shows that the lateral hydraulic gradient in the Upper Bulgo Sandstone is about 1:170, which is a little flatter than what is expected to be the natural gradient. This could be due to a slight increase in horizontal permeability due to subsidence-induced bedding plane separation in the Upper Bulgo Sandstone.

In the Lower Bulgo Sandstone, there is a clear reversal of hydraulic gradient (1:65 from north to south). Although this is a mining depressurisation effect, the head is still about 120 m above atmospheric pressure. There is potential for water in the Lower Bulgo Sandstone sequence (at approximately 300 m depth) to reverse direction and flow towards mine workings.

Based on core-measured permeabilities, groundwater velocities will be in the order of 1 cm/year laterally in the Bulgo Sandstone and 10 cm/year vertically across the Bald Hill Claystone at the Longwall 10 goaf hole.

3.4 HYDRAULIC PROPERTIES

SCT Operations (2007) conducted horizontal and vertical permeability measurements on rock core derived from the Longwall 10 goaf hole for Hawkesbury Sandstone, Bald Hill Claystone and Bulgo Sandstone. These values can be taken as lower limits on likely field permeabilities as they cannot account for macro-permeability due to natural and induced joints/fractures.

The results are summarised in Table 6. In general, the horizontal to vertical anisotropy (Kx/Kz) was found to be in the order of 2 for sandstone strata, and 5 for claystone strata.

Indicative permeabilities for the various stratigraphic units, summarised in Table 7, are informed by SCA pumping tests and model calibration at Kangaloon (KBR, 2008), model calibration at Mangrove Mountain (Alkhatib and Merrick, 2006), and model estimates at Dendrobium Mine (GHD Geotechnics, 2007).

Initial permeabilities adopted for numerical modeling are listed in Table 8.

Table 6. Measured Core Permeabilities of Stratigraphic Units

Unit	Relative Depth	Horizontal Permeability Kx [m/d]	Vertical Permeability Kz [m/d]
Hawkesbury Sandstone	Shallow [53 m] Mid [89 m] Deep [113 m]	1.2×10^{-3} 1.1×10^{-3} 0.6×10^{-3}	4.8×10^{-4} 6.8×10^{-4} 1.5×10^{-4}
Bald Hill Claystone	-	1.0×10^{-5}	8.3×10^{-6}
Bulgo Sandstone	Upper [180 m] Lower [253 m]	5.7×10^{-5} 5.8×10^{-6}	5.2×10^{-5} 1.6×10^{-6}

After: SCT Operations Pty Ltd (2007)

Table 7. Indicative Hydraulic Properties of Stratigraphic Units

Unit	Hydrogeological Description	Horizontal Permeability Kx [m/d]	Vertical Permeability Kz [m/d]
Hawkesbury Sandstone	Unconfined Aquifer	0.01 - 1	0.0005 – 0.5
Bald Hill Claystone	Aquitard	1×10^{-5}	1×10^{-6}
Bulgo Sandstone	Leaky Confined Aquifer	4×10^{-4} – 0.07	3×10^{-4} – 0.007
Stanwell Park Claystone	Aquitard	1×10^{-4}	-
Scarborough Sandstone	Leaky Confined Aquifer	0.01 – 0.04	-
Wombarra Claystone	Aquitard	1×10^{-4}	-
Coal Cliff Sandstone	Leaky Confined Aquifer	1×10^{-4} – 0.02	-
Bulli Coal Seam	Aquifer	0.04	-
Loddon Sandstone	Confined Aquifer	1×10^{-4}	-

After: GHD Geotechnics (2007); KBR (2008); Alkhatib & Merrick (2006)

Table 8. Initial Permeabilities in the Numerical Model

Unit	Relative Depth	Horizontal Permeability Kx [m/d]	Vertical Permeability Kz [m/d]	Kx /Kz
Hawkesbury Sandstone	Superficial	0.2	0.1	2
	Upper	0.1	0.05	2
	Lower	0.01	0.005	2
Bald Hill Claystone		$1x10^{-5}$	$2x10^{-6}$	5
Bulgo Sandstone	Upper	0.001	$2x10^{-4}$	5
	Lower	$1x10^{-4}$	$2x10^{-5}$	5
Stanwell Park Claystone		$3x10^{-5}$	$6x10^{-6}$	5
Scarborough Sandstone	Upper	0.01	$5x10^{-3}$	2
	Lower	0.01	$5x10^{-3}$	2
Wombarra Claystone	-	$3x10^{-5}$	$6x10^{-6}$	5
Coal Cliff Sandstone	-	0.001	$5x10^{-4}$	2
Bulli Coal Seam	-	0.05	0.025	2
Loddon Sandstone	-	$1x10^{-4}$	$2x10^{-5}$	5

4.0 GROUNDWATER SIMULATION MODEL

4.1 Model Software and Complexity

The United States Geological Survey three-dimensional, finite difference, modular, groundwater flow model MODFLOW (McDonald and Harbaugh, 1988) was used to simulate the impact of underground mining scenarios on the hydrogeological regime. The MODFLOW code is the most widely used code for groundwater modeling and is presently considered an industry standard. Version 5 of Groundwater Vistas (GV) was adopted as the graphic user interface to MODFLOW 96.

To handle the observed vertical changes in groundwater head within a given formation, and expected goaf fracturing, 13 model layers have been used (Figure 29). This includes subdivision of Hawkesbury Sandstone into 2 layers, Bulgo Sandstone into 2 layers, and Scarborough Sandstone into 2 layers.

4.2 Model Geometry

The model domain is discretised into 327,600 cells arranged into 13 layers comprising 140 rows and 180 columns. The dimensions of the model cells are uniformly 100 m in both directions as shown in Figure 31. The model extent is 18 km from west to east and 14 km from south to north, covering an area of approximately 252 km^2.

The south-eastern corner of the model extent crosses the Illawarra Escarpment and reaches the sea (Figure 31). This allows the inclusion of a significant natural boundary condition at regional scale.

Figure 31 also shows the drainage network incorporated in the model and the topography of the land surface. Mine outlines are shown (in grey) for Longwalls 1-17, 18-19A and 20-44; for old workings (in aqua) at Darkes Forest and Helensburgh; and for first workings (in aqua) at North Cliff.

Representative model cross sections are displayed in Figure 32. The elevation of the base of the Bulli Coal Seam is well defined over most of the model extent. The interface elevations for other layers were propagated from this base using measured thicknesses where available, and median thicknesses otherwise (as listed in Figure 29).

4.3 Model Stresses and Boundary Conditions

Rainfall infiltration has been imposed uniformly over the model extent as a fraction of the long-term 1894-2006 Darkes Forest median monthly rain (74 mm/month). The infiltration rate was set initially at 10 percent, guided by the model calibration of Alkhatib and Merrick (2006) in the Hawkesbury Sandstone of Mangrove Mountain.

The main streams in the area, denoted in Figure 33[a] (in blue and green), were established as "river" cells in model layer 1 using the MODFLOW RIV package. This allows water exchange in either direction between the stream and the aquifer. The river conductances were set at 5-50 m^2/day. Minor drainage lines were established as "drain" cells in model layer 1 using the MODFLOW DRN package (shown in yellow in Figure 33a). This allows groundwater to discharge to the drainage lines as baseflow. The drain conductances were set at 2.5 m^2/day.

The only specified heads in the model were set at the sea boundary in model layer 1 (which equates to the Scarborough Sandstone to the east of the escarpment).

"Drain" cells were used to represent mining. The old workings and first workings at neighbouring mines were given invert levels equal to the top of the Bulli Seam to represent flooded workings at atmospheric pressure. These are shown in Figure 33b (in yellow). Mining at the Metropolitan Mine was simulated by invert levels set at the bottom of the coal seam. This was done separately for Longwalls 1-14 (shown in green in Figure 33b), to coincide with mining status at the time of early Longwall 10 goaf hole piezometric measurements, and for Longwalls 15-44 (shown in pink in Figure 33b), to represent the end of mining. The initial drain conductance was set at 10 m^2/day.

4.4 MODEL VARIANTS

The model was developed in stages, with increasing complexity during its evolution. The model variants are:

- Steady state pre-mining model.
- Steady state model including neighbouring old workings and first workings. Calibration of superficial aquifer against regional inferred groundwater level contour map.
- Steady state model of Longwalls 1-14 (no fractured zone), including neighbouring old workings and first workings. Calibration against LW10 and PM02 piezometers.
- Steady state model of Longwalls 1-14 (with fractured zone), including neighbouring old workings and first workings. Calibration against LW10 and PM02 piezometers.
- Steady state model of Longwalls 1-44 (with fractured zone), including neighbouring old workings and first workings. Worst case simulation.
- Transient model of recovery after the end of mining.

4.5 Calibration

Two calibrated models have been developed for model variant 4, called Model A and Model B. In each case, calibration was automated using PEST software and zoned regions. Each layer was assumed uniform except for the fractured zone above Longwalls 1-14, where separate Kz was permitted in Layers 7-11 (Stanwell Park Claystone down to the Bulli Seam). In the case of Model A, PEST was run in two steps: (1) calibration of horizontal permeability (Kx) only; (2) with Kx fixed at optimal values, calibration of vertical permeability (Kz) only. In the case of Model B, PEST was run in a single step with simultaneous calibration of Kx and Kz.

The two models differ in physical properties according to Table 9, but they have similar performance according to Table 10. The inferred median vertical permeability in the fractured zone is higher than the host value by a factor of 8 in Model A and 14 in Model B.

Table 9. Calibrated Horizontal and Vertical Permeabilities [m/day]

	MODEL A			MODEL B		
	HOST Kx	HOST Kz	FRACTURE Kz	HOST Kx	HOST Kz	FRACTURE Kz
SUPERFICIAL AQUIFER	0.10	1.0		0.10	1.0	
UPPER HAWKESBURY SANDSTONE	0.026	0.50		0.027	0.33	
LOWER HAWKESBURY SANDSTONE	0.017	5.0E-04		5.4E-03	5.0E-04	
BALD HILL CLAYSTONE	1.0E-05	3.8E-06		8.6E-06	1.3E-05	
UPPER BULGO SANDSTONE	5.0E-03	1.4E-03		1.5E-02	2.0E-03	
LOWER BULGO SANDSTONE	1.0E-04	1.1E-05		1.0E-03	2.9E-05	
STANWELL PARK CLAYSTONE	3.0E-04	6.0E-05	3.5E-05	1.0E-05	6.0E-05	6.0E-04
UPPER SCARBOROUGH SANDSTONE	1.0E-03	6.2E-03	0.052	3.0E-04	6.7E-03	0.093
LOWER SCARBOROUGH SANDSTONE	6.1E-03	5.2E-03	0.057	0.033	1.0E-03	0.50
WOMBARRA CLAYSTONE	2.9E-04	7.3E-06	5.8E-05	1.0E-03	6.0E-05	1.4E-05
COAL CLIFF SANDSTONE	2.4E-04	1.1E-03	5.9E-03	1.3E-04	9.2E-04	0.019
BULLI COAL SEAM	0.026	0.034		0.030	0.030	
LODDON SANDSTONE	1.0E-05	2.0E-05		1.0E-05	2.0E-06	

Table 10. Calibration Performance

	DEEP		SHALLOW	
	MODEL A	MODEL B	MODEL A	MODEL B
Number of Data	13	13	24	24
Average Residual [m]	-3.4	-3.3	-16.1	-15.4
Root Mean Square (RMS) [m]	13.1	13.4	19.7	18.9
Scaled Root Mean Square (SRMS) [%]	9.9	10.1	14.3	13.7

Both models have a Scaled Root Mean Square (SRMS) statistic of about 10% for calibration against the deep head profiles measured in Metropolitan Hole PM02 and the Longwall 10 goaf hole. The average difference between measured and simulated values is 3 m, with a slight bias to overestimation. The scattergram for deep heads, in Figure 34[a], shows that head-pairs lie close to the line of perfect correlation. The performance is not as good for the shallow aquifer, with a SRMS statistic of about 14% for each model, and an average residual of 15-16 m. The scattergram in Figure 34[b] shows systematic overestimation. The reason for this is imprecision in ground surface elevations along drainage lines where nearly all shallow piezometers are placed. The use of a digital elevation model at 25 m resolution proved to have insufficient accuracy for incised streams.

Figure 35 shows the calibrated Model B simulation of groundwater levels in the Hawkesbury Sandstone (Layer 2). Layer 1 shows the same pattern but many model cells are dry along the ridgelines (as expected). Figure 35[a] shows the whole model extent, while Figure 35[b] shows a close-up of the mining area for better comparison with the inferred contour map of Figure 10. There is very good agreement between observed and simulated patterns, despite the model's tendency to overestimate groundwater heads along drainage lines.

The groundwater heads in the Bald Hill Claystone (Figure 36[b]) preserve the pattern that occurs in overlying Hawkesbury Sandstone layers. Beneath the Bald Hill Claystone, the groundwater heads start to show responses to mining (Figure 36[c]). Figure 37 shows the gradual increase in depressurisation effects from Layer 6 (Lower Bulgo Sandstone) through Layer 9 (Lower Scarborough Sandstone) to the maximum effect in Layer 12 (Bulli Seam). *[Note the change in colour scale between Figure 36 and Figure 37.]*

4.6 WATER BALANCE

The only sources of aquifer recharge in the model are rainfall and stream leakage. The latter is simulated to be about 3 ML/day, with slight enhancement from mining (Table 11).

Table 11. Simulated Water Balance for Calibration Models

	SIMULATED FLOW RATE [ML/day]				CHANGE since OLD WORKINGS [%]	
Recharge	PRE-MINING	OLD WORKINGS	MODEL A	MODEL B	MODEL A	MODEL B
RAIN	57.98	57.98	57.98	57.98	0.0%	0.0%
RIVERS	3.12	3.18	3.20	3.35	0.4%	5.2%
TOTAL	61.10	61.17	61.18	61.33	0.0%	0.3%
Discharge						
RIVERS	44.22	43.34	43.32	40.28	0.0%	-7.1%
MINOR CREEKS ("drains")	15.47	14.82	14.81	13.23	-0.1%	-10.8%
SEA	1.42	1.38	1.38	1.53	-0.1%	11.1%
OLD WORKINGS	0.00	1.63	1.54	5.86	-5.5%	260%
LONGWALLS 1-14			0.14	0.31		
TOTAL	61.10	61.16	61.19	61.21	0.0%	0.1%
Mass Balance Error			0.02%	0.23%		

There are multiple opportunities for groundwater discharge. Those implemented in the model are baseflow to major streams (represented by the "river" algorithm in MODFLOW), baseflow to minor streams (represented by the "drain" algorithm in MODFLOW), outflow to the sea (represented by "constant heads" in MODFLOW), mine inflow to the old workings, and mine inflow to Longwalls 1-14 (at the time of model calibration).

Baseflow to the rivers accounts for about 70% of the total discharge under natural pre-mining conditions, with minor creeks accepting about 25%. Modelling suggests that the old workings are receiving about 1.5-1.6 ML/day. Model B gives a much higher value of nearly 6 ML/day for the old workings, which is unreasonably high. Model B also gives an inflow of 0.3 ML/day to the current Metropolitan Mine, and this too is considered high.

At this time there is no metered water balance for the mine, but the water make is expected to be less than 0.1 ML/day. This figure is based on water loss in ventilation, water removed in product coal, an absence of significant flows from intersected geological structures, and the fact that the mine is regarded as a "dry mine". Model A reports a reasonable estimate of 0.14 ML/day.

Model B gives a higher mass balance error than Model A, and had numerical convergence difficulties. It is concluded that Model A is a better representation of real conditions.

According to Model A, the mining of Longwalls 1-14 has caused negligible changes in discharge volumes to natural features, but has induced about 0.4% extra leakage from streams.

4.7 Sensitivity Analysis

Figure 38 illustrates the ability of Model A and Model B to replicate the observed vertical groundwater head profiles at the two deep holes (LW10 goaf hole and PM02). Model A and Model B have similar performance. When all mining stresses are removed (from Model A) to represent natural pre-mining conditions, the model suggests that the total head would be nearly constant with depth. Although the vertical gradient at PM02 is mild, it does appear that some influence from past mining has propagated to this location.

Also illustrated in Figure 38 is the sensitivity of vertical gradients to the presence/absence of a fractured zone, and the assumed influence of the neighbouring old workings. The old workings on their own can account for most of the observed head reduction with depth. The mining of Longwalls 1-14 has added marginally to the decline in head at both locations.

Performance is demonstrably worse if the fractured zone were to be ignored.

Sensitivity analysis was performed (using Model A) on the mine drain conductance parameter by varying the assumed value over two orders of magnitude (1 – 100 m^2/day). Performance statistics are listed in Table 12 for calibration targets at all levels in PM02 and the LW10 goaf hole. The simulated mine inflow at Longwalls 1-14 varied from 100 to 250 m^3/day. Calibration performance deteriorated rapidly away from the base case [10 m^2/day].

Table 12. Sensitivity Analysis for Drain Conductance at Longwalls 1-14

DRAIN CONDUCTANCE [m²/d]	SRMS [%]	AVERAGE RESIDUAL [m]	LW 1-14 INFLOW [m^3/d]
1	15.4	-5.3	247
3	16.9	-7.9	177
10 [base]	9.9	-3.4	140
30	13.9	-7.9	98
100	21.0	-13.2	159

Sensitivity analysis was performed also on the uniform rain infiltration rate, as reported in Table 13. The rate was varied from half to double the base rate [10%]. Very little change in mine inflow was noticed. There was a mild improvement in calibration performance by reducing rain infiltration to 7.5%, but this particular run has a relatively high mass balance discrepancy (0.24%).

Table 13. Sensitivity Analysis for Rain Infiltration Rate

RAIN RECHARGE	SRMS [%]	AVERAGE RESIDUAL [m]	LW 1-14 INFLOW [m^3/d]
5%	10.8	4.9	135
7.5%	9.8	0.4	180
10% [base]	9.9	-3.4	140
12.5%	10.7	-6.8	142
15%	11.9	-9.7	152

5.0 SCENARIO ANALYSIS

5.1 LONGWALLS 1-44

In order to assess possible mining impacts under worst case conditions, a steady state simulation has been made at the completion of planned mining, based on Model A properties, with a pervasive fractured zone over all Longwalls 1-44. The old workings are assumed also to remain active sinks at atmospheric pressure.

Figures 39 and 40 show the simulated groundwater head contours in Layers 3-5 (Figure 39) and Layers 6, 9 and 12 (Figure 40). These figures should be compared with corresponding Figures 36 and 37 at the end of Longwall 14 mining.

The groundwater heads in the Bald Hill Claystone (Layer 4; Figure 39[b]) preserve the pattern that occurs in overlying Hawkesbury Sandstone layers. Beneath the Bald Hill Claystone, the groundwater heads start to show progressively increasing responses to mining. Depressurisation effects are discernible in the Bulgo Sandstone and are pervasive in the Scarborough Sandstone and lower layers (Figure 40). *[Note the change in colour scale between Figure 39 and Figure 40.]*

5.2 WATER BALANCE

Table 14 documents the water balance for the prediction model and for earlier model variants. The model suggests a total mine inflow of about 0.5 ML/day at steady state.

Table 14. Simulated Water Balance for Prediction Model

	SIMULATED FLOW RATE [ML/day]				CHANGE since OLD WORKINGS [%]	
Recharge	PRE-MINING	OLD WORKINGS	MODEL A	LW 1-44	MODEL A	LW 1-44
RAIN	57.98	57.98	57.98	57.98	0.0%	0.0%
RIVERS	3.12	3.18	3.20	3.22	0.4%	1.2%
TOTAL	61.10	61.17	61.18	61.20	0.0%	0.1%
Discharge						
RIVERS	44.22	43.34	43.32	42.97	0.0%	-0.9%
MINOR CREEKS ("drains")	15.47	14.82	14.81	14.64	-0.1%	-1.2%
SEA	1.42	1.38	1.38	1.37	-0.1%	-0.8%
OLD WORKINGS	0.00	1.63	1.54	1.44	-5.5%	-12%
LONGWALLS 1-14			0.130	0.019		
LONGWALLS 15-44				0.525		
TOTAL	61.10	61.16	61.18	60.96	0.0%	-0.3%

Predicted changes in baseflow on specific streams are detailed in Table 15 for the old workings and for mining of Longwalls 1-44.

Table 15. Simulated Baseflow for Prediction Model

Stream	SIMULATED BASEFLOW [ML/day]			BASEFLOW CHANGE since PRE-MINING [%]		BASEFLOW CHANGE since OLD WORKINGS [%]
	PRE-MINING	OLD WORKINGS	LW 1-44	OLD WORKINGS	LW 1-44	LW 1-44
WORONORA RIVER	4.56	4.49	4.44	-1.4%	-2.7%	-1.3%
HONEYSUCKLE CREEK	0.83	0.82	0.80	-1.8%	-4.3%	-2.6%
LAKE WORONORA	4.01	3.97	3.91	-0.9%	-2.4%	-1.6%
WARATAH RIVULET	4.98	4.81	4.83	-3.4%	-3.0%	0.4%
CREEK THROUGH LW1	1.39	1.35	1.34	-3.2%	-4.0%	-0.7%
All Streams	41.1	40.2	39.7	-2.3%	-3.3%	-1.0%

The simulated baseflow in Waratah Rivulet converts to a value of about 0.23 ML/day per km^2. This agrees well with the recorded low streamflow at station GS2132102 (Figure 19 in Gilbert & Associates, 2008).

The model also has assumed a uniformly fractured zone above the entire mined seam across all longwall panels, without recognition of partial protection above the chain pillars. As a result, the model is being conservative by overpredicting the likely magnitude of depressurisation effects. Notwithstanding, the groundwater model calculates only a negligible reduction in baseflow for all streams. Gilbert & Associates (2008; Figure 21) report a cumulative inflow to the reservoir of approximately 800,000 ML over 31 years. As such, the potential reduction in cumulative average inflows to the Woronora Reservoir is considered to be negligible.

This is consistent with the findings of Southern Coalfield Inquiry (Department of Planning, 2008):

> *"No evidence was presented to the Panel to support the view that subsidence impacts on… shallow or deep aquifers have resulted in any measurable reduction in runoff to the* ***water supply system*** *operated by the Sydney Catchment Authority or to otherwise represent a threat to the water supply of Sydney or the Illawarra region."*

In addition, this finding is consistent with the conclusions of separate hydrological studies undertaken by Gilbert & Associates (Appendix C of the Environmental Assessment) (peer reviewed by Dr Walter Boughton) which relevantly conclude that there is no evidence of loss of flow from the system as a result of mining effects nor is any expected as a result of the proposed future mining.

5.3 Recovery Simulation

The recovery simulation deactivates all mine drain cells (new and old workings), and commences with simulated heads at the end of the mining of Longwall 44. The model is run in transient mode for 100 years with specific yield 0.02 (all layers) and storage coefficient 0.00001 (all layers). Recovery is monitored at the two deep holes (PM02 and LW10 goaf), as shown in Figure 41. Note that the Hawkesbury Sandstone head is not perceptibly altered by the mining history beneath.

At the LW10 goaf hole, the Lower Bulgo Sandstone and the Lower Scarborough Sandstone both recover by 50% after about 20 years. The deepest formations, represented by the Loddon Sandstone (model layer 13), take longer to recover, attaining 50 % recovery after about 55 years.

Recovery at the PM02 hole is considerably more rapid, with the Lower Bulgo Sandstone and the Lower Scarborough Sandstone both recovering by 50% after about 7 years. The Loddon Sandstone will take about 21 years for half-recovery.

After 100 years, the Loddon Sandstone will achieve about 85% recovery at the LW10 goaf hole, and about 95% recovery at the PM02 hole.

5.4 Sensitivity Analysis

Storage coefficient [S] is the parameter that controls the rate of recovery of groundwater head. Sensitivity analysis was performed on this parameter by increasing it from the base case [10^{-5}] by a factor of 10 [to 10^{-4}]. The results for the LW10 goaf hole and PM02 hole are displayed in Figure 42.

The recovery times are about 3-4 times longer with a higher storage coefficient. At the LW10 goaf hole, 100 years is insufficient for half-recovery in the deepest formations. The Loddon Sandstone will achieve about 20% recovery at this time at the LW10 goaf hole, and about 65% recovery at the PM02 hole.

A comparison of half-recovery times is given in Table 16.

Table 16. Time Required for 50% Recovery

	LW10 GOAF HOLE		PM02 HOLE	
	S=0.00001	S=0.0001	S=0.00001	S=0.0001
LOWER BULGO SANDSTONE	18 years	42 years	7 years	27 years
LOWER SCARBOROUGH SANDSTONE	18 years	41 years	7 years	23 years
LODDON SANDSTONE	55 years	>100 years	21 years	74 years

6.0 SUBSIDENCE IMPACTS ON THE GROUNDWATER RESOURCE

6.1 POTENTIAL IMPACTS OF LONGWALLS 20-44

6.1.1 Subsidence Mechanism

The location of proposed Longwalls 20 to 44 is shown in Figure 1. The prediction of subsidence parameters and the assessment of mine subsidence impacts due to proposed Longwalls 20 to 44 are documented in a report by MSEC (2008).

The maximum predicted incremental subsidence is 830 mm due to Longwall 21 alone, while the maximum cumulative subsidence due to Longwalls 20 to 44 is 1280 mm (above Longwall 23). Taking previously extracted longwalls into account, the maximum predicted total subsidence is 1280 mm (above Longwall 23), the same as the maximum cumulative subsidence.

6.1.1.1 Conceptual Models

Transitory and permanent changes in the transmissive and storage properties of overburden rock may occur as a result of the proposed longwalls. Above goaf zones changes will occur in fracture porosity and permeability, due to opening up of existing joints, new fractures, and bed separation.

Given that mining is dynamic, a leading tensional stress at one location will be followed by a compressional stress, and then another tensional phase. Cracks that might open up in the tensional phase will close at least partially in the compressional phase. Local fracture permeability will increase, and then decrease towards the natural value. Rib areas can be expected to have permanently enhanced permeability, with potential for preferential groundwater flow paths.

Underground backfilling of the mine void by goaf injection or underground emplacement into the old underground workings were considered, but relative to other transmissive and storage properties of overburden rock, would have negligible influence on the groundwater resource.

6.1.1.2 Changes in Hydraulic Properties

Changes in hydraulic properties can cause substantial changes in groundwater heads and flow patterns. If the effects reach the surface, baseflow to streams can be reduced. Permeability increases will have accompanying reductions in hydraulic gradients, in accordance with Darcy's Law. As one increases, the other must decrease to maintain the same flow. Changes in hydraulic gradients cannot occur without accompanying changes in groundwater levels and pressures. Pronounced changes in groundwater levels can occur without any significant drainage into a mine.

6.1.1.3 Changes in Groundwater Flow

MSEC (2008) state that some stream bedrock fracturing and dilation of the underlying strata are likely. A consequence is the diversion of some surface waters to subterranean flow.

6.1.2 Drainage Mechanism

6.1.2.1 Mine Inflows

The formation of a fractured zone above the goaf will encourage additional mine inflow as mining progresses. Although there is no metered water balance for the mine, the mine is described as a "dry mine" and the water make is expected to be less than 0.1 ML/day. Numerical modelling gives a consistent inflow (0.1 ML/day) for Longwalls 1-14, and an anticipated inflow of about 0.5 ML/day at the completion of Longwall 44.

To explain the observed vertical hydraulic gradients measured at the Longwall 10 goaf hole, the numerical model required the assumption of significant influence from old workings at Darkes Forest and Helensburgh, and development workings at North Cliff. The model predicts a total inflow of about 1.5 ML/day to these mines currently, distributed fairly evenly with about 0.5 ML/day each. At the end of mining of Longwall 44, the inflow to old/new workings is predicted to drop marginally to 1.4 ML/day, and the inflow to Longwalls 1-14 is expected to drop to about 0.02 ML/day.

6.1.2.2 Depressurisation

The experience gained from the Longwall 10 goaf hole suggests that substantial depressurisation of the aquifers in the fractured zone above the goaf is restricted to a height of less than 130 m from the top of the seam. Transient pressure effects have been observed to propagate to a height of about 300 m above the seam (at Piezo165 on Figure 25).

Although the Hawkesbury Sandstone could be a productive aquifer of economic importance, water supply protection prevents its development. The only registered production bores in the vicinity of the Project are at distances greater than 3 km from Metropolitan Colliery, and are at shallower depths within the Hawkesbury Sandstone. It is not known whether the bores are still in use. Although depressurisation within the deep groundwater system would propagate to these distances, the effects would not reach Hawkesbury Sandstone levels.

The numerical modelling confirms that the Bald Hill Claystone protects the Hawkesbury Sandstone from significant changes in head. Groundwater modelling suggests a negligible reduction in baseflow (Section 5.2). Although the model is not able to simulate perched water tables, it is expected from observed isolation between perched and regional water tables that no loss in baseflow would be experienced.

The Narrabeen Group sandstones that overlie the mined coal seam, although aquifers in the strict sense of the word, are not regarded as having any economic value.

6.1.3 Potential Impacts on Surface Water Bodies

The main role of groundwater in the elevated aquifers of the Southern Coalfield is to provide baseflow to streams and to support ecosystem function. Longwall mining can have an effect on shallow groundwater flow paths, baseflow to streams, stream water quality, and riverine ecosystems. The effects are highly variable and site-specific.

6.1.3.1 Changes in Water Quality

A summary of the groundwater quality monitoring results at the Metropolitan Colliery is provided in Attachment A.

Assessment of the potential surface water quality effects are provided in the surface water assessment (Appendix C of the Environmental Assessment).

6.1.3.2 Changes in Water Balance

There is no convincing evidence that cracking in creek and river beds causes any net change in the overall water balance of a stream. If local pools are dried out or lowered in water level, localised ecosystem impacts can occur.

Based on the analysis of the conceptual groundwater system (Section 3), there would be no loss of groundwater yield to the Woronora Reservoir. Groundwater modelling suggests a negligible reduction in cumulative average inflows to the Woronora Reservoir (Section 5.2).

6.1.3.3 Effects on Surface Ecosystems

While there will be some impact on the structure of the aquifers, the effects are of no consequence as the aquifer is not in productive use. The substantial depth of cover protects the shallow aquifers that are in connection with streams and ecosystems from transmitted effects due to reduction in groundwater pressures.

Excess rainfall produces a permanent perched water table within swamp sediments and outcropping sandstone that is independent of the natural water table in the Hawkesbury Sandstone. The growth of dense vegetation in upland swamps and the low ground gradient prevent the formation of an open channel that would otherwise transport water and sediments. As the swamps are essentially rainfall-fed, the water levels within the upland swamps fluctuate seasonally with climatic conditions.

Piezometers installed in upland swamps within Metropolitan Colliery leases have shown permanent water levels at or close to the surface topography. For the period 2007-2008, swamp water levels at the three monitored sites varied from ground level to more than 3 m below ground in sympathy with rainfall.

Based on the analysis of the conceptual groundwater system, there is no expected dewatering of swamps from depressurisation at depth.

Although some surface cracking might occur at the upland swamps, it is expected that any such cracking would fill with sediment within a relatively short period of time (in the order of days). The sediments in the upland swamps are described by Young (1986) as "silty clays with very high organic contents" and "silty coarse-medium sands". Gilbert and Associates (2007) report that "soils exposed during the installation of monitoring bores in several larger upland swamps in Honeysuckle and Bee Creeks further north in the Waratah Rivulet Catchment indicate that these upland swamps are formed over a relatively thin (1.5 to 2.5 m deep) deposit of loose sandy silty alluvial/colluvial material which overlies weathered sandstone bedrock". Should a fracture occur, there will be a huge volume of sediment available for sedimentation within the cracks.

There is potential evidence of crack sedimentation within groundwater piezometer UTGW2 (located within Metropolitan Colliery leases and above a previously mined area). Although this monitoring site is in a different geomorphological setting (i.e. the piezometer is located immediately adjacent to a free flowing creek channel and not within an upland swamp), and in a system where limited *in situ* sediment loads are available (relative to an upland swamp), monitoring records show there was an initial drop in water levels in response to longwall mining, which was followed by recovery of water levels. This occurred after a wet event, and it is possible that sediment was transported to the cracked site via water movement which then filled the crack to the extent that groundwater level effects diminished significantly.

Very little drainage of water is expected from the perched water table in the swamp to the regional water table in the underlying sandstone, as the sandstone bedrock is massive in structure and permeability decreases with depth. Surface cracking that may occur would be superficial in nature (i.e. would be relatively shallow) and would terminate within the unsaturated part of the low permeability sandstone. Due to the very low hydraulic gradient of the water table within a swamp, lateral movement of water through the swamp towards a crack would be very small and very slow. In addition, a preliminary study conducted by the SCA on the effects of borefield extraction under a swamp "clearly show no interaction between the water levels in Butler's Swamp and the water being extracted from the sandstone aquifer" (SCA, 2007a). This supports the argument that the regional aquifer is hydraulically disconnected from perched water in the upland swamps.

Further, as the free-draining fractured zone that is to be expected above a goaf zone does not extend as high as 130 m above the seam, the perched water in the upland swamps would not be impacted directly by the fractured zone above the goaf. The only possibility for impact is through superficial tensile cracking associated with a moving subsidence trough, and that is likely to be transitory.

Given the minor nature of potential tensile cracking and the hydrogeological characteristics of upland swamps, there is very little potential for any measurable change in swamp moisture conditions. Any changes in swamp moisture as a result of cracking are expected to be immeasurable when compared to the scale of seasonal and even individual rainfall event based changes in swamp groundwater levels. BHP Billiton (2006; 2007) has monitored soil moisture and mine subsidence in a number of swamps that overlie longwall mining operations. BHP Billiton (2006; 2007) report that the study has identified no significant difference between the overall soil moisture conditions observed in the swamps subject to mine subsidence and those that have not. BHP Billiton (2007) state that:

> *"The overall soil surface moisture conditions of those swamps that have been mined under closely follow the conditions observed in the swamps that have not been mined under."*

6.2 PROPOSED GROUNDWATER MONITORING PROGRAM

The regulatory process in NSW is such that specific monitoring details are developed as part of the Subsidence Management Plan approvals process for specific longwall mine developments. The current groundwater monitoring program has been developed in consultation and with the approval of the SCA and in accordance with their monitoring protocols.

The current groundwater monitoring program monitors the shallow aquifer system along streams for Longwalls 10 to 17, and also at three (3) northerly locations in upland swamps. The variation of groundwater pressures with depth is monitored at eight (8) depths to 300 m below ground level above Longwall 10 (i.e. the Longwall 10 Goaf Hole), and at eight (8) depths to 500 m below ground level at exploration hole PM02 to the west of Lake Woronora.

This existing program would be augmented by the Longwall 18-19A groundwater monitoring program which includes:

- three sets of deep multi-level piezometers to the Bulli seam on ridgelines (i.e. in recharge areas) along Fire Roads 9E, 9G and 9H;

- three sets of deep multi-level groundwater sampling boreholes on ridgelines (i.e. in recharge areas) along Fire Roads 9E, 9G and 9H;
- paired bores at a swamp location (SWGW1 and SWGW2); and
- nested piezometers to approximately 60 m (near the base of the Hawkesbury Sandstone) immediately adjacent to a pool on a tributary stream (RTGW1).

The augmentation to the existing monitoring program is described below, shown in Figure 43, and summarised in Table 17.

Table 17. Proposed Groundwater Monitoring Sites

BORE	EASTING (MGA)	NORTHING (MGA)	DEPTH	REASON
9EGW1	309462	6216053	35m, 110m, 170m, 230m, 330m, 370m, 400m, 440m	Multi-level piezometers in deep hole to Bulli Seam in recharge zone
9HGW1	308142	6214590	35m, 80m, 160m, 200m, 225m, 390m, 423m, 466m	Multi-level piezometers to 180 m on ridge (i.e. recharge zone), over LW19A
RTGW1	309579	6215108	20m 60m (or to base of Hawkesbury sandstone)	Nested piezometer immediately adjacent to a pool
9GGW1	310976	6214296	35m, 110m, 170m, 230m, 330m, 370m, 400m, 440m	Multi-level piezometers in deep hole to Bulli Seam in recharge zone
SWGW1	307868	6214142	20m (or 2 m below the sandstone aquifer water table)	Sandstone aquifer beneath upland swamp (Tributary D), over LW19A
SWGW2	307868	6214147	5m (or to auger refusal in swamp)	Perched water table in upland swamp (Tributary D), over LW19A

6.2.1 Groundwater Quality

It is recommended the current groundwater quality monitoring programmes undertaken as part of the Longwall 14-17 and Longwall 18-19A Environmental Monitoring Programs be extended to include all new bores that have standpipes (namely RTGW1, SWGW1, SWGW2).

6.2.2 Groundwater Monitoring Schedules

The current monitoring schedule should be extended to the proposed new bores, namely continuous data logging at 15 minute intervals with data downloaded and reported monthly.

6.3 PROPOSED GEOLOGICAL INVESTIGATION PROGRAM

In addition to the proposed groundwater monitoring program, a geological investigation program should be developed and implemented progressively over the Project life to manage the potential for unexpected groundwater related effects, including:

- long in-seam exploration boreholes (Figure 43) to identify any geological anomolies in advance of longwall mining;
- surface mapping (ground-truthing) of geological characteristics; and
- further analysis of geomorphic expressions.

The above activities would focus on the identification of potential conduits (e.g. faults, dykes, joint systems)[3] and include extrapolation from areas external to the underground mining zone.

[3] Consistent with Recommendation 18 of the Southern Coalfield Inquiry report (Department of Planning, 2008).

7.0 CLIMATE CHANGE AND GROUNDWATER

The effects of climate change on groundwater are projected to be negative in some places on earth, but positive in other places. In the Netherlands, for example, beneficial effects are anticipated (Kamps et al., 2008). There it is expected that coastal water tables will rise but evapotranspiration will reduce in response to the adaptation of vegetation to higher levels of carbon dioxide. Modelling shows more pronounced seasonal water table fluctuations by accounting for vegetation feedback mechanisms (Kamps et al., 2008). Plants are expected to have a lower water demand under higher carbon dioxide levels due to production of more biomass, increased leaf area index, and a shorter time to reach the saturation point for carbon demand (Kamps et al., 2008).

In New Hampshire USA, on the other hand, negative effects on the water table are expected due to the onset in spring recharge 2-4 weeks earlier (Mack, 2008). This shift will allow a longer period for evapotranspiration prior to summer months, at which time groundwater availability is likely to decrease.

The modelling of climate change effects needs to take into account complex vegetation and hydrologic feedback mechanisms, coupled surface water and groundwater interactions, and inter-annual temporal variations. Very few modelling studies have been conducted so far. Hunt et al. (2008) reported on the difficulties to be overcome in doing comprehensive modelling using newly released integrated GSFLOW software (MODFLOW plus PRMS).

Order of magnitude estimates can be found by ignoring feedback mechanisms and changing the currently calibrated rain infiltration percentage. However, more intense rainfall events would be expected to increase fast runoff and lead to a reduction in infiltration. This should be taken into account to allow for short-term temporal variations.

In parts of south-eastern Australia, annual rainfall is expected to change by -10% to +5% by 2030 (Pittock, 2003), roughly the time of completion of mining. In addition, annual average temperatures are projected to increase by 0.4 to 2.0°C (relative to 1990) at that time.

The approach taken here is to conduct steady state simulations at the completion of mining (Longwall 44) for two scenarios:

- Rainfall infiltration reduced by 10%; and
- Rainfall infiltration reduced by 20%.

As the calibrated rain infiltration is 10%, the two scenarios are equivalent to assumed rain infiltration of 9% and 8% respectively. The results of the simulations are summarised in Table 18 in terms of baseflow reductions for pertinent streams and water bodies, and for all streams in the model domain.

Table 18. Predicted changes in baseflow due to climate change.

Stream	SIMULATED BASEFLOW [ML/day]			BASEFLOW CHANGE due to CLIMATE CHANGE [%]	
	LW 1-44 [8% Rain]	LW 1-44 [9% Rain]	LW 1-44 [10% Rain]	LW 1-44 [8% Rain]	LW 1-44 [9% Rain]
WORONORA RIVER	3.58	4.01	4.44	-19.2%	-9.5%
HONEYSUCKLE CREEK	0.52	0.66	0.80	-35.2%	-17.6%
LAKE WORONORA	3.24	3.58	3.91	-17.1%	-8.4%
WARATAH RIVULET	3.90	4.36	4.83	-19.1%	-9.7%
CREEK THROUGH LW1	1.05	1.20	1.34	-21.2%	-10.1%
All Streams	31.8	35.9	39.7	-19.9%	-9.7%

Overall, due to reduced water table levels, the percentage reduction in baseflow is similar to the assumed reduction in rain infiltration. Streams with lower baseflow are more severely affected; e.g. for a 20% reduction in rain infiltration, Honeysuckle Creek is predicted to suffer a 35% reduction in baseflow. On the other hand, for the same conditions, Lake Woronora's reduction is 17%. The anticipated climate change effects on baseflow in the Woronora Special Area are far greater than any changes in baseflow induced by mining (i.e. by more than 2 orders of magnitude).

Muller et al. (2008) investigated the impact of climate change on the water balance of open-cut mining and post-mining areas in Central Germany, using a coupled groundwater/soilwater model. As pit lakes accept groundwater discharge and increase the area of free-water evaporation over pre-mining conditions, open-cut mining is expected to exacerbate climate change impacts.

Longwall mining, on the other hand, is likely to have a negligible incremental effect on baseflow. However, there could be a marginal positive benefit in tempering the evapotranspiration reduction that will result from climate change, due to an initial reduction in regional water table levels close to groundwater discharge reaches.

8.0 MANAGEMENT AND MITIGATION MEASURES

Valley closure and valley bulging are important mechanisms that result in observed upsidence. Valley bulging occurs naturally but can be accelerated by underground mining. Any sudden change in the topography of a river bed will transfer a higher proportion of flow below ground, likely temporarily, as the new openings are in-filled by subsequent deposition of sediment. To date, there is no evidence that cracking in creek and river beds causes any net change in the overall water balance of a stream (Gilbert and Associates, 2008).

The main role of groundwater in the shallow groundwater system of the Southern Coalfield is to provide baseflow to streams and to support ecosystem function. Potential impacts to the local ecosystem are separately assessed in Appendix C (surface water assessment), Appendix D (aquatic ecology assessment) and Appendix G (terrestrial flora and fauna impact assessment) of the Environmental Assessment.

Localised surface water quality impacts will occur in the form of reduced dissolved oxygen and increased salinity, iron oxides and manganese where diverted shallow groundwater re-emerges downstream of an impact site. This is due to enhanced rock-water interactions as shallow groundwater flows past newly opened rock surfaces. Water quality impacts persist for only a short distance downstream of the groundwater discharge point, where iron causes discolouration of stream waters to an orange/brown colour, and can smother benthic organisms. Water quality impacts are likely to ameliorate naturally.

Near-surface fracturing can occur from horizontal tension at the edges of a subsidence trough. An impact on a perched water table level has been observed at one monitored site (UTGW2) above Longwall 14. Subsequent heavy rains were able to replenish the perched aquifer to its normal water level within 4-6 weeks of the mining impact event.

Above goaf zones there will be substantial changes in fracture porosity and permeability, due to opening up of existing joints, new fractures, and bed separation. Changes in hydraulic properties can cause substantial changes in groundwater heads and flow patterns. Permeability increases will have accompanying reductions in hydraulic gradients, with associated changes in groundwater levels and pressures. However, pronounced changes in groundwater levels can occur without any significant drainage into a mine, particularly from the Narrabeen Group rocks that form the overburden at the Metropolitan Colliery.

The groundwater pressures in the depressurised zone immediately above a goaf zone will recover slowly with time, over many decades, but this is of little consequence. The Narrabeen Group sandstones that overlie the mined coal seam are not regarded as having any economic value in the Southern Coalfield.

At the Metropolitan Colliery there will be an intermediate (constrained) zone in the overburden that maintains its integrity, and isolates shallow and deep aquifers. This means that river bed cracking due to longwall mining does not imply permanent loss of shallow water to deep mines.

At this time there is no evidence of permanent mining-induced changes in the groundwater levels of shallow aquifers in connection with streams and ecosystems.

Remediation of expected manageable impacts is focused on sealing of voids and fractures with grout (e.g. PUR), either as spot injections in river beds, or construction of grout curtains or blankets. These are further explained in the Environmental Assessment main text.

9.0 MODEL LIMITATIONS

The numerical model is designed to simulate the propagation of depressurisation effects throughout the entire aquifer system. It cannot simulate the effects of near-surface tensile cracking due to subsidence of the land surface.

The model also is designed to replicate the saturated part of the groundwater system close to land surface. It is not able to simulate the occurrence of near-surface perched water tables. Groundwater modelling suggests a negligible reduction in baseflow (Section 5.2). Due to the observed isolation between perched and regional water tables, the expectation is that there will be no effect on baseflow derived from perched aquifers.

At this stage the model has adopted uniform properties in layers and uniform rainfall recharge. As more data are gathered, the spatial distributions of aquifer properties and rainfall distribution can be refined.

The model also has assumed a uniformly fractured zone above the entire mined seam across all longwall panels, without recognition of partial protection above the chain pillars. As a result, the model is being conservative by overpredicting the likely magnitude of depressurisation effects. Chain pillar effects can be taken into account for mining operations by having a finer model grid or a variable grid with refinement only in the area of mining.

10.0 CONCLUSIONS

The data supports three separate groundwater systems:

- Deep groundwater system.
- Shallow groundwater system.
- Perched groundwater system - associated with swamps and outcropping sandstone.

Based on the analysis of the conceptual groundwater system based on piezometer measurements, there is expected to be:

- no dewatering of swamps from depressurisation at depth; and
- no loss of groundwater yield to the Woronora Reservoir.

As would be expected, a lateral hydraulic gradient towards mine workings has developed in the Lower Bulgo sequence (within the deep groundwater system at approximately 300 m depth) i.e. a depressurisation effect. This is in the opposite direction to the natural hydraulic gradient. There is a pronounced increase in vertical hydraulic gradient over current longwalls, as observed at the Longwall 10 goaf hole. Groundwater modelling, however, has demonstrated that most of the reduction in pressures at depth has been due to past mining at Darkes Forest and Helensburgh.

Based on groundwater modelling, there is expected to be:

- extensive depressurisation of aquifers beneath the Bald Hill Claystone;
- negligible reduction in cumulative average inflows to the Woronora Reservoir;
- a final mine inflow in the order of 0.5 ML/day to Longwalls 1-44 at the completion of mining; and
- eventual recovery of formation groundwater pressures over many decades.

11.0 REFERENCES

Alkhatib, M. and Merrick, N.P., 2006, Groundwater Simulation and Optimisation Modelling of the Kulnura-Mangrove Mountain Aquifer Systems. Final Report for Gosford-Wyong Councils Water Authority, Research Report NCGM 2006/14, November 2006, 170p.

Bangalay Botanical Surveys, 2008, Metropolitan Coal Project Baseline Flora Survey – Proposed Longwall Mining Area.

BHP Billiton (2006) Understanding Swamp Conditions Field Inspection Report – Summer 2006. Unpublished report.

BHP Billiton (2007) Understanding Swamp Conditions Field Inspection Report – Winter 2006 and Summer 2007. Unpublished report.

Biosis Research, 2007, Dendrobium Coal Mine and Elouera Colliery Flora and Fauna Environmental Management Program Annual Monitoring Report.

Dendrobium Technical Services Staff, 2007, Monthly Report No 42 to the Dams Safety Committee for the Period April 2007. File: DSC Monthly Report April07.pdf.

Department of Land and Water Conservation, 2002, The NSW State Groundwater Dependent Ecosystem Policy.

Department of Planning, 2008, Impacts of underground coal mining on natural features in the Southern Coalfield: strategic review.

Earth Tech, 2003, Swamps of the Woronora Plateau: Understanding Swamp Conditions. BHP Billiton – Illawarra Coal.

FloraSearch and Western Research Institute (2008) Metropolitan Coal Project Terrestrial Flora and Fauna Impact Assessment.

Geosensing Solutions, 2008, A compilation of surface geological features in the western portion of Metropolitan Colliery. April 2008.

GHD Geotechnics, 2007, Dendrobium Area 3, Predicted Hydrogeologic Performance. Attachment F to the Dendrobium Area 3 Environmental Assessment.

Gilbert and Associates, 2007, Review of Possible Effects of Subsidence on Surface Drainages for Subsidence Management Plan (Longwall Panels 18 to 19A).

Gilbert and Associates, 2008, Metropolitan Coal Project Surface Water Assessment.

Grey, I. and Ross, J., 2003, Groundwater Investigation for Contingency Drought Relief in the Sydney Region – Results of Desk Study. Parsons Brinckerhoff Report 2114127A PR_2984 for Sydney Water Corporation and Sydney Catchment Authority.

Hatton, T. and Evans, R., 1998, Dependence of ecosystems on groundwater and its significance to Australia. LWRDC Occasional Paper No 12/98.

Hunt, R. J., Walker, J. F. and Doherty, J., 2008, Using GSFLOW to simulate climate change in a northern temperate climate. In: Poeter, Hill, & Zheng, MODFLOW and More 2008: Ground Water and Public Policy - Conference Proceedings, Golden Colorado, 109-113.

Kamps, P., Nienhuis, P. and Witte, F., 2008, Effects of climate change on the water table in the coastal dunes of the Amsterdam Water Supply. In: Poeter, Hill, & Zheng, MODFLOW and More 2008: Ground Water and Public Policy - Conference Proceedings, Golden Colorado, 125-129.

KBR, 2008, Upper Nepean (Kangaloon) Borefield Project Environmental Assessment. Report prepared for the Sydney Catchment Authority.

Keith, D., 1994, Floristics, structure and diversity of natural vegetation in the O'Hares Creek catchment, south of Sydney. Cunninghamia 3(3) pp. 543-594. Royal Botanic Gardens, Sydney.

Keith, D., Rodoreda, S., Holamn, L. and Lemmon, J., 2006, Monitoring Change in Upland Swamps in Sydney's Water Catchments: the Role of Fire and Rain. DEC and Sydney Catchment Authority.

Mack, T. J., 2008, Simulation of water use increases and potential climate change on the ground-water availability of southeastern New Hampshire. In: Poeter, Hill, & Zheng, MODFLOW and More 2008: Ground Water and Public Policy - Conference Proceedings, Golden Colorado, 114. [Abstract]

McDonald, M.C. and Harbaugh, A.W., 1988, MODFLOW, A Modular Three-Dimensional Finite Difference Groundwater Flow Model. U.S. Geological Survey, Open File Report 91-536, Denver.

Merrick, N. P., 2007, Groundwater information provided by piezometric monitoring in the Longwall 10 goaf hole at Metropolitan Colliery. AccessUTS Pty Ltd report for Helensburgh Coal Pty Ltd. Project C07/44/001, September 2007, 13p.

Moffitt, R. S., 2000, A Compilation of the Geology of the Southern Coalfield: Notes to Accompany the 1:100000 Southern Coalfield Geological Map. Department of Mineral Resources Geological Survey Report No. GS1998/277.

MSEC, 2008, The prediction of subsidence parameters and the assessment of mine subsidence impacts on natural features and surface infrastructure resulting from the proposed extraction of proposed Longwalls 20 to 44 at Metropolitan Colliery in support of an Environmental Assessment. Report prepared for Helensburgh Coal Pty Ltd.

Muller, M., Mansel, H. and Pfutzner, B., 2008, Investigating the influence of climate change on the water balance of mining and post-mining areas using coupled groundwater/surface water modelling. In: Poeter, Hill, & Zheng, MODFLOW and More 2008: Ground Water and Public Policy - Conference Proceedings, Golden Colorado, 115-119.

Russell, G.N., 2007, Hawkesbury Sandstone groundwater attributes and geological features. Poster paper in CD Proceedings, 'Hydrogeology over the Years' UTS/UNSW 20th Anniversary Symposium, July 2007.

SCA, 2007a, SCA provides information on Kangaloon pumping trial to Federal Government. Website: http://www.sca.nsw.gov.au/news/media/103.html Date accessed: 10 October 2007.

SCA, 2007b, The Design of a Hydrological and Hydrogeological Monitoring Program to Assess the Impact of Longwall Mining in SCA Catchments. Draft for Discussion.

SCT Operations Pty Ltd, 2007, Summary of Results of Longwall 10 Goaf Hole Monitoring. Report No. MET3131 for Helensburgh Coal Pty Ltd, 30 May 2007. 16p & Appendices & CD.

SCT Operations Pty Ltd, 2008, Preliminary Results of VW Piezometer installation In Exploration Hole PM02.

Tomkins, K.M. and Humphreys, G.S., 2006, Technical Report 2: Upland swamp development and erosion on the Woronora Plateau during the Holocene. Sydney Catchment Authority and Macquarie University, Sydney Collaborative Research Project.

Waring, C., Hankin, S., and Peterson, M., 2007, Longwall 10 Goaf Hole Hydro-Geophysical and Hydro-Geochemical Investigations. ANSTO Report C-949 for Metropolitan Colliery, June 2007. 20p.

Young, A., 1986, The geomorphic development of dells (upland swamps) on the Woronora Plateau NSW. *Zeitschrift fur Geomorphologie* **30**, 317-327.

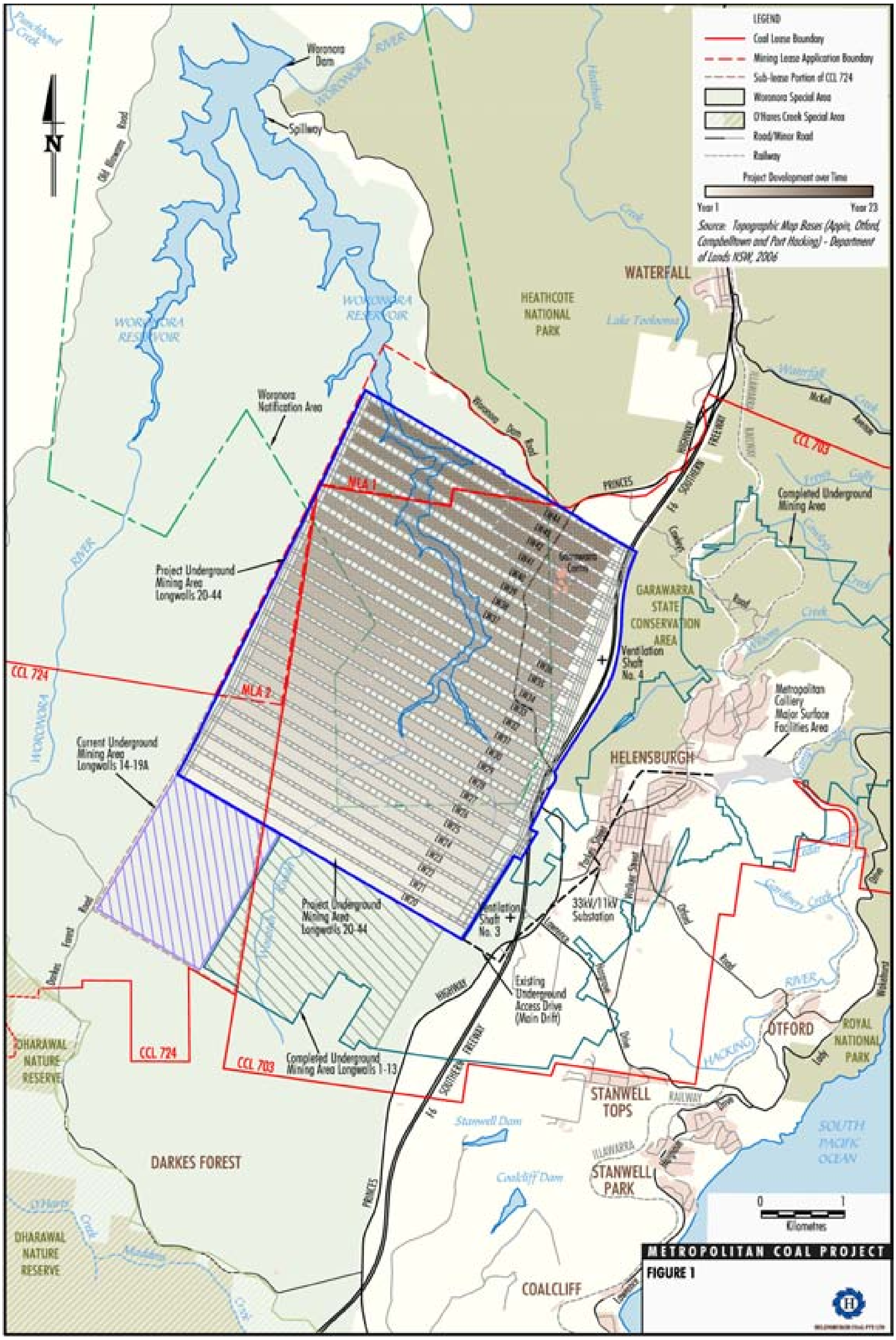


Figure 1. Project location.

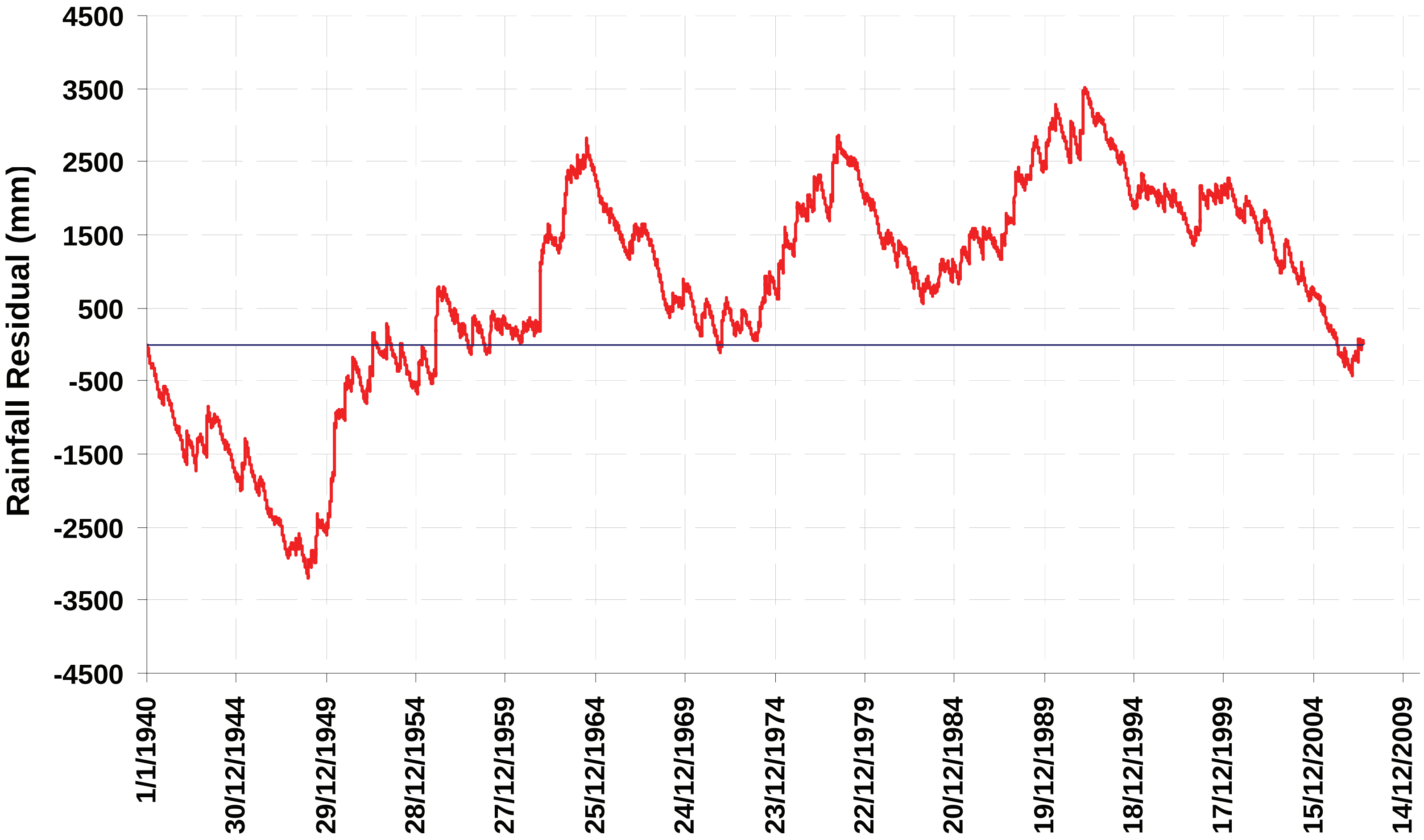


Figure 2. Rainfall – Residual Mass Curve (since 1940) [from Gilbert and Associates, 2008].

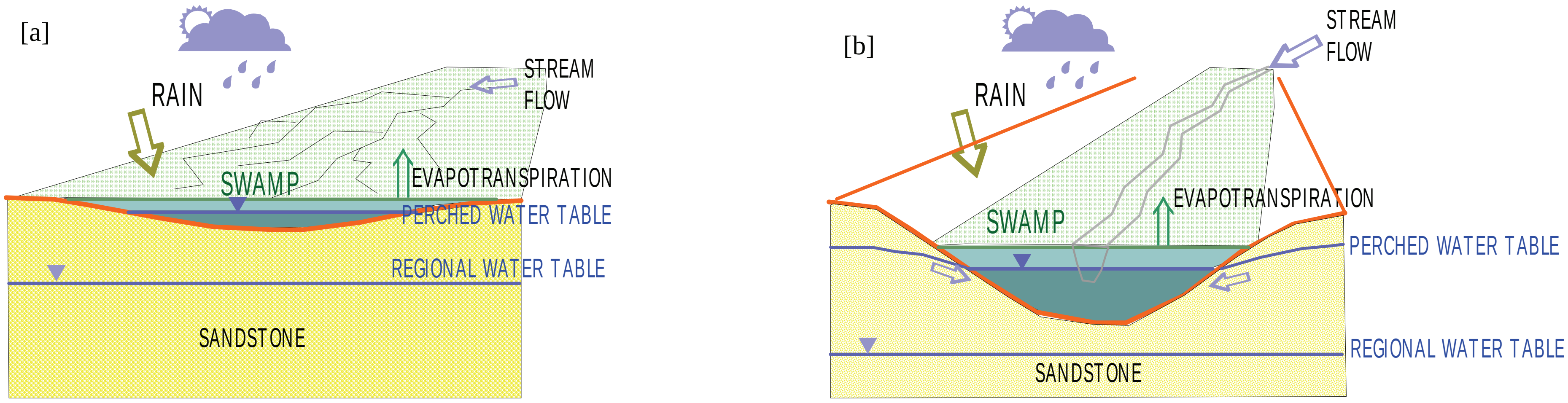


Figure 3. Conceptual model of upland swamps:
[a] headwater upland swamp; [b] in-valley upland swamp

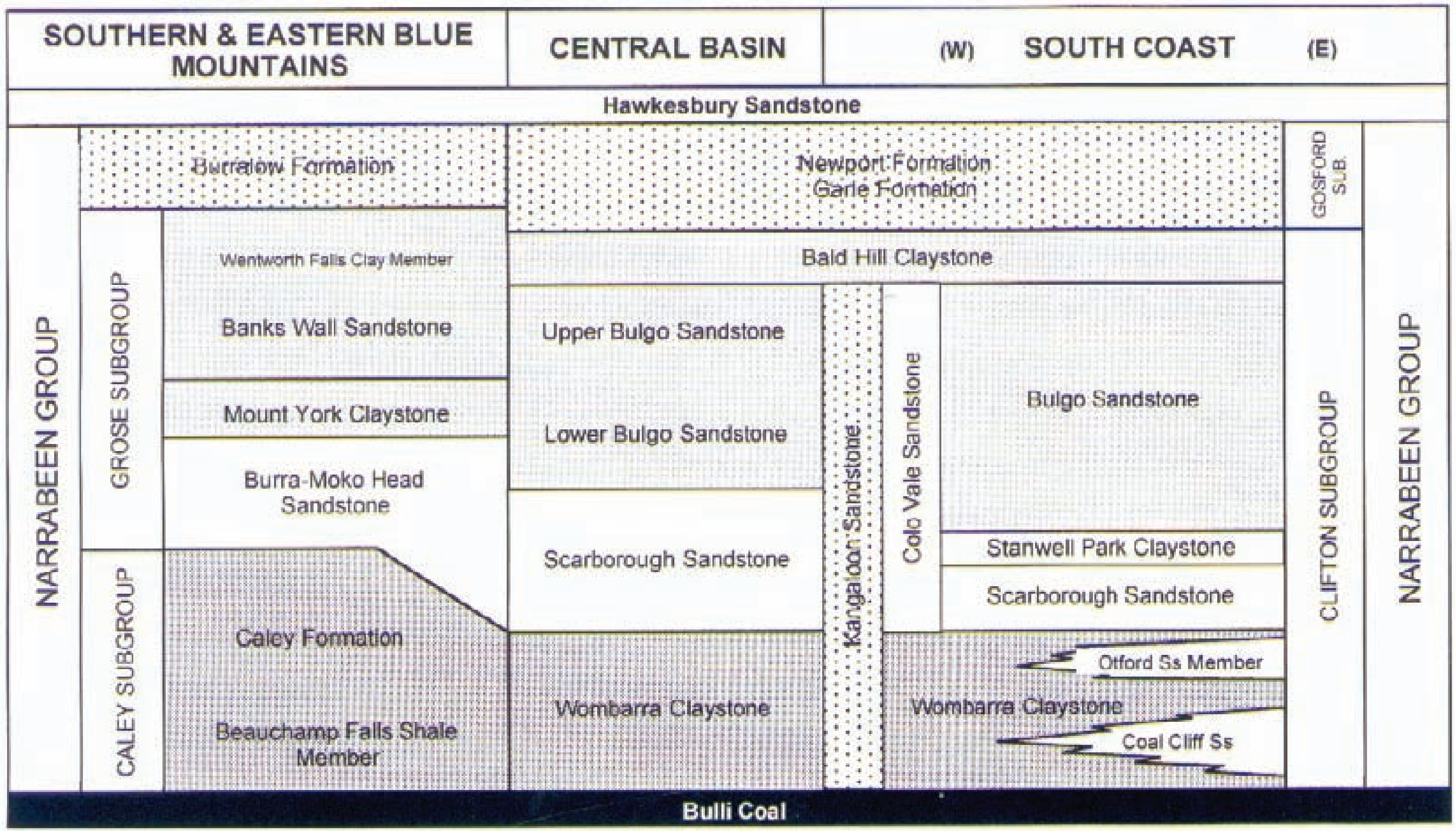


Figure 4. General stratigraphy and facies changes across the Narrabeen Group from the Southern Coalfield (right) to the Western Coalfield (left) [from Moffitt, 2000].

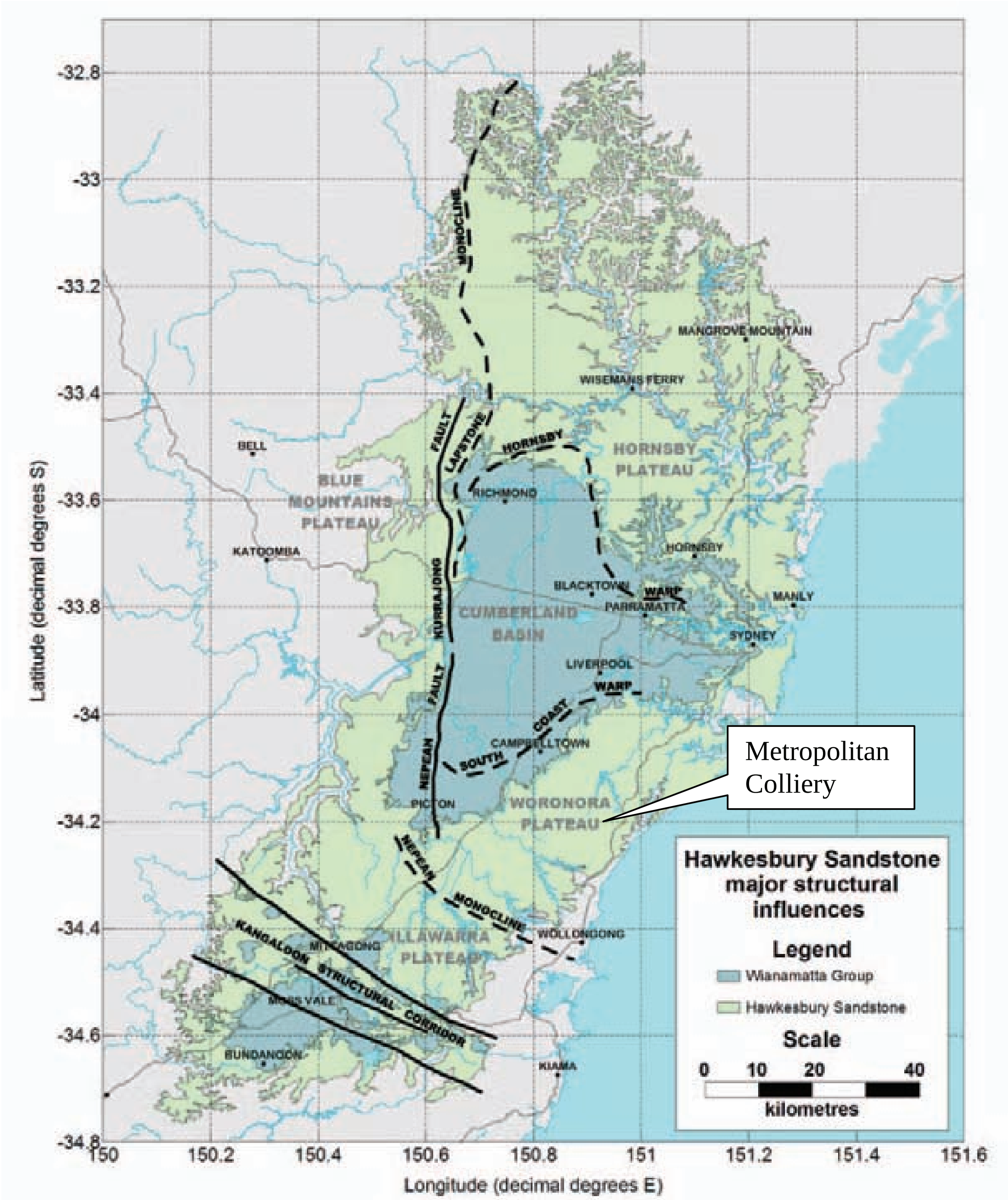


Figure 5. Hawkesbury Sandstone outcrop extent [from Russell, 2007].

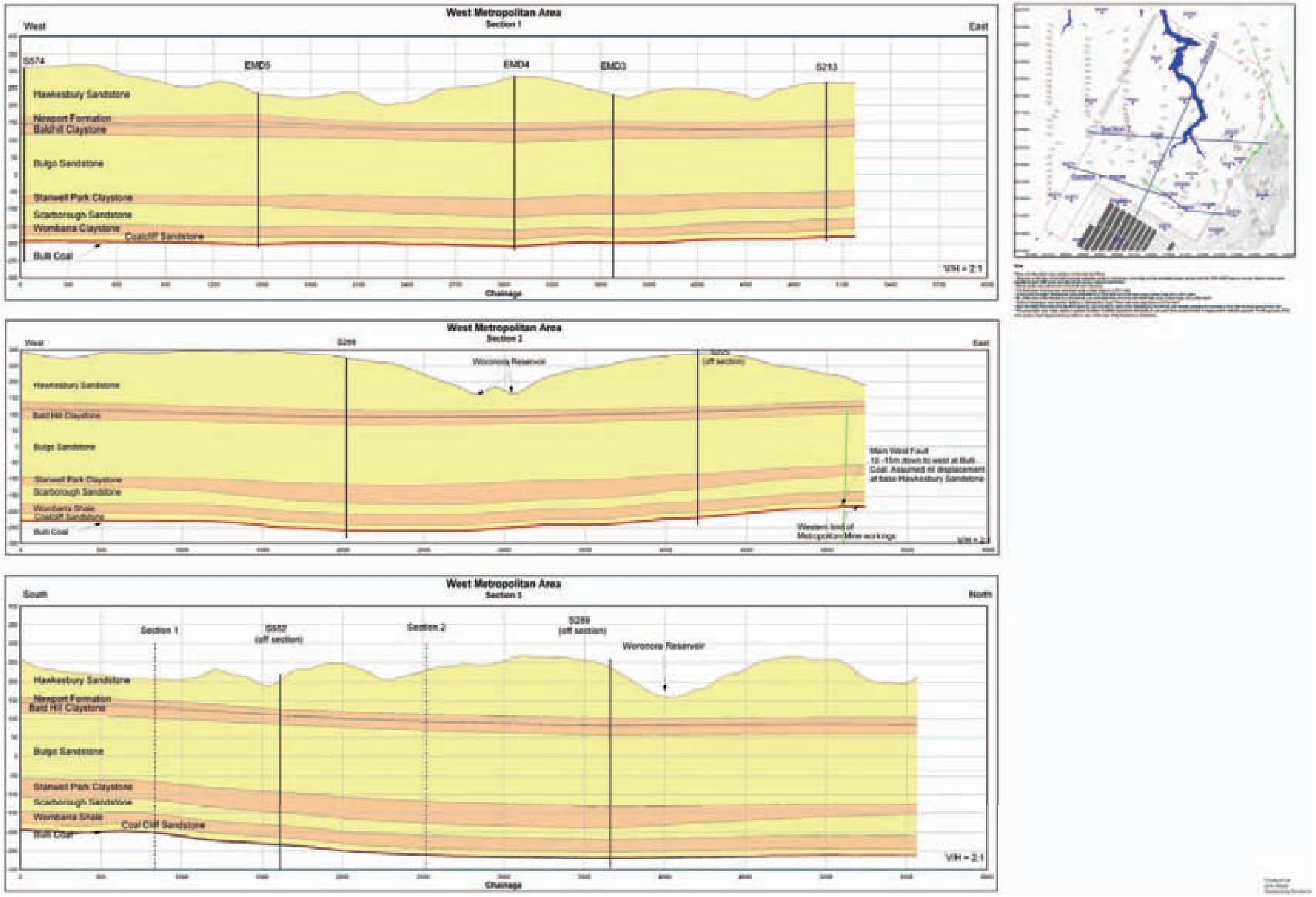


Figure 6. Metropolitan Geological Cross Sections [from Geosensing Solutions, 2008].

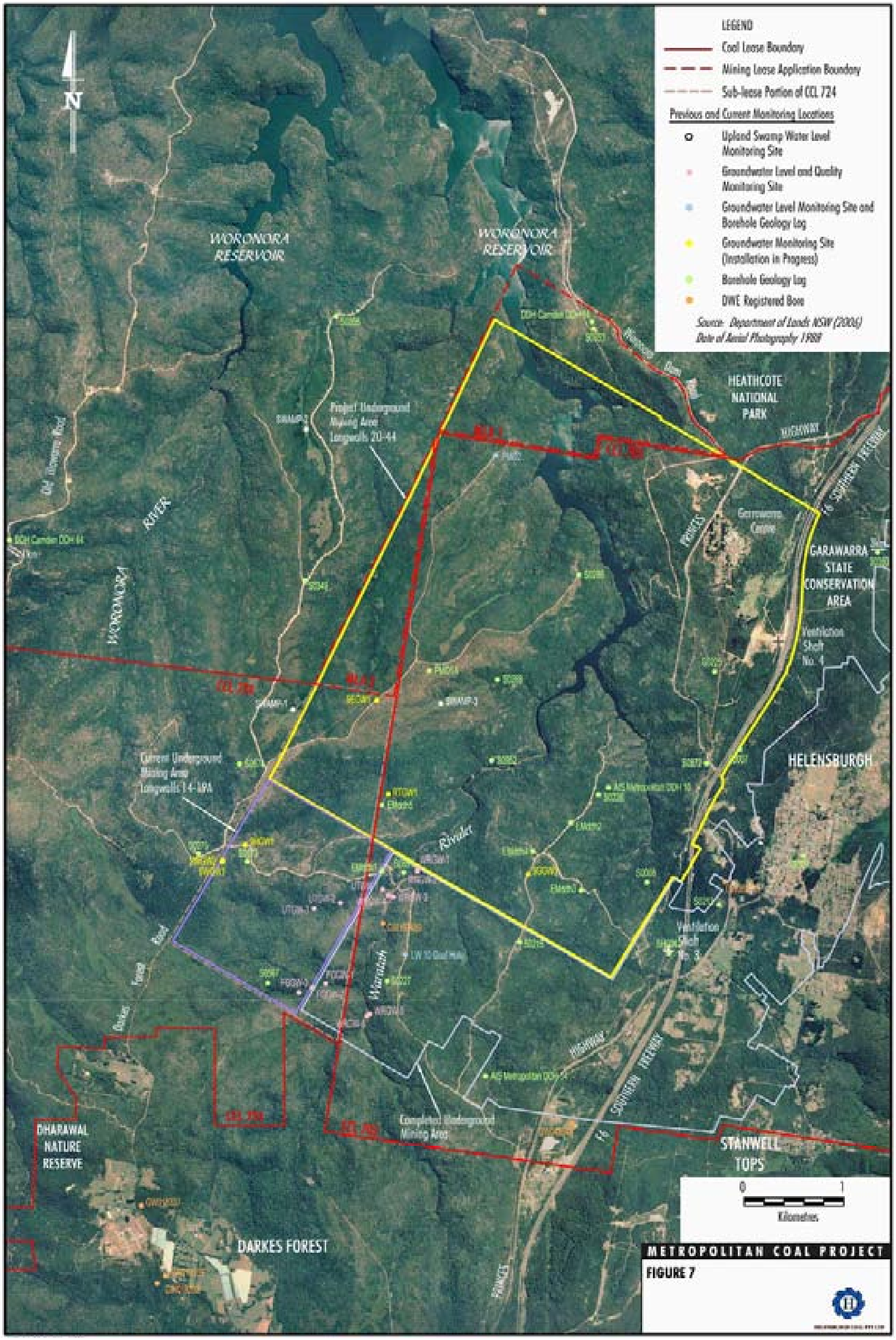


Figure 7. Locations of groundwater monitoring sites, borehole geology logs and DWE registered bores.

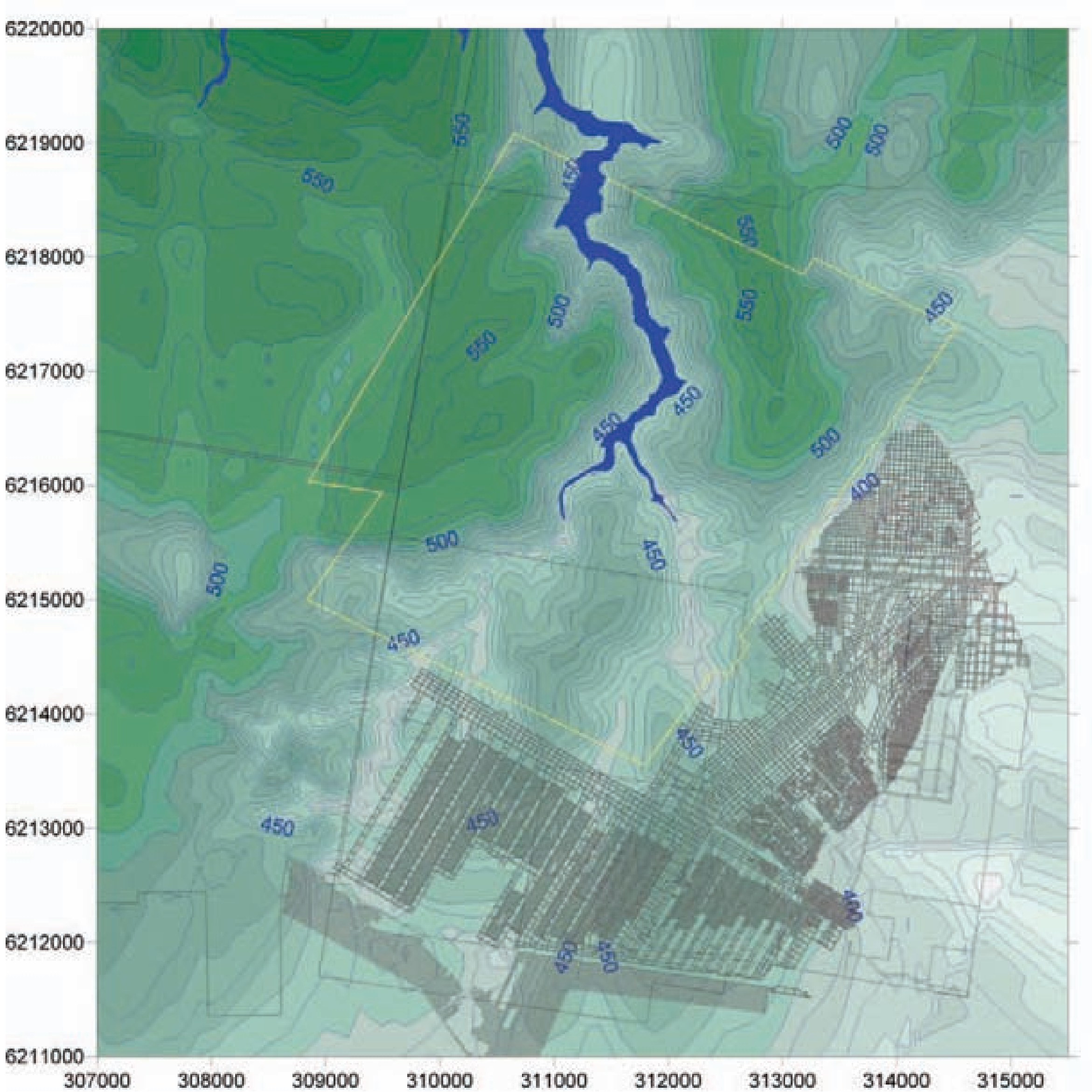


Figure 8. Depth of cover contours [from Geosensing Solutions, 2008].

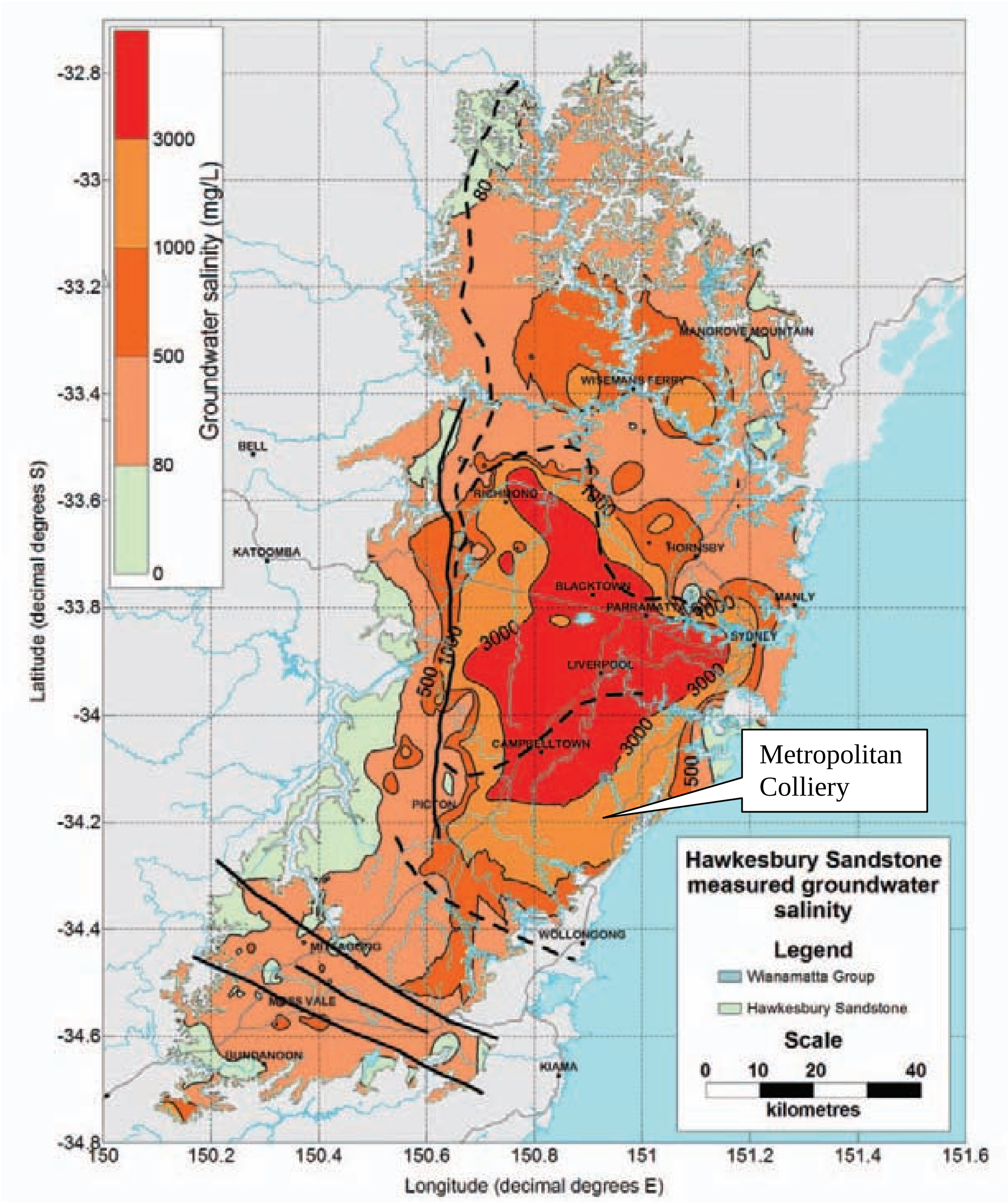


Figure 9. Groundwater salinity pattern in the Hawkesbury Sandstone [from Russell, 2007].

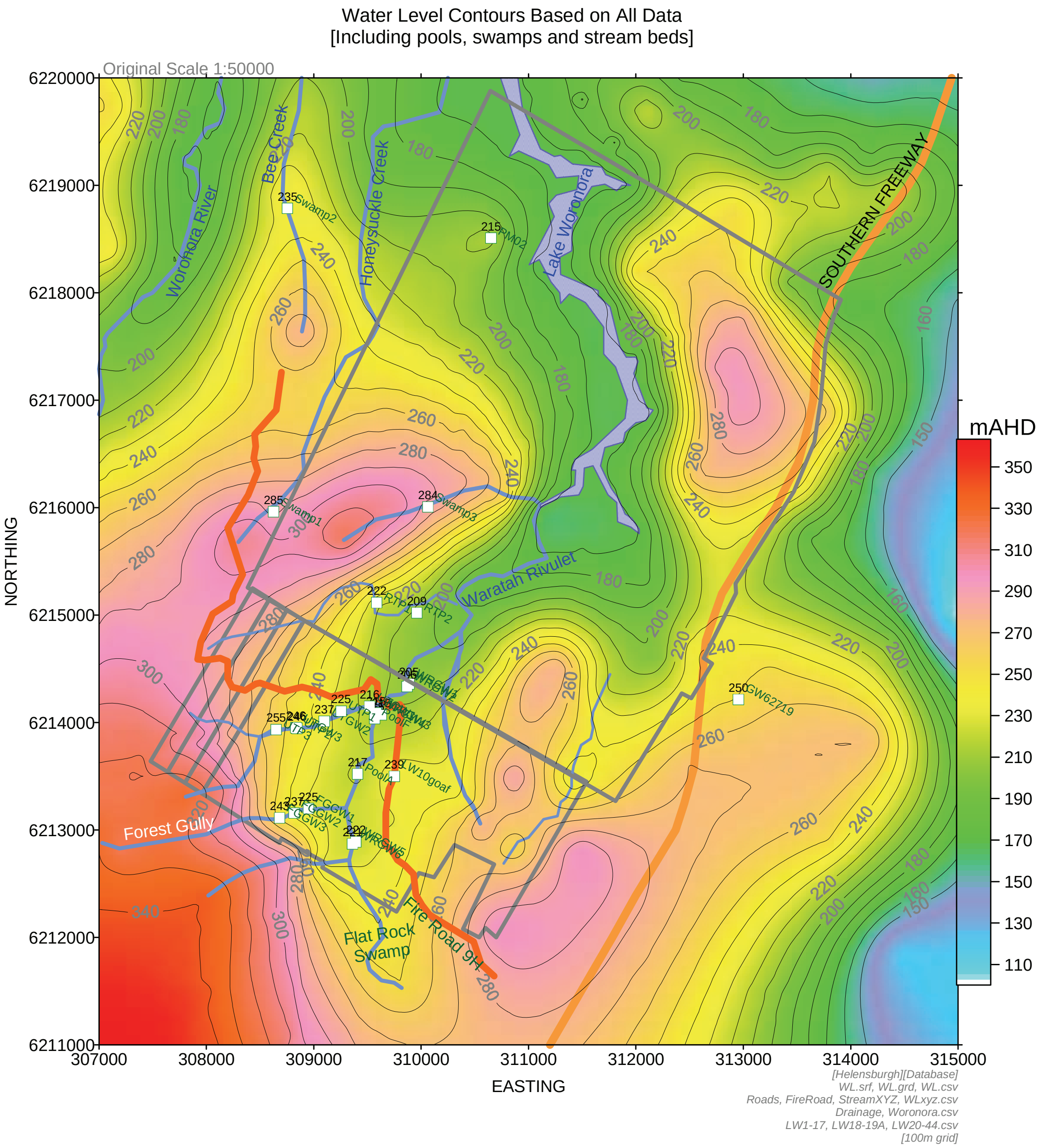


Figure 10. Inferred groundwater level contours (mAHD), on the assumption that groundwater levels are equal to streambed elevations.

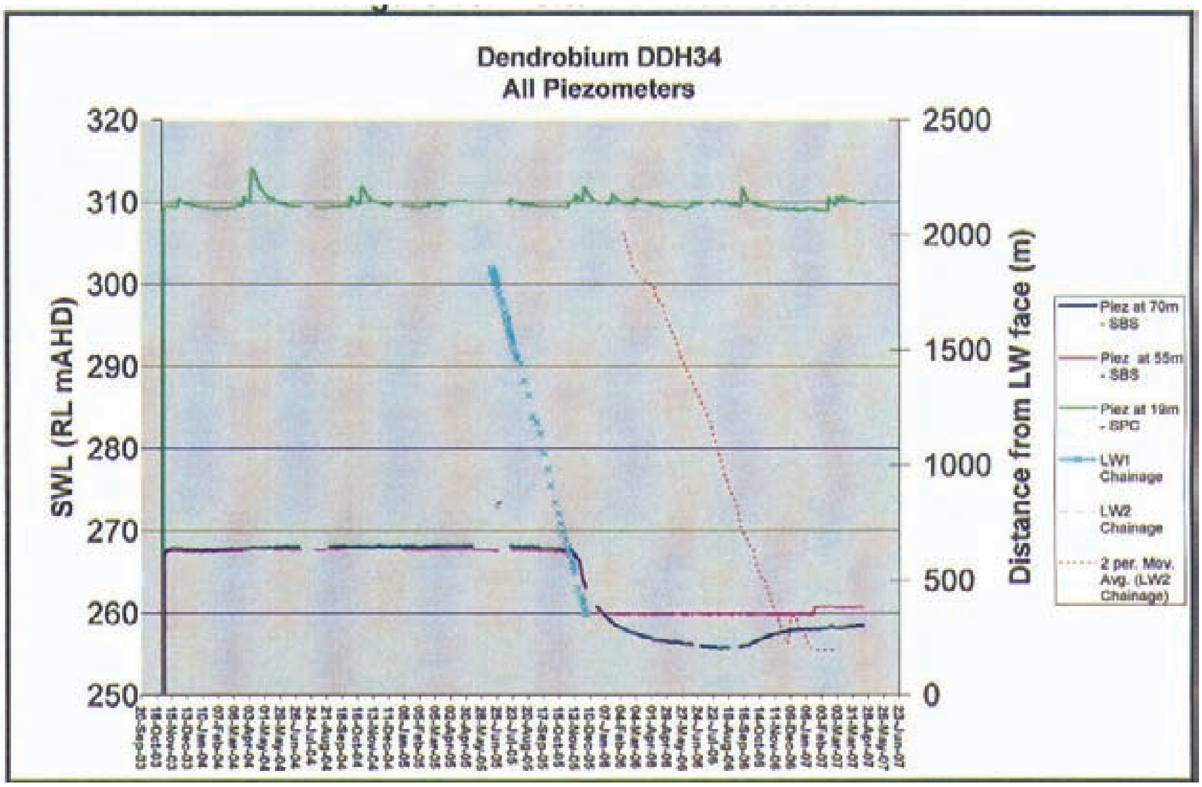


Figure 11. Time variations in total head at Dendrobium Area 1 Site 4: Bore DDH34A [from Dendrobium Technical Services Staff, 2007 (with permission)].

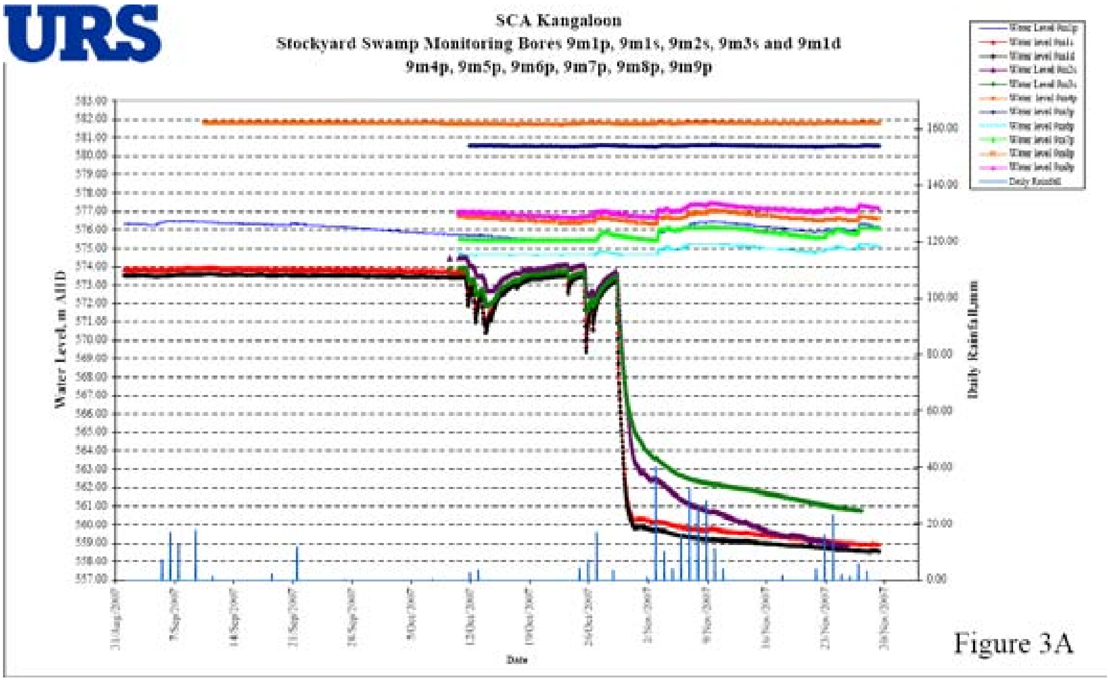


Figure 12. Kangaloon swamp monitoring for a pumping trial beneath Stockyard Swamp [from KBR (2008) – Upper Nepean (Kangaloon) Borefield Project].

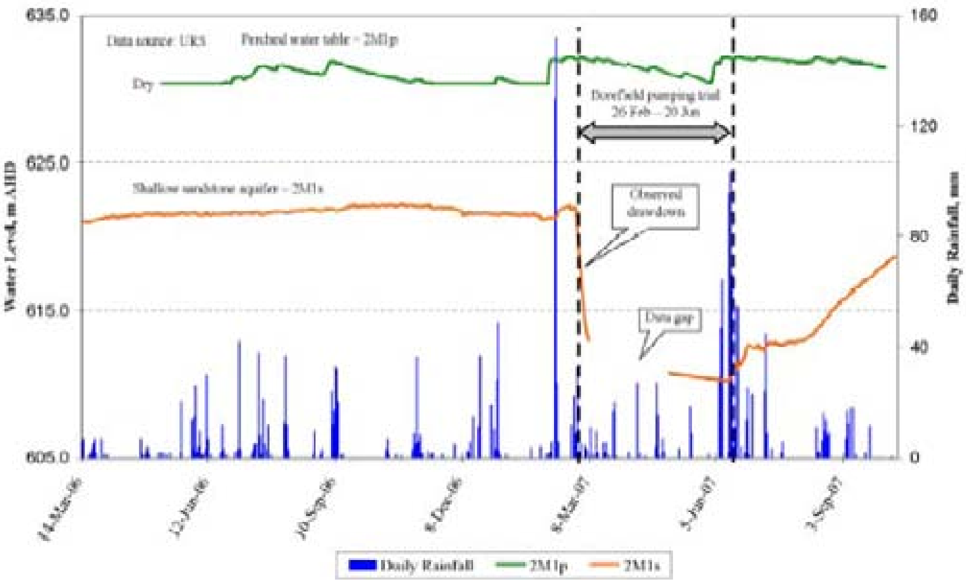


Figure 13. Kangaloon swamp monitoring for a pumping trial beneath Butlers Swamp [from KBR (2008) – Upper Nepean (Kangaloon) Borefield Project].

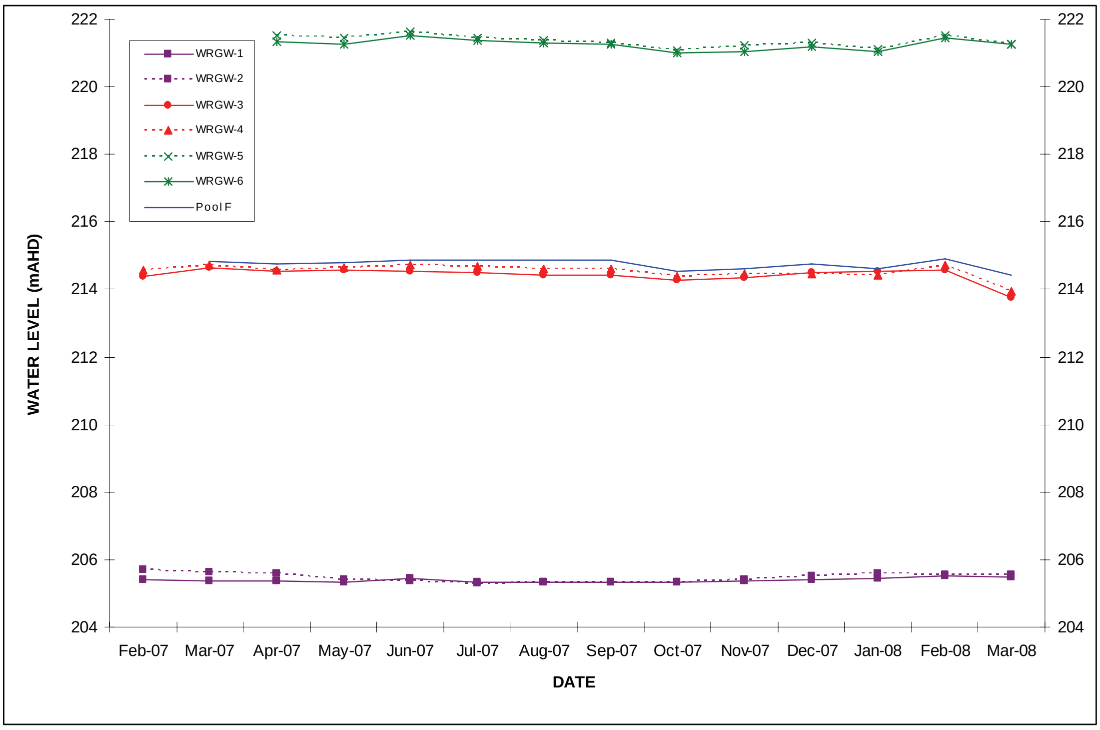


Figure 14. Month-averaged groundwater levels (mAHD) along Waratah Rivulet, compared with Pool F water level.

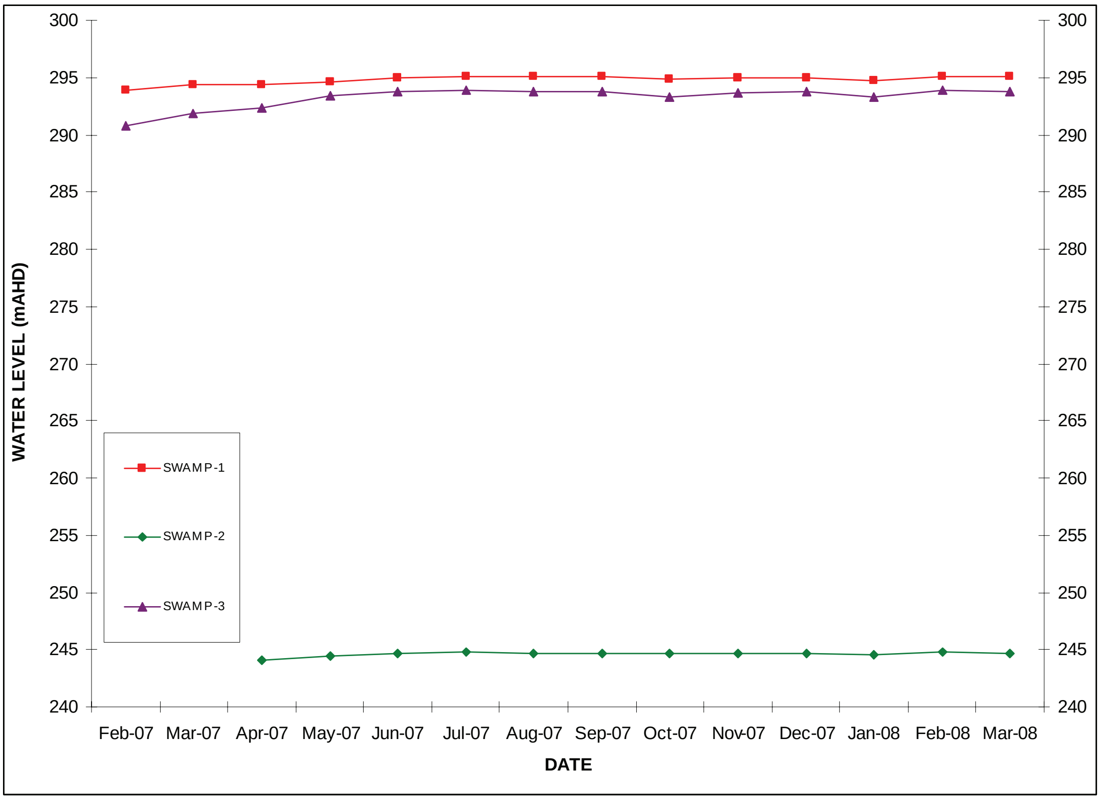


Figure 15. Month-averaged perched groundwater levels (mAHD) in upland swamps.

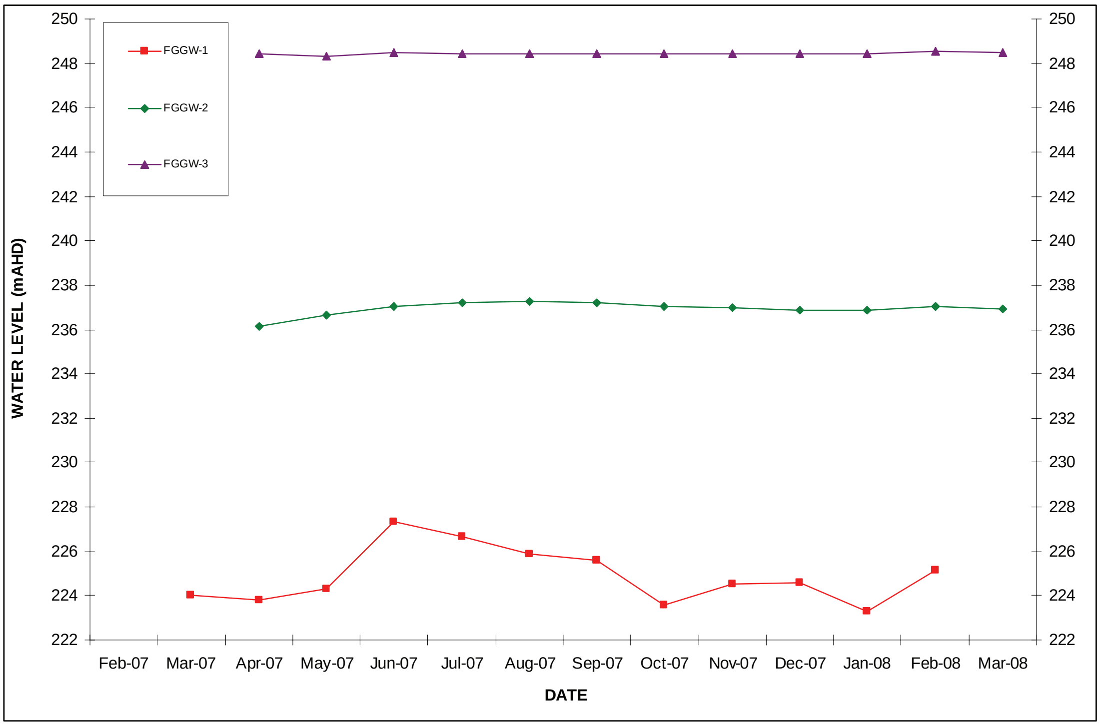


Figure 16. Month-averaged groundwater levels (mAHD) along Forest Gully.

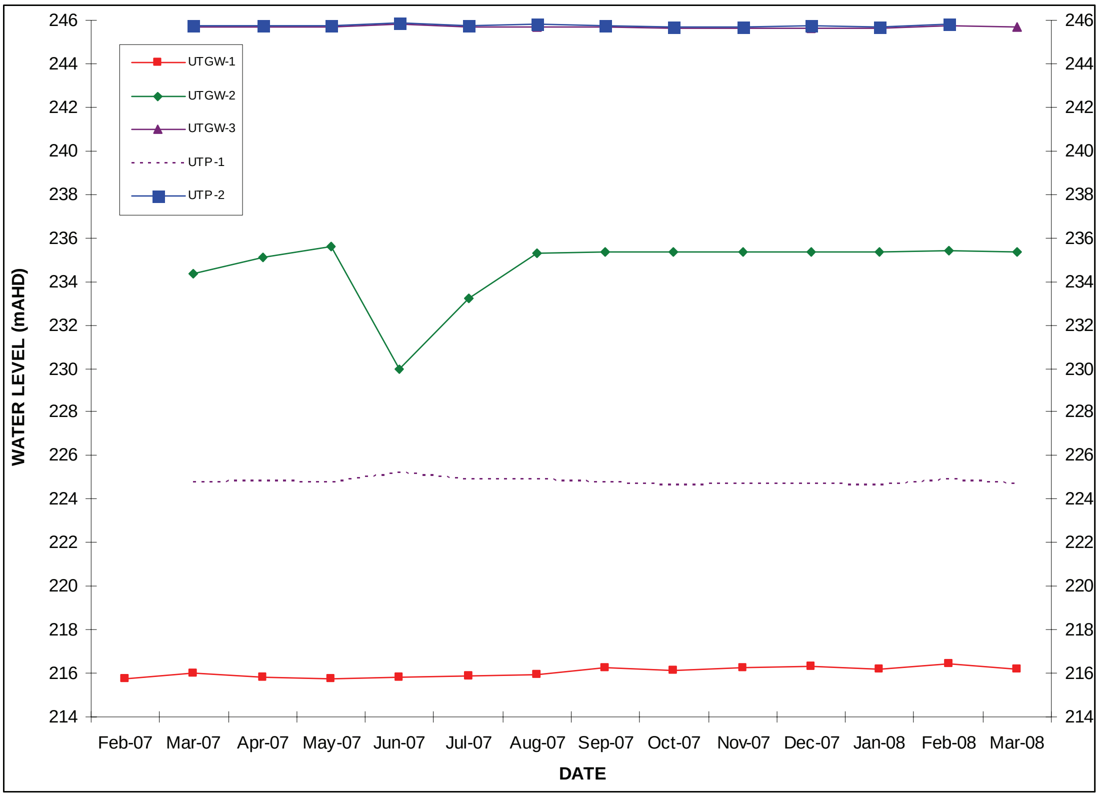


Figure 17. Month-averaged groundwater levels (mAHD) along Unnamed Tributary, compared with pool water levels at UTP1 and UTP2.

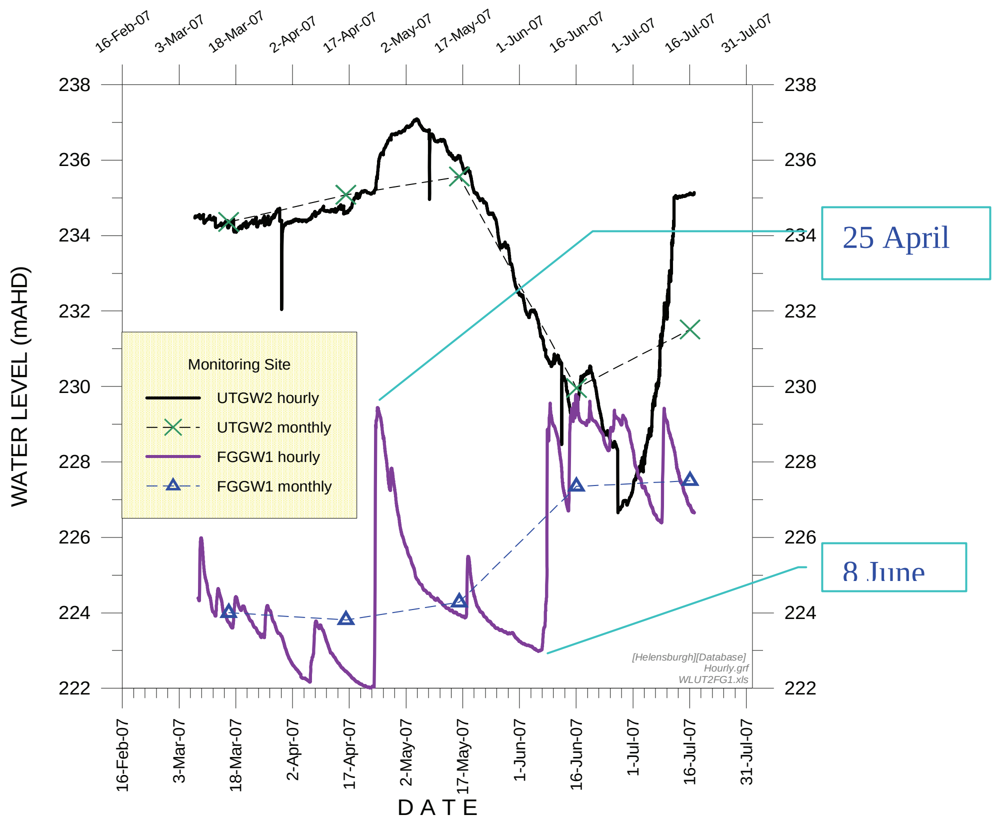


Figure 18. Hourly and month-averaged groundwater levels (mAHD) along Unnamed Tributary at monitoring bore UTGW2 and Forest Gully at monitoring bore FGGW1.

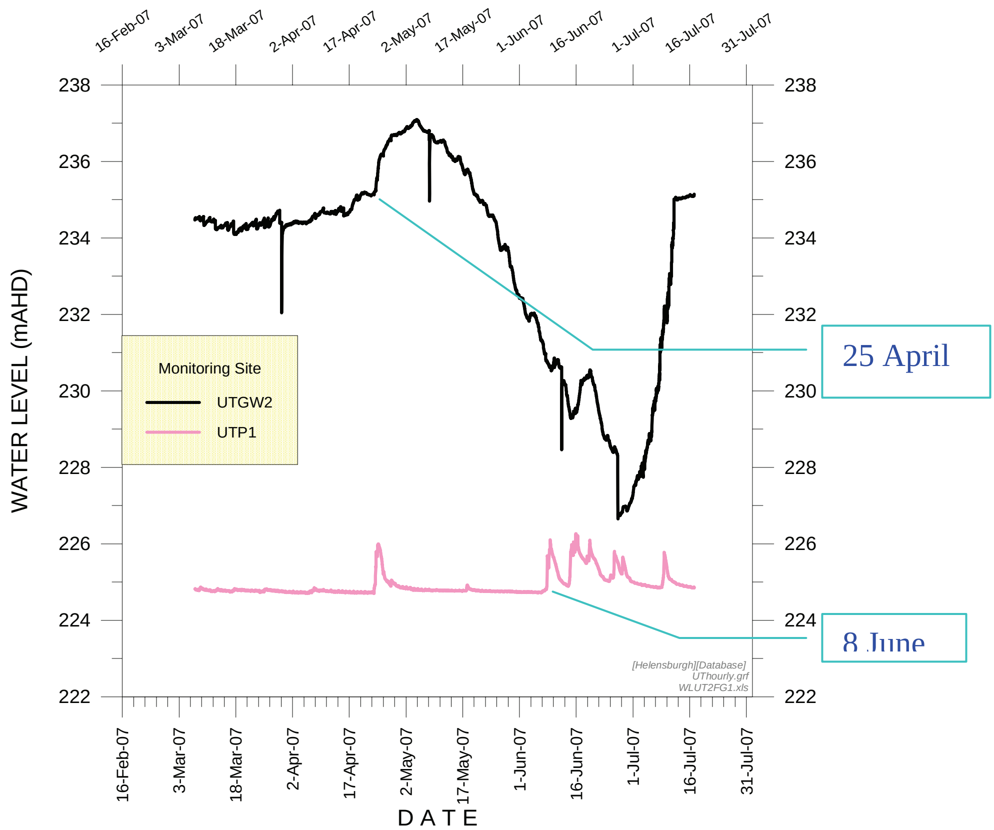


Figure 19. Hourly groundwater levels (mAHD) along Unnamed Tributary at monitoring bore UTGW2 and monitoring pool UTP1.

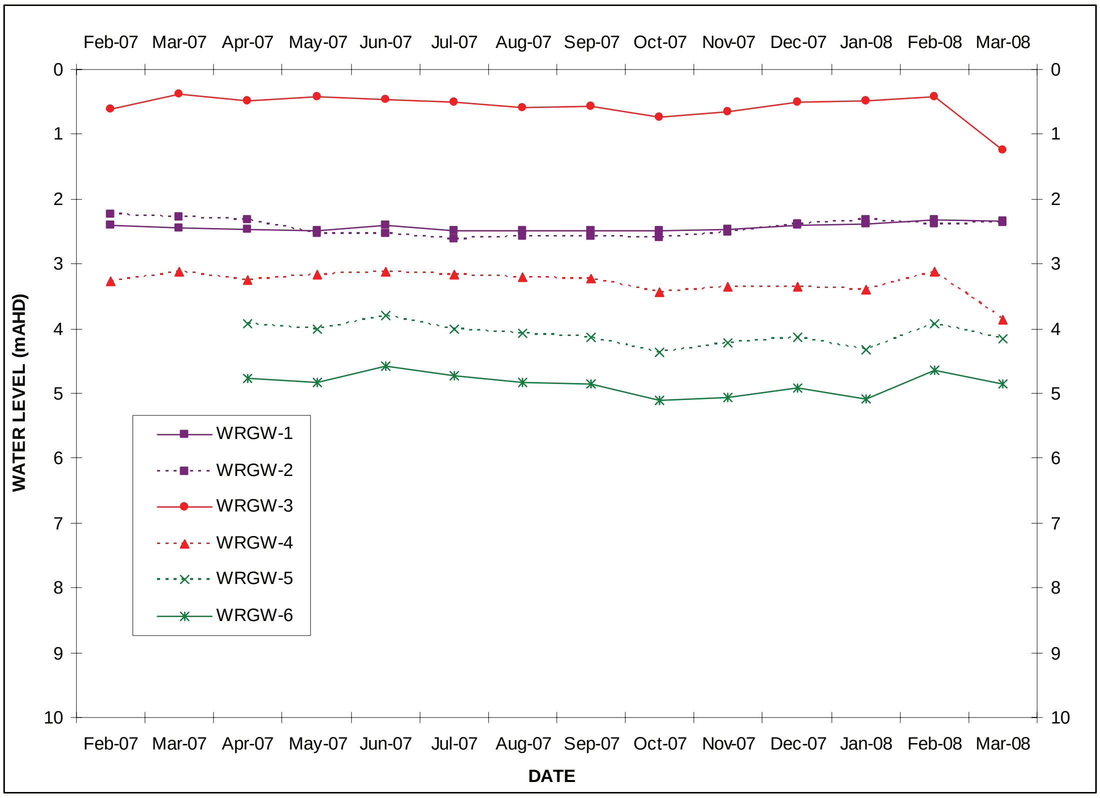


Figure 20. Month-averaged depths to groundwater (m) along Waratah Rivulet.

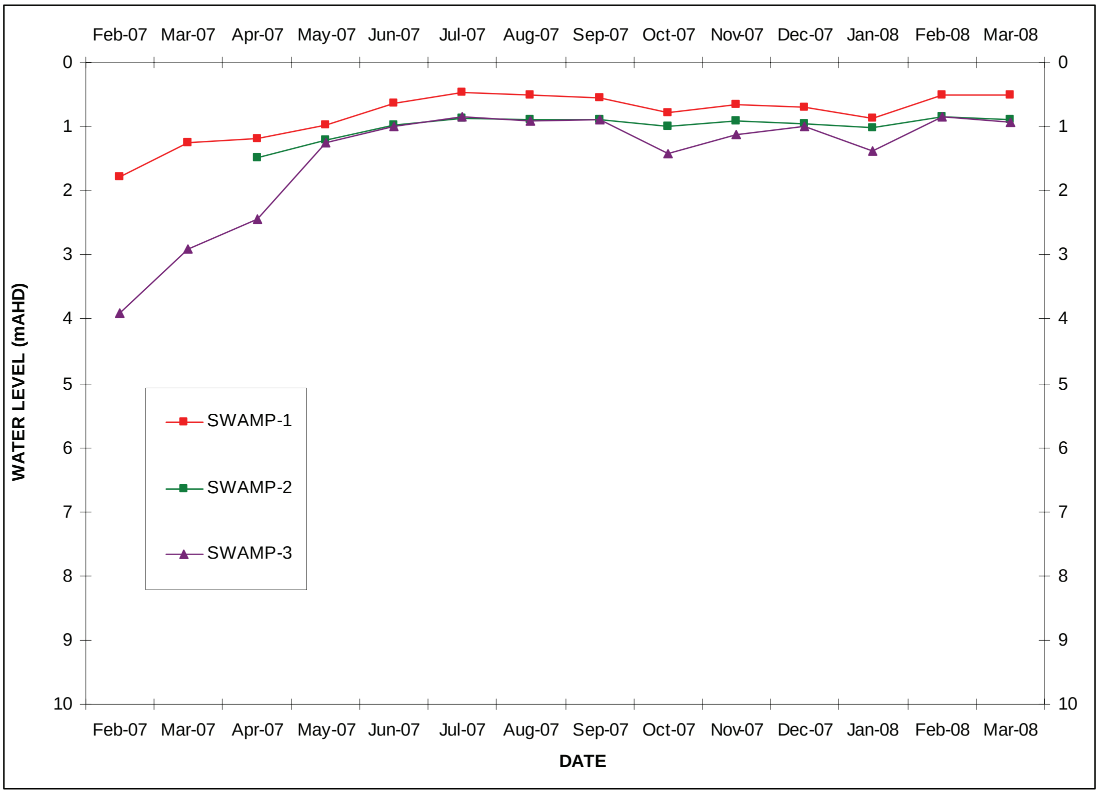


Figure 21. Month-averaged depths to perched groundwater (m) in upland swamps.

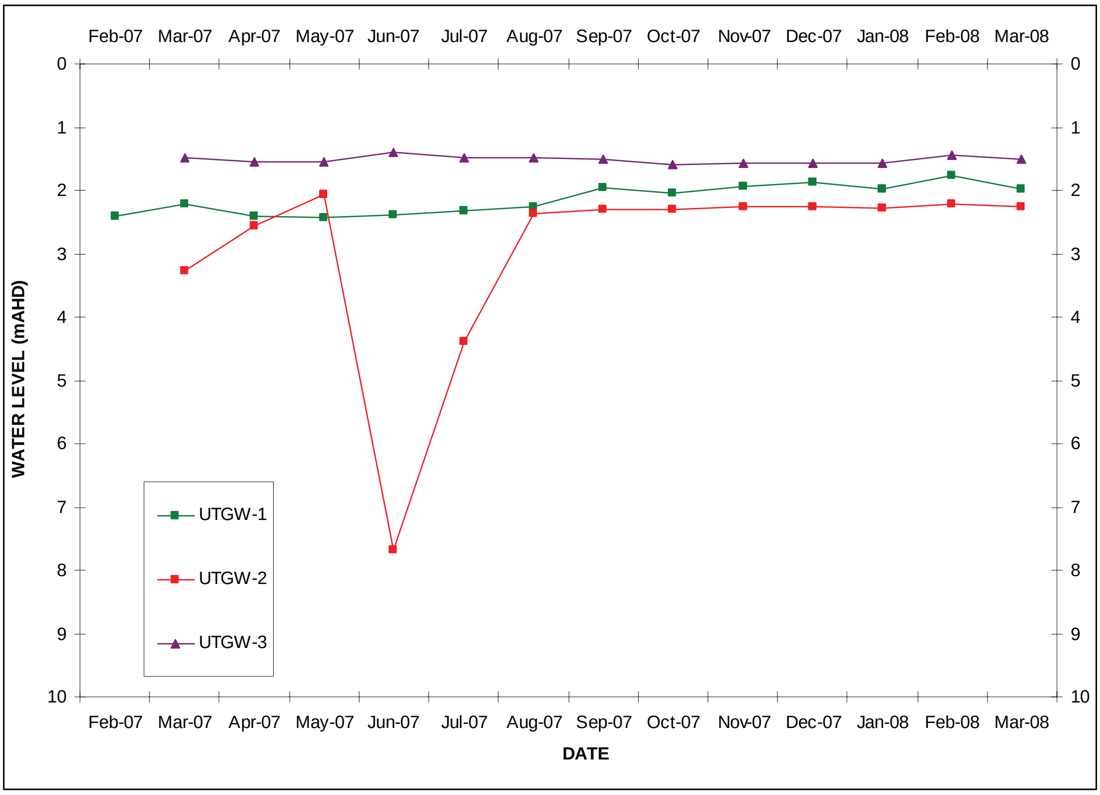


Figure 22. Month-averaged depths to groundwater (m) along Unnamed Tributary.

Figure 23. Month-averaged depths to groundwater (m) along Forest Gully.

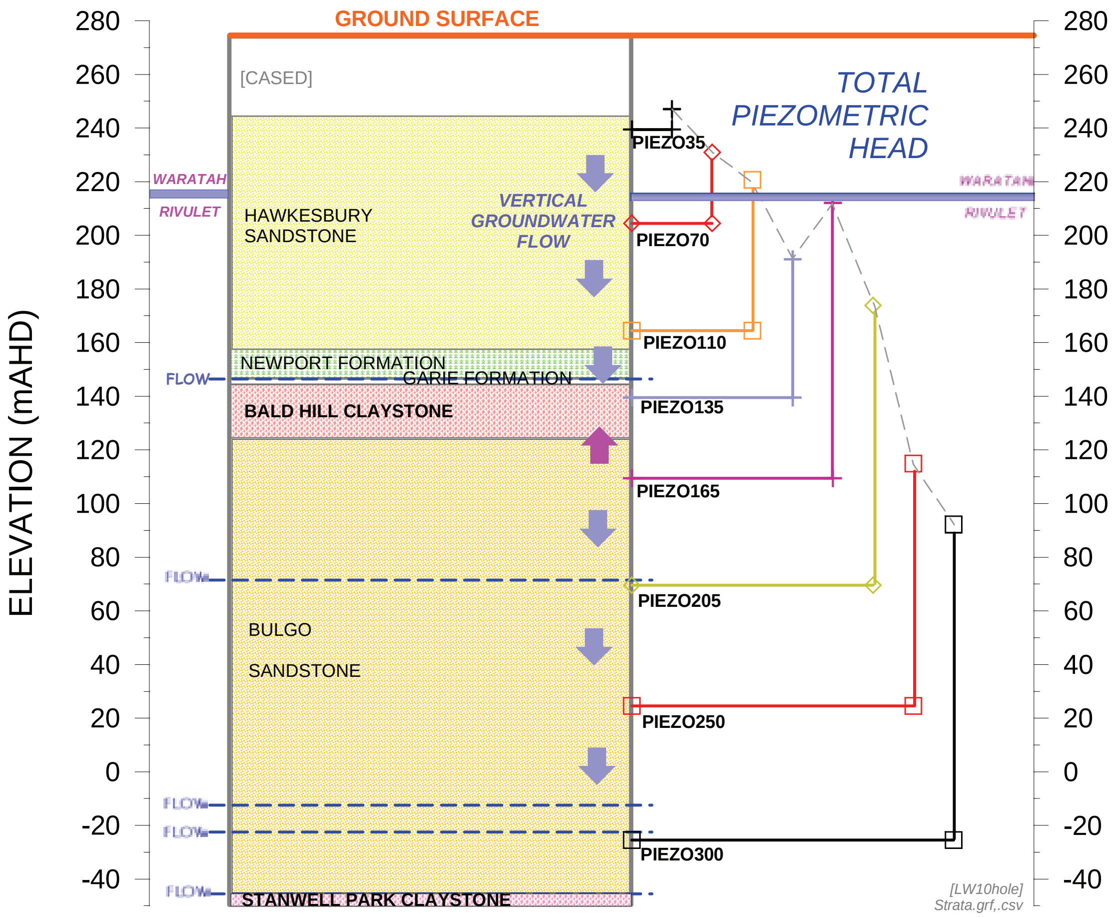


Figure 24. Vertical groundwater flow directions and relative elevations of piezometers, averaged total piezometric heads and Waratah Rivulet Pool A level in the context of the stratigraphic section at the Longwall 10 goaf hole.

.

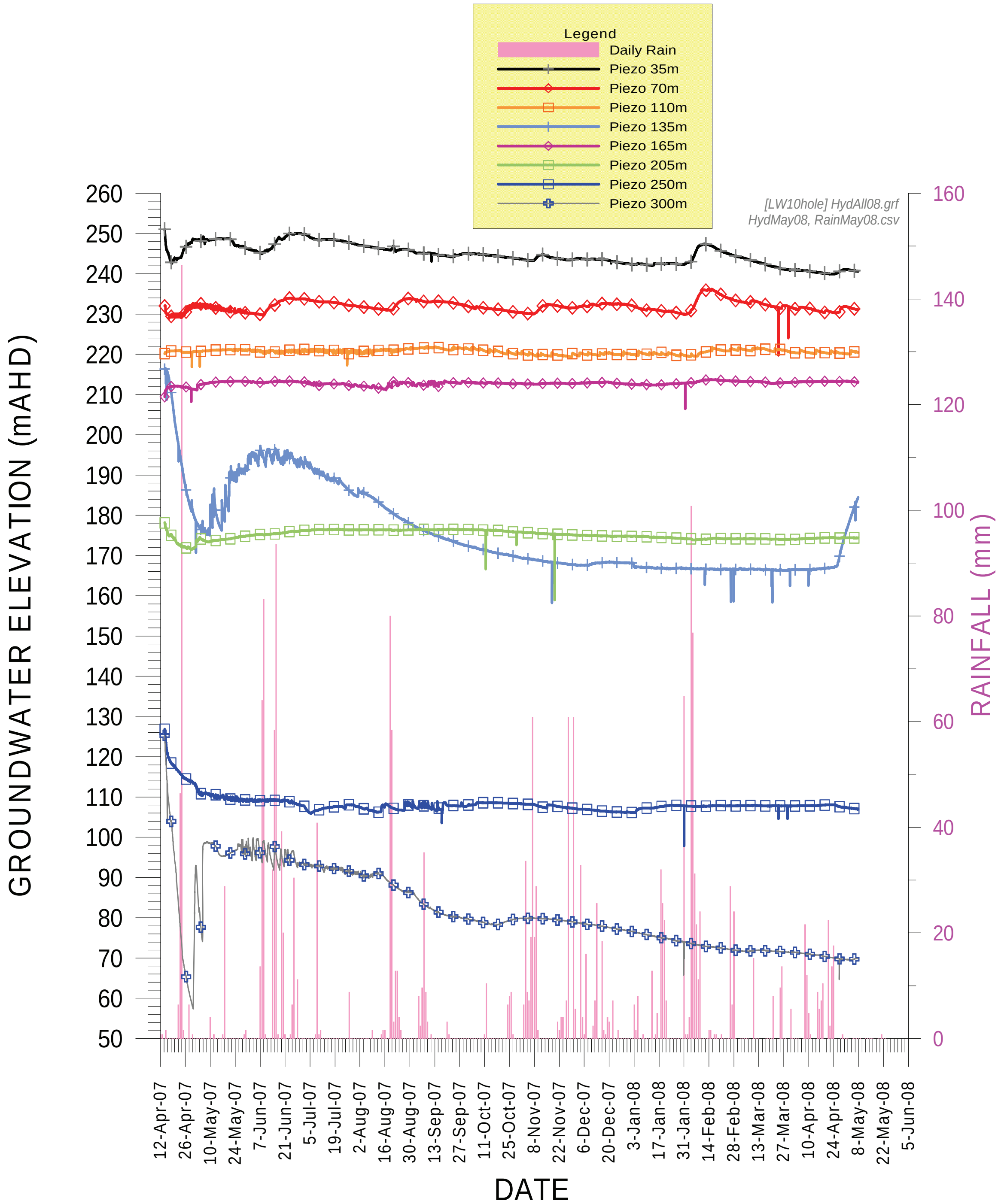


Figure 25. Time variations in total groundwater head at all piezometers in the Longwall 10 goaf hole.

[Note: Daily rainfall at pluviometer PV1 on Waratah Rivulet is shown as a bar graph.]

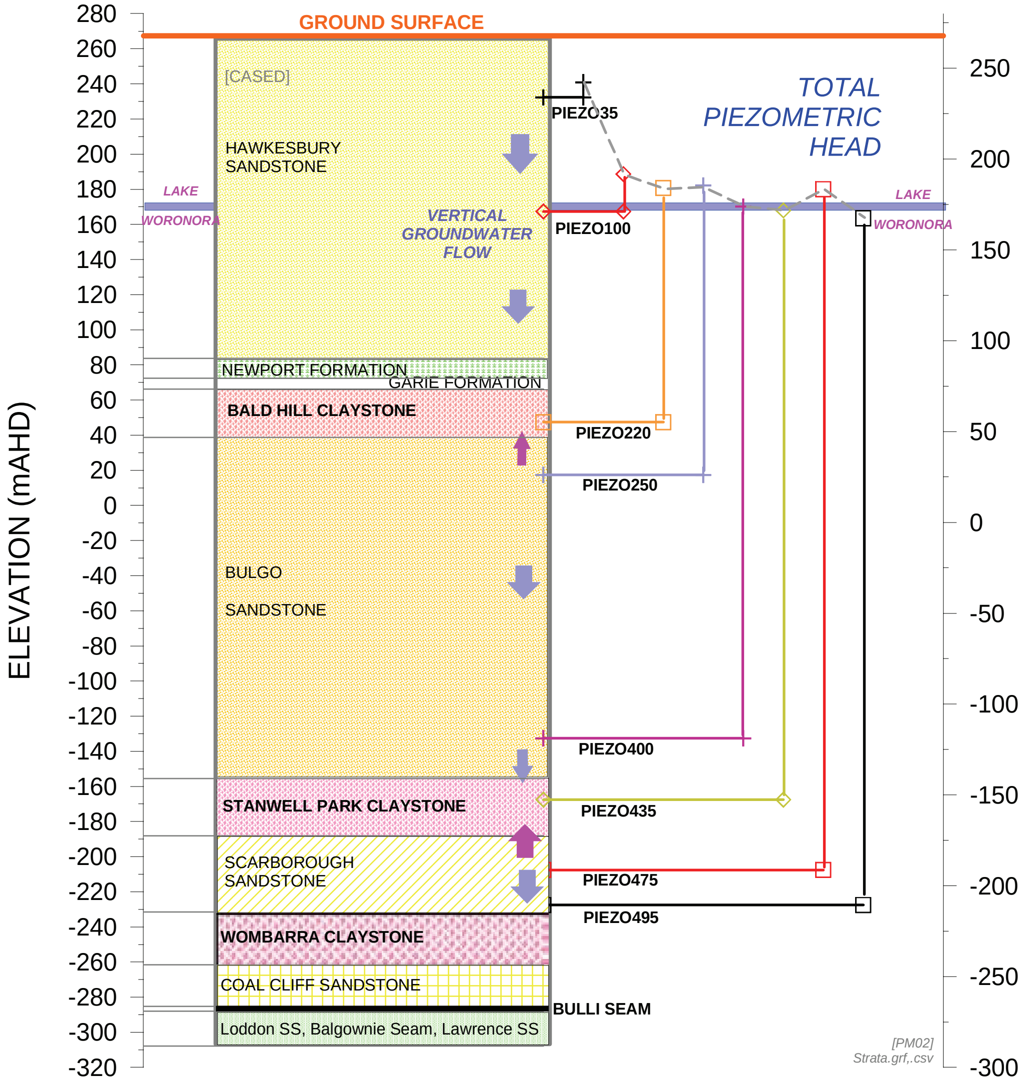


Figure 26. Vertical groundwater flow directions and relative elevations of piezometers, averaged total piezometric heads and Lake Woronora level in the context of the stratigraphic section at the Metropolitan Hole PM02.

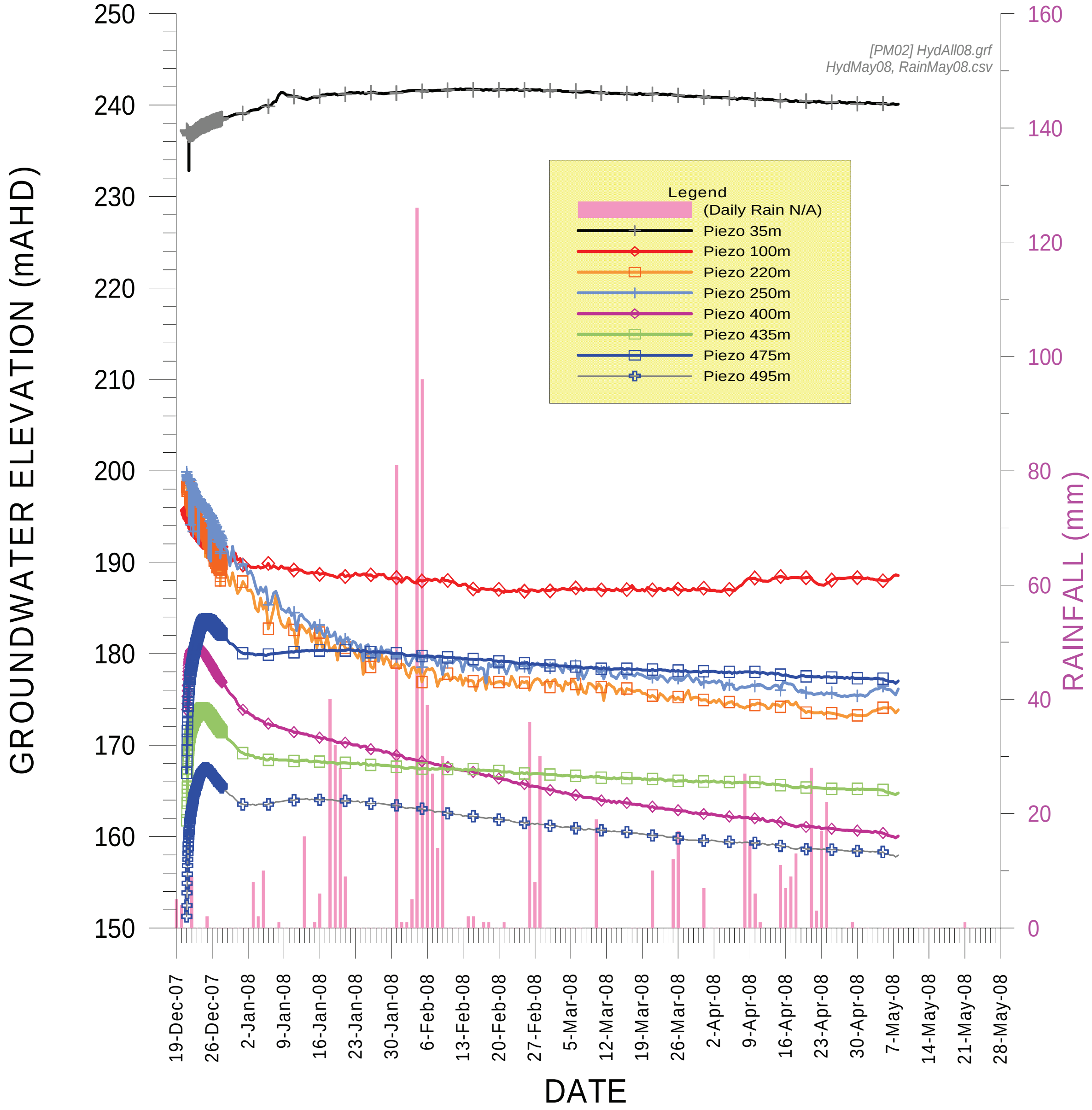


Figure 27. Time variations in total groundwater head at all piezometers in the Metropolitan PM02 hole.

[Note: Daily rainfall at pluviometer PV1 on Waratah Rivulet is shown as a bar graph.]

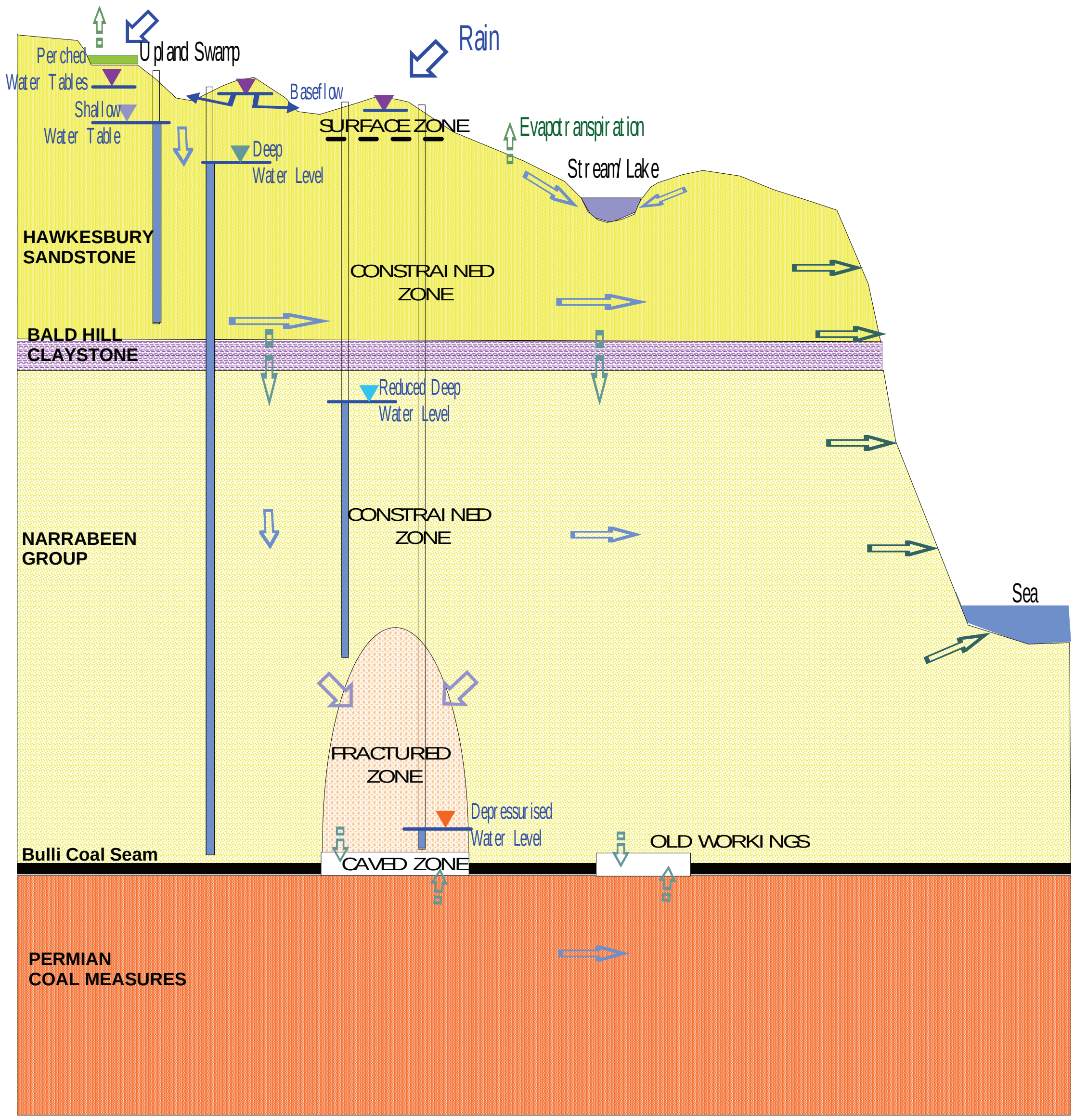


Figure 28. Conceptual hydrogeological model.

MEDIAN THICKNESS (m)	*LAYER*		*LITHOLOGY*
30	**1**		**SUPERFICIAL AQUIFER**
65	**2**		**UPPER HAWKESBURY SANDSTONE**
65	**3**		**LOWER HAWKESBURY SANDSTONE**
29	**4**		**BALD HILL CLAYSTONE**
87	**5**		**UPPER BULGO SANDSTONE**
87	**6**		**LOWER BULGO SANDSTONE**
23	**7**		**STANWELL PARK CLAYSTONE**
20	**8**		**UPPER SCARBOROUGH SANDSTONE**
20	**9**		**LOWER SCARBOROUGH SANDSTONE**
32	**10**		**WOMBARRA CLAYSTONE**
20	**11**		**COAL CLIFF SANDSTONE**
3	**12**		**BULLI COAL SEAM**
(100)	**13**		**LODDON SANDSTONE**

Figure 29. Numerical model layers.

SOUTH

NORTH

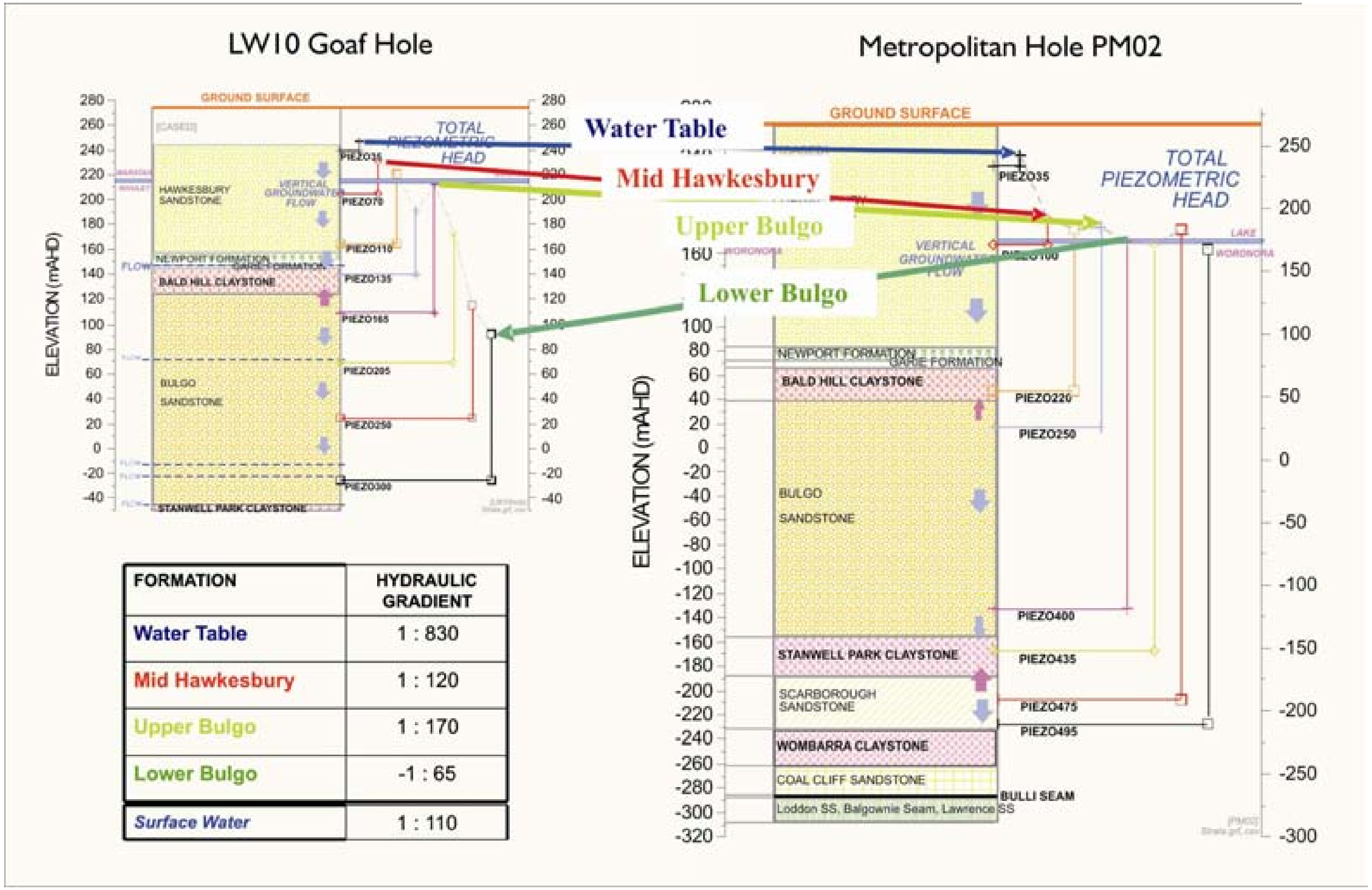


Figure 30. Relative groundwater levels between the Longwall 10 goaf hole and Metropolitan Hole PM02.

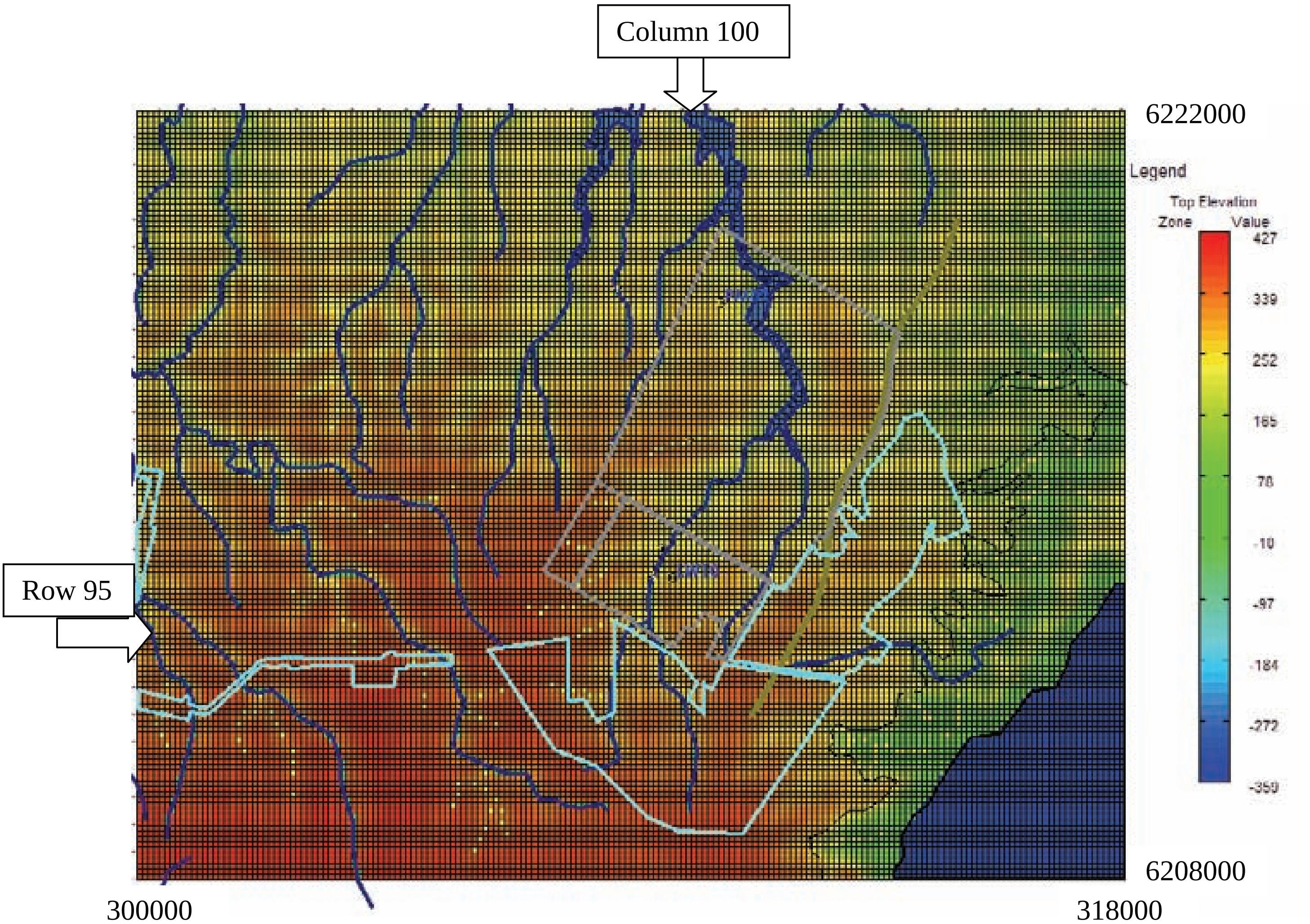


Figure 31. Model extent, surface topography, drainage network and mine outlines

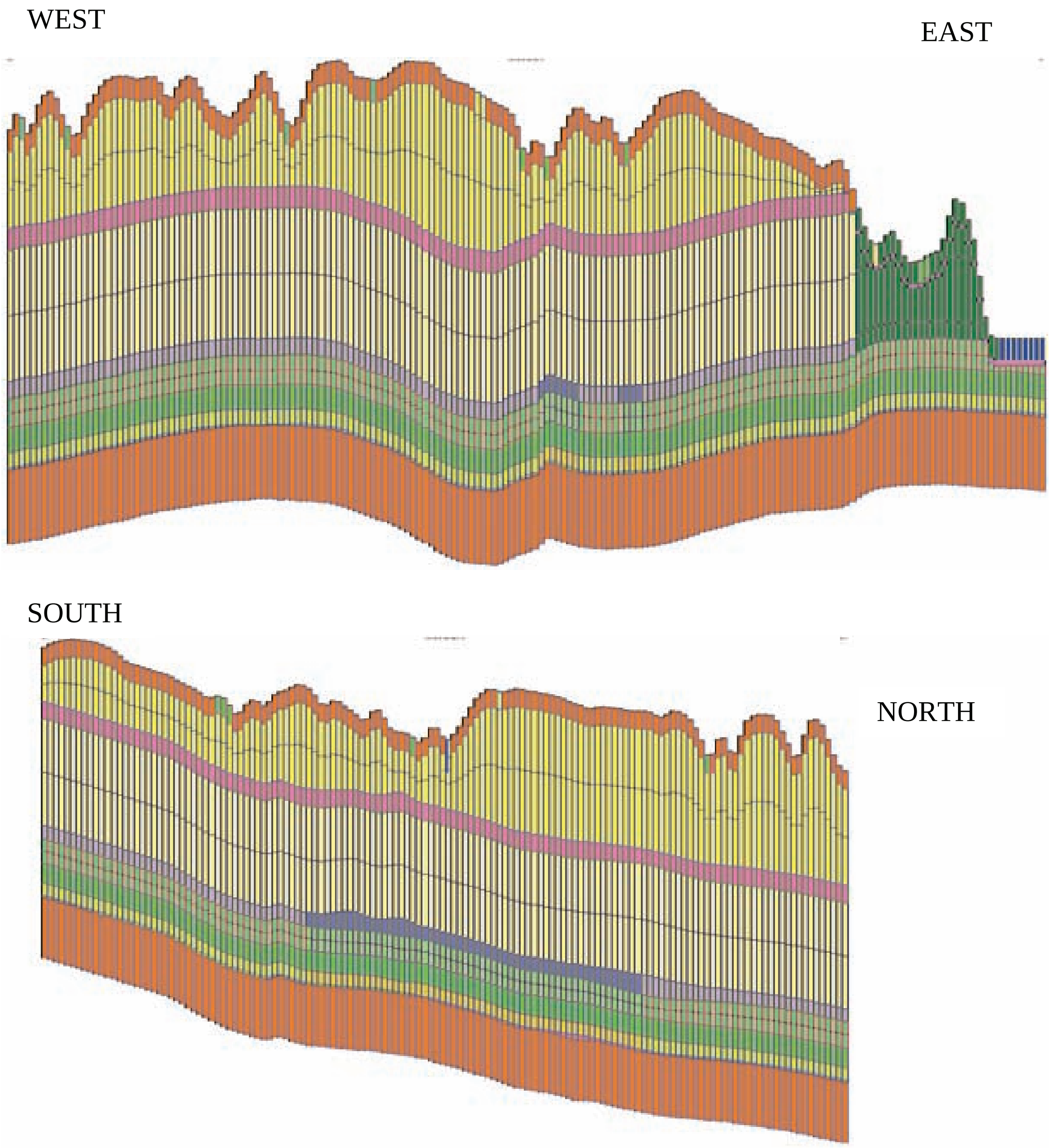
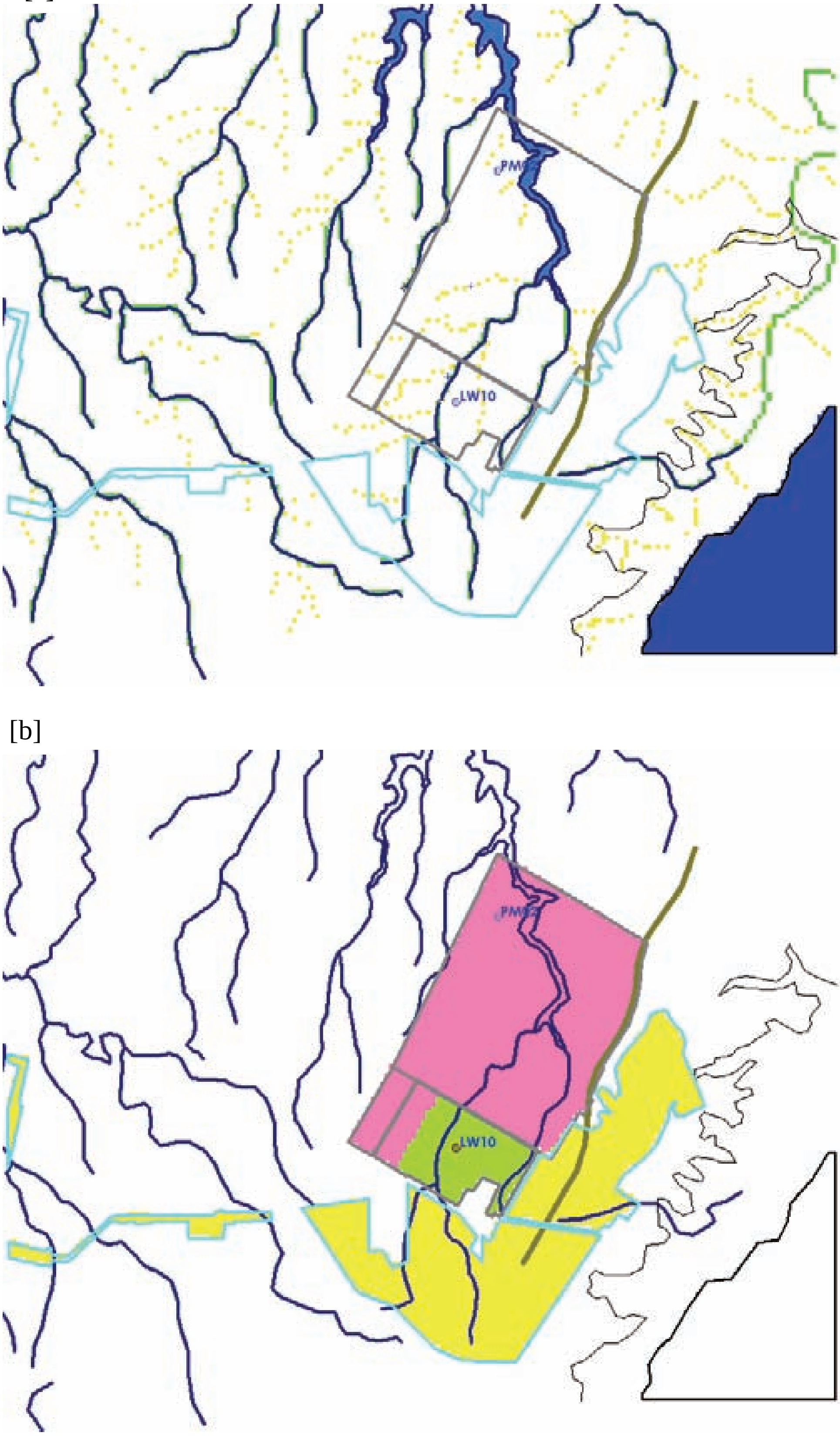


Figure 32. Representative model cross-sections along Row 95 (West-East) and Column 100 (South-North)

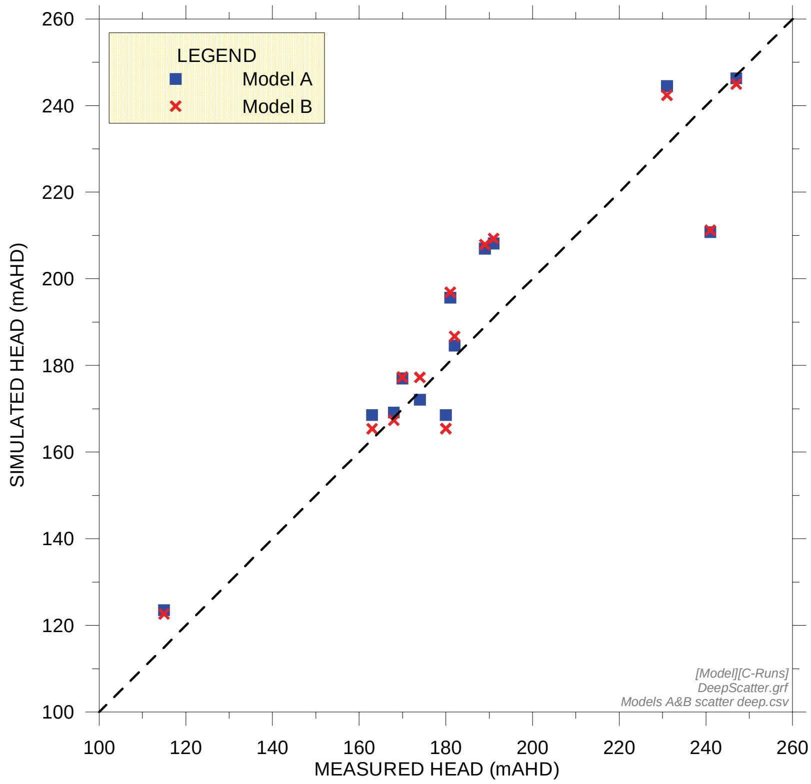
[a]



[b]

Figure 33. Boundary conditions applied to [a] model layer 1 and [b] model layer 12

[a]



[b]

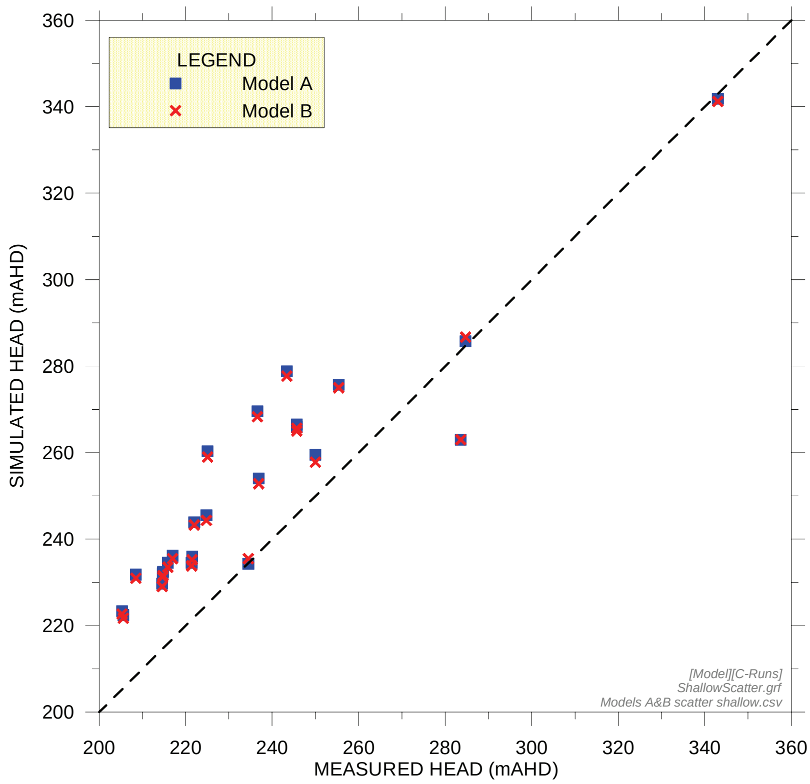
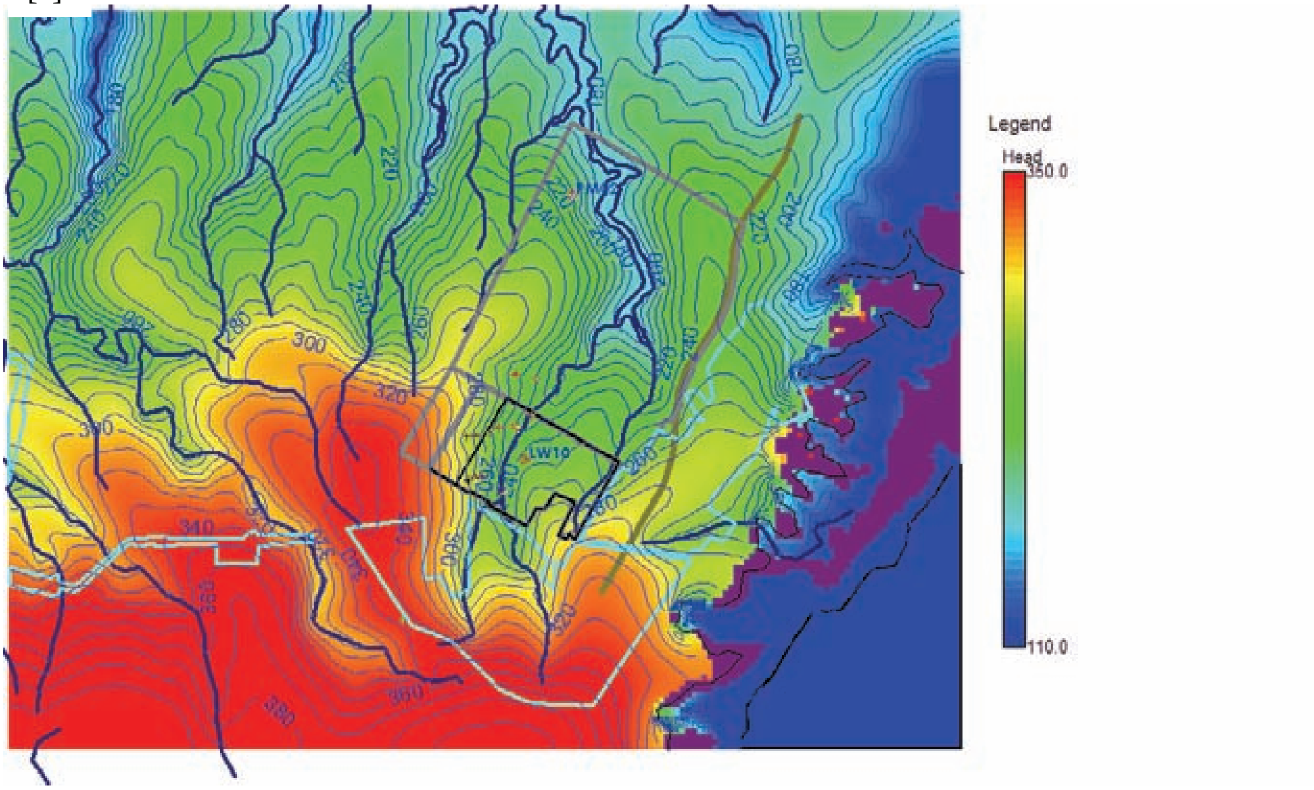


Figure 34. Scattergrams for [a] deep heads and [b] shallow heads

[a]



[b]

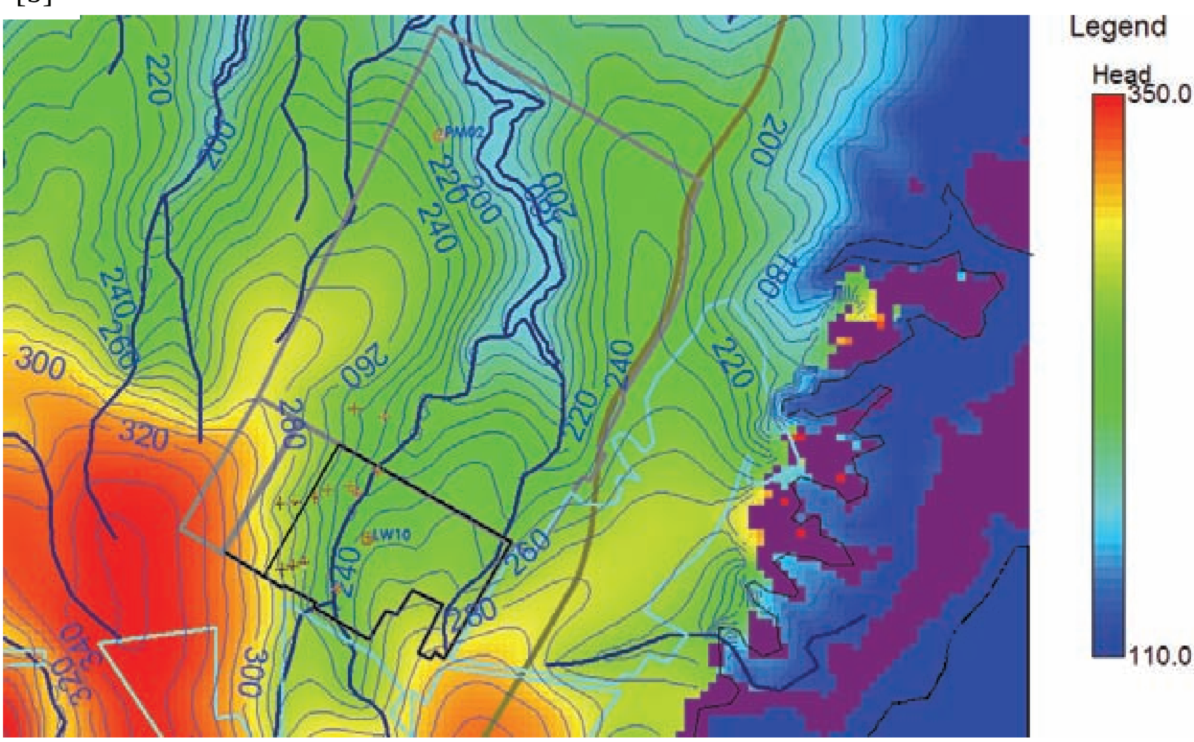
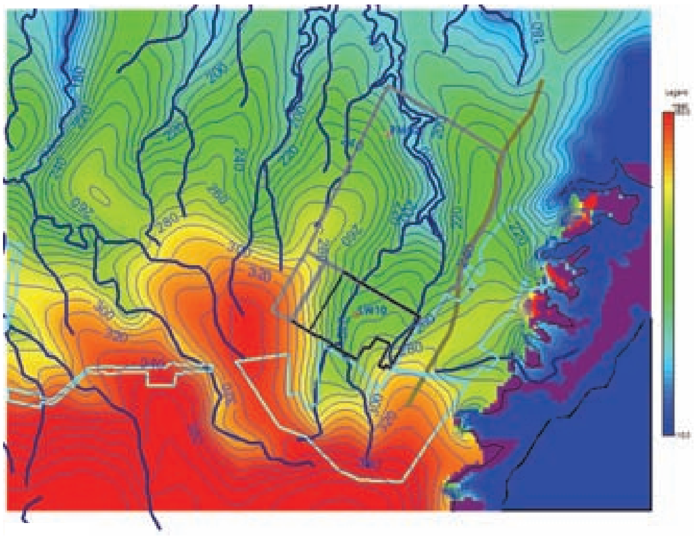
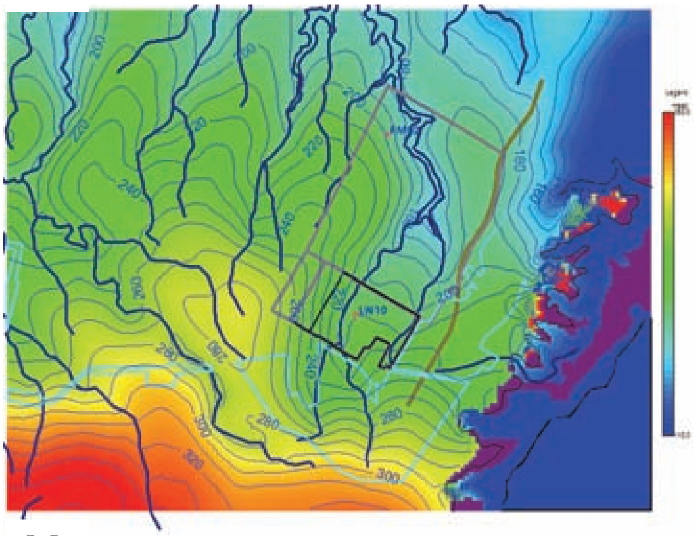


Figure 35. Simulated Hawkesbury Sandstone groundwater levels (layer 2):
[a] whole model extent; [b] mining area

[a]



[b]



[c]

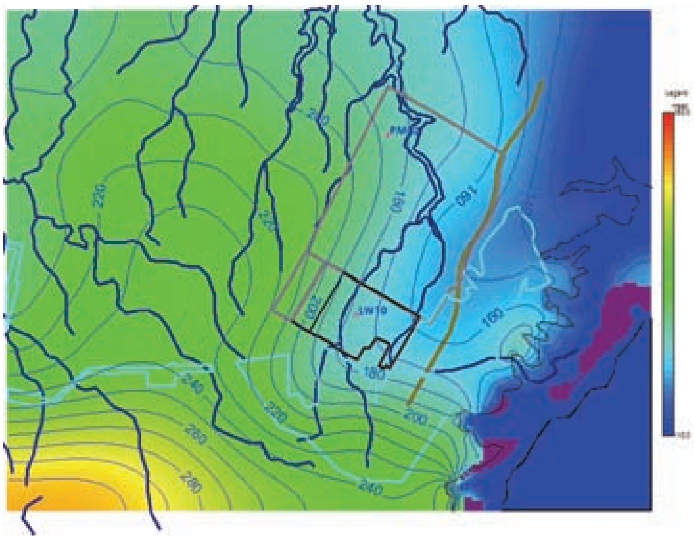
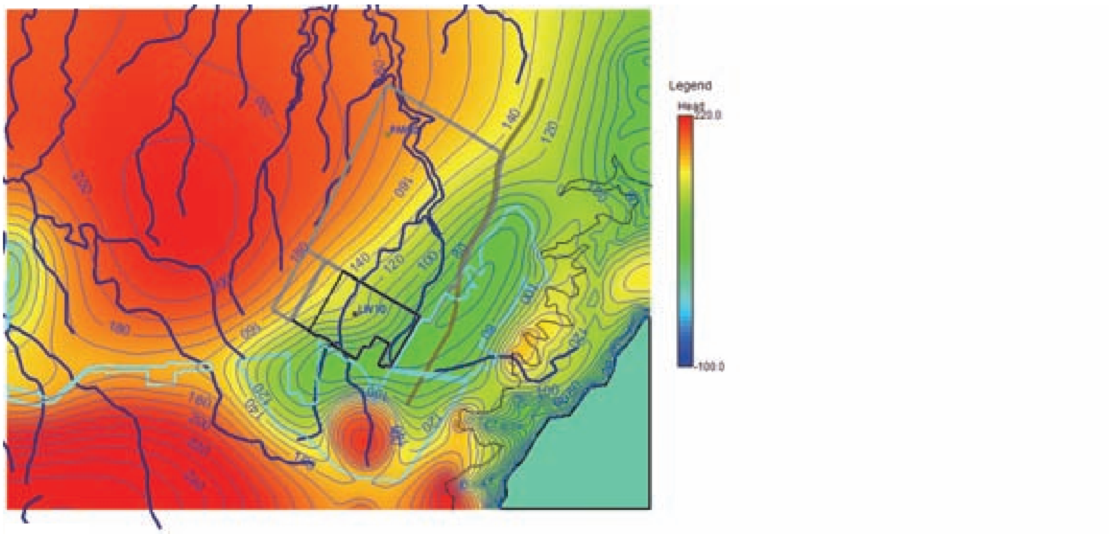
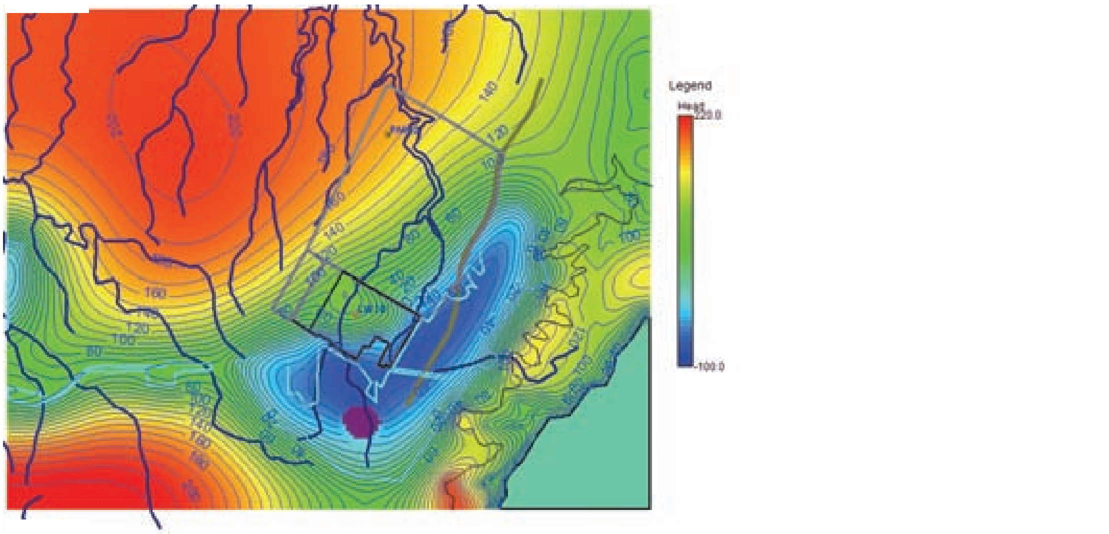


Figure 36. Simulated groundwater levels at the end of Longwall 14 mining: [a] Layer 3 (Lower Hawkesbury Sandstone); [b] Layer 4 (Bald Hill Claystone); [c] Layer 5 (Upper Bulgo Sandstone)

[a]



[b]



[c]

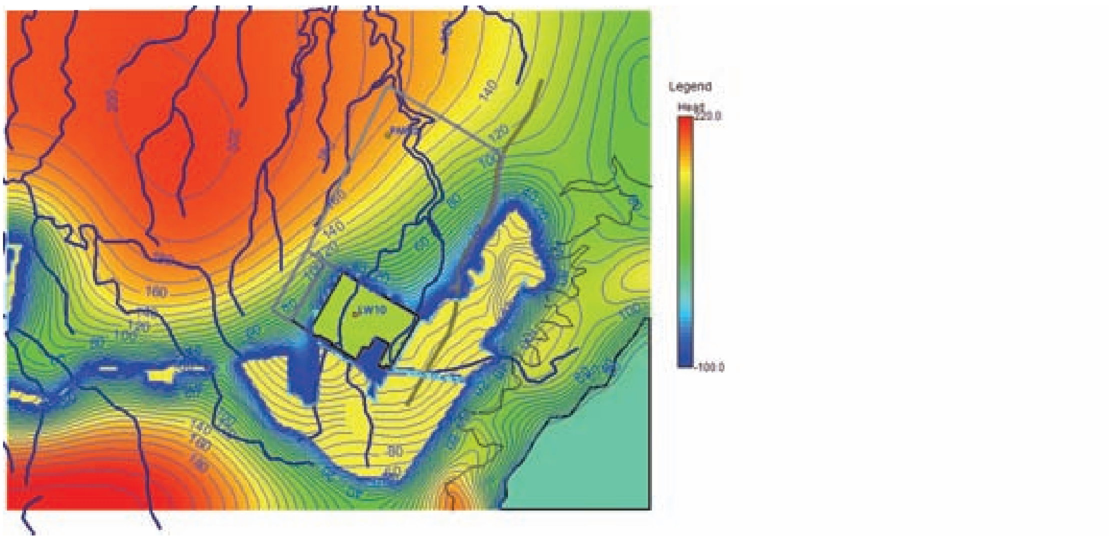


Figure 37. Simulated groundwater levels at the end of Longwall 14 mining: [a] Layer 6 (Lower Bulgo Sandstone); [b] Layer 9 (Lower Scarborough Sandstone); [c] Layer 12 (Bulli Coal Seam)

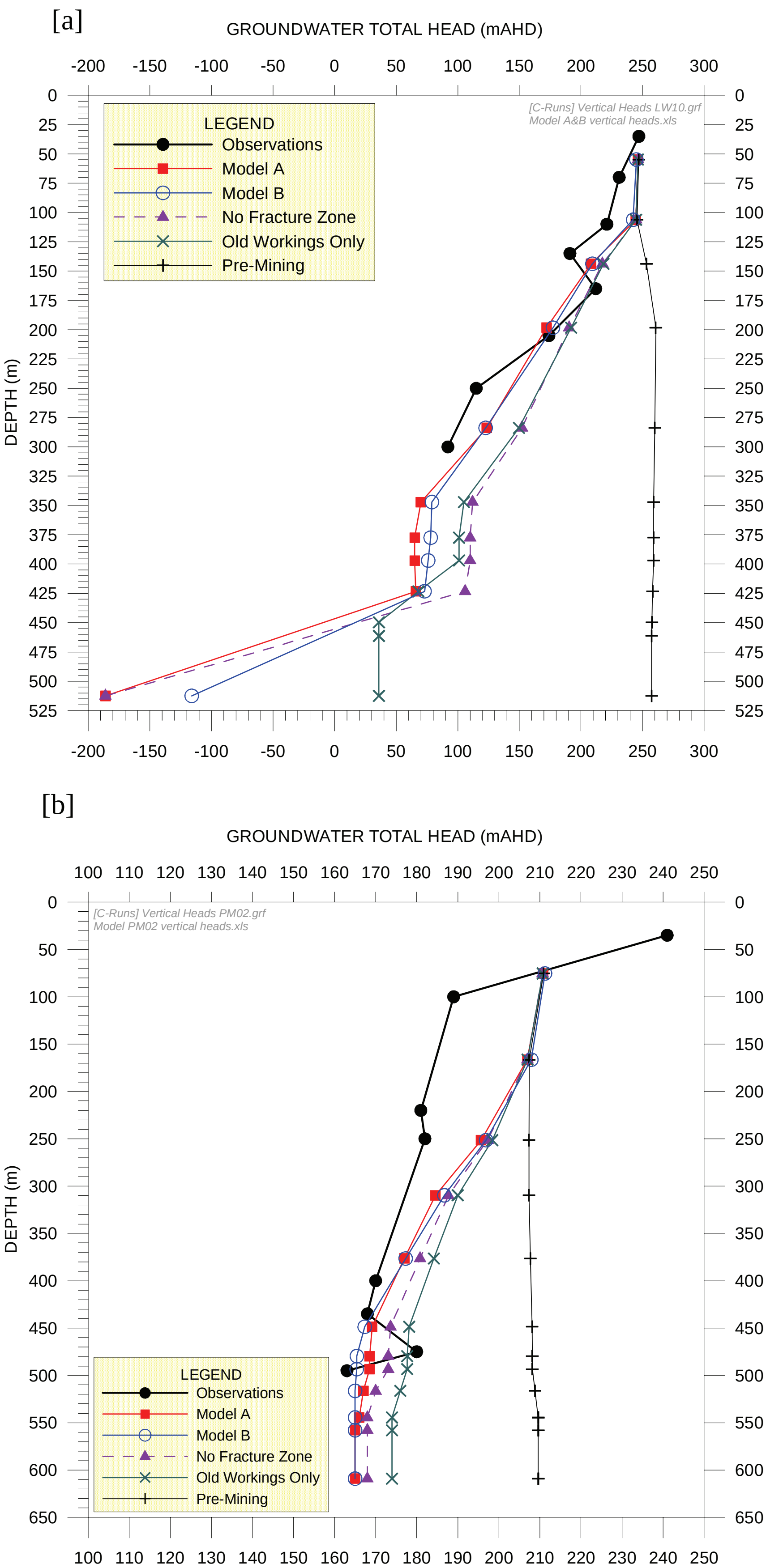
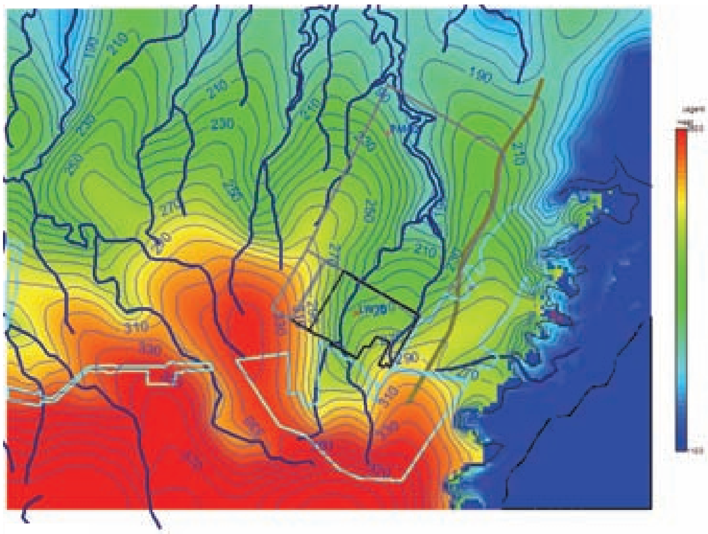
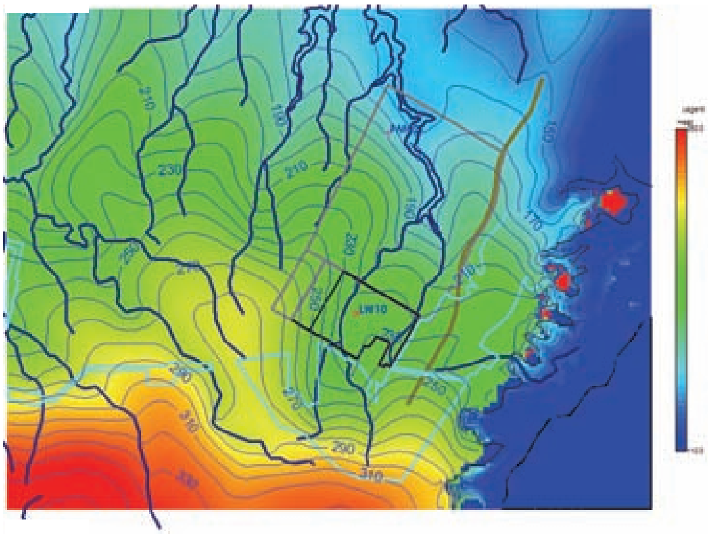


Figure 38. Vertical head profiles for [a] LW10 goaf hole and [b] hole PM02

[a]



[b]



[c]

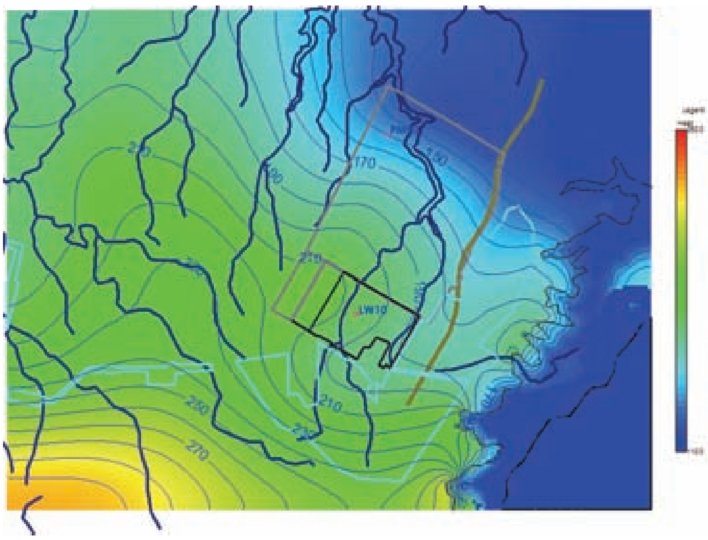
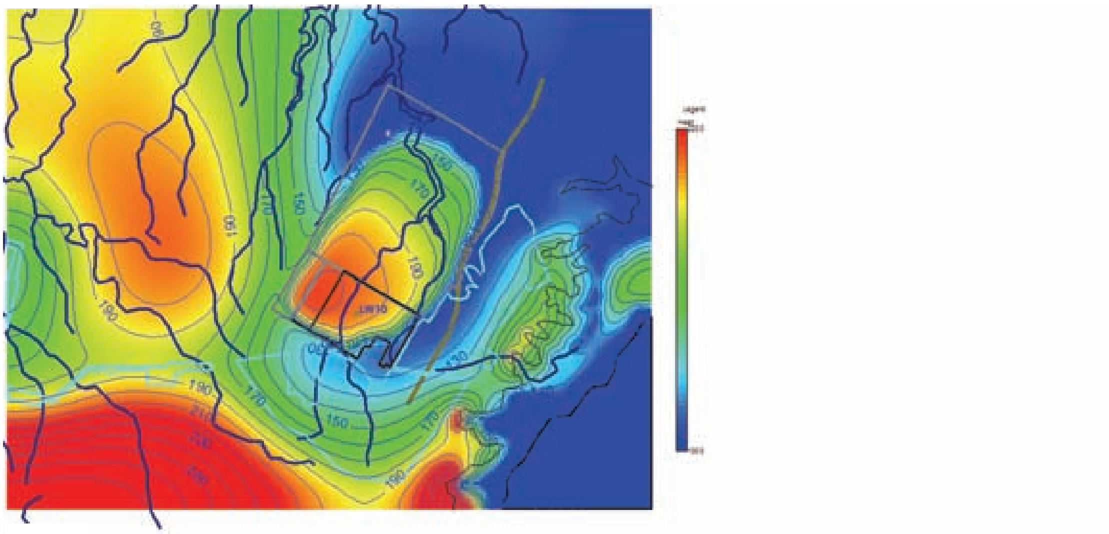
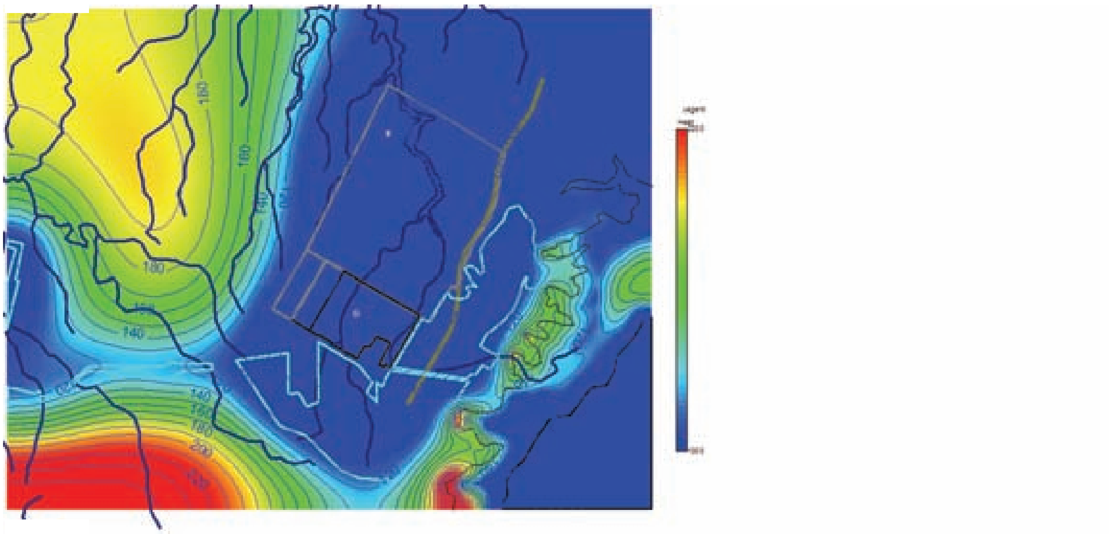


Figure 39. Simulated groundwater levels at the end of Longwall 44 mining: [a] Layer 3 (Lower Hawkesbury Sandstone); [b] Layer 4 (Bald Hill Claystone); [c] Layer 5 (Upper Bulgo Sandstone)

[a]



[b]



[c]

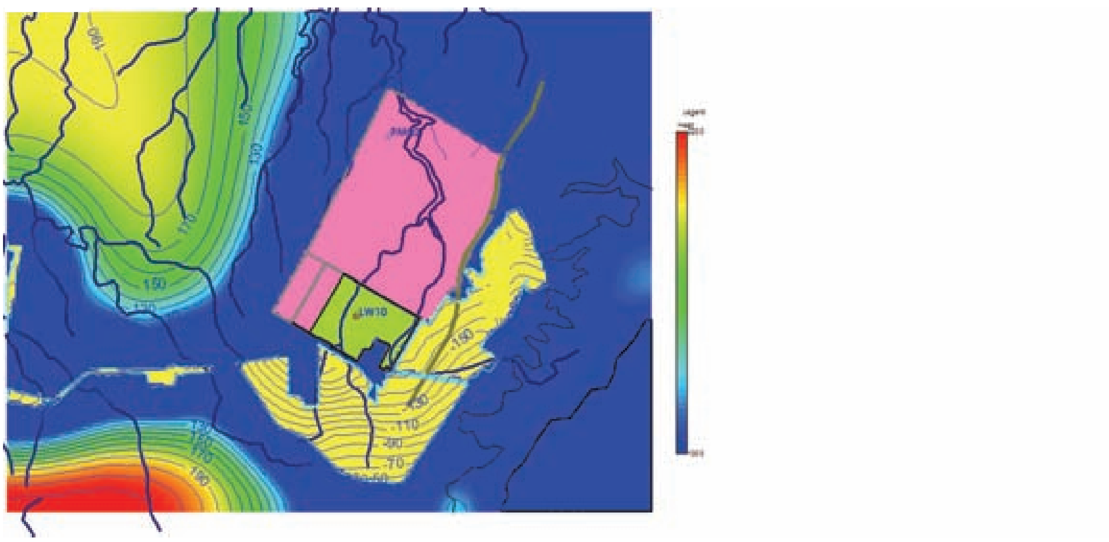
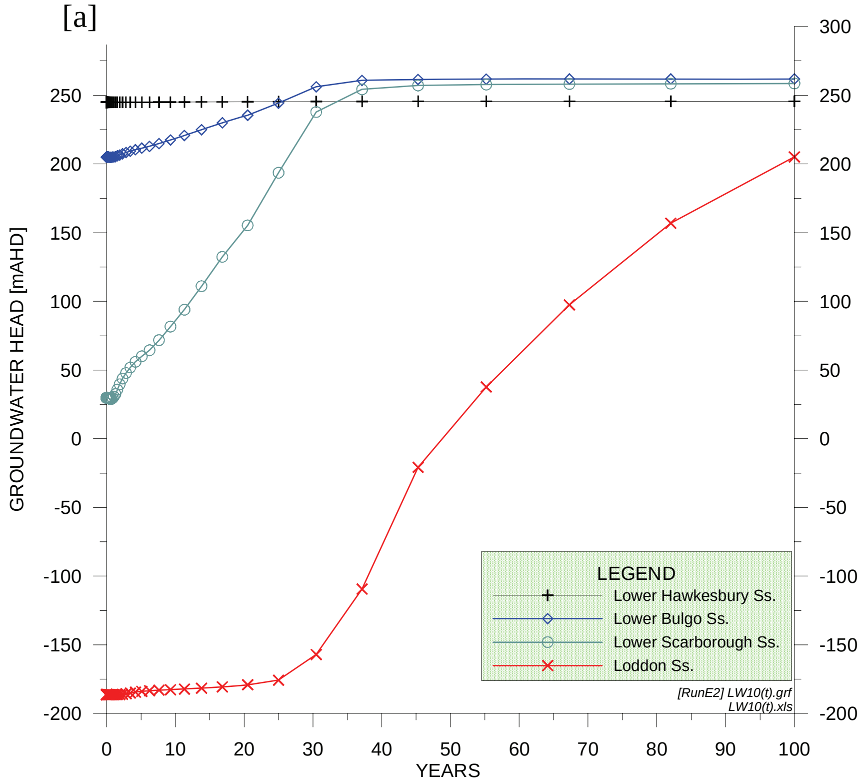


Figure 40. Simulated groundwater levels at the end of Longwall 44 mining:
[a] Layer 6 (Lower Bulgo Sandstone); [b] Layer 9 (Lower Scarborough Sandstone); [c] Layer 12 (Bulli Coal Seam)

[a]



[b]

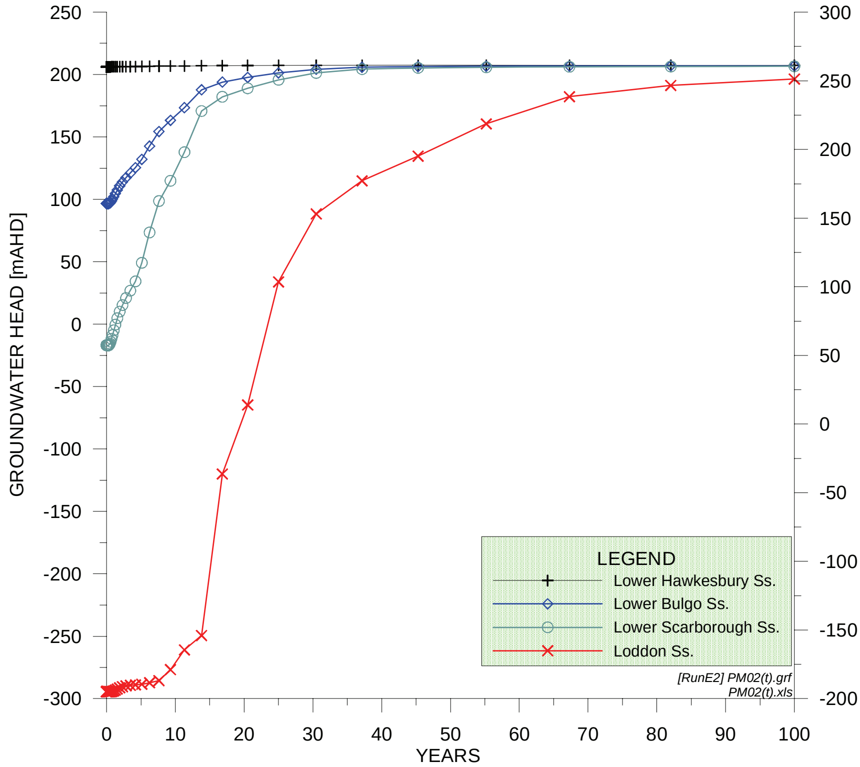


Figure 41. Recovery hydrographs after cessation of mining (storage coefficient 0.00001) for [a] LW10 goaf hole and [b] hole PM02

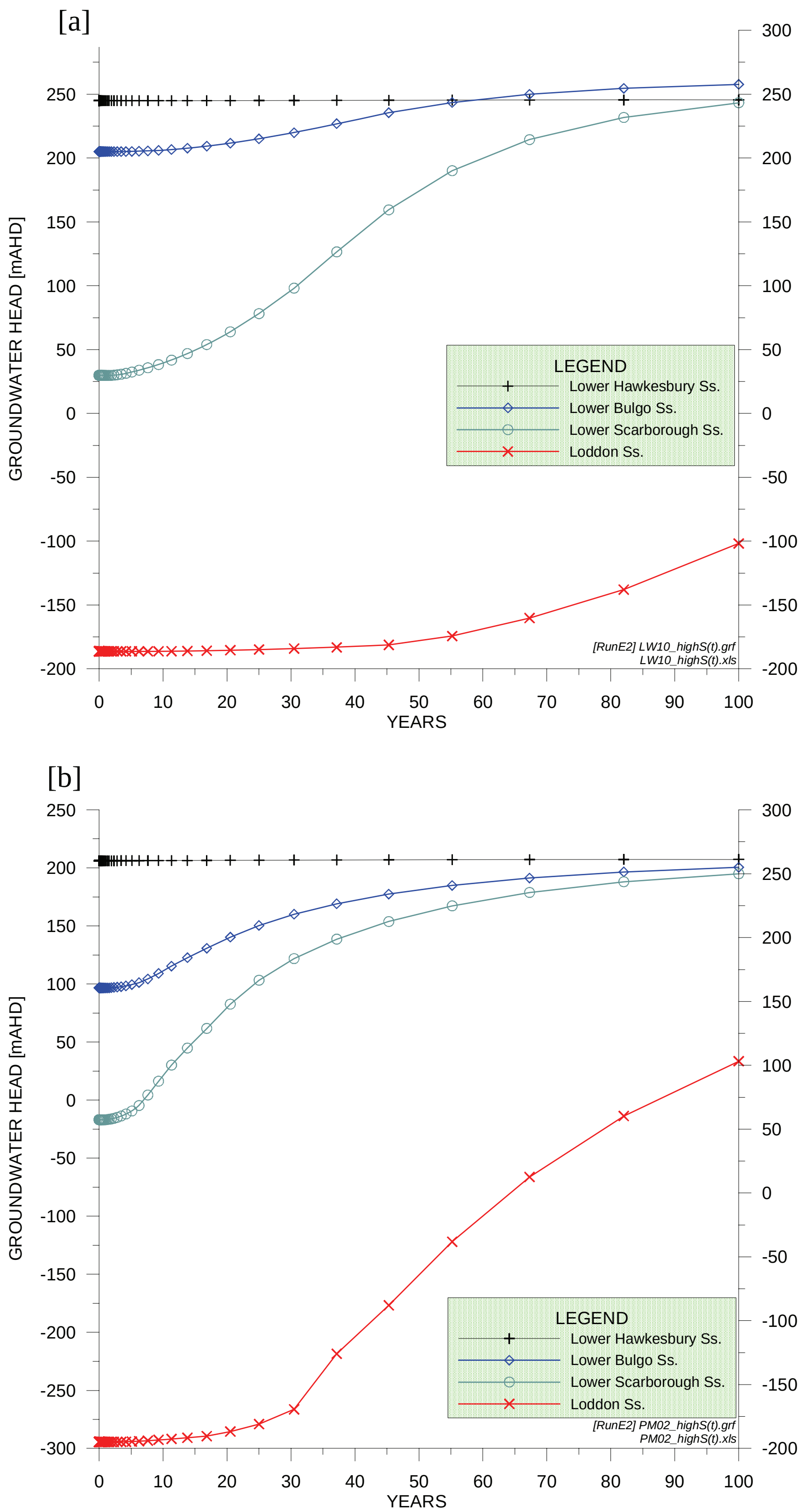


Figure 42. Recovery hydrographs after cessation of mining (storage coefficient 0.0001) for [a] LW10 goaf hole and [b] hole PM02

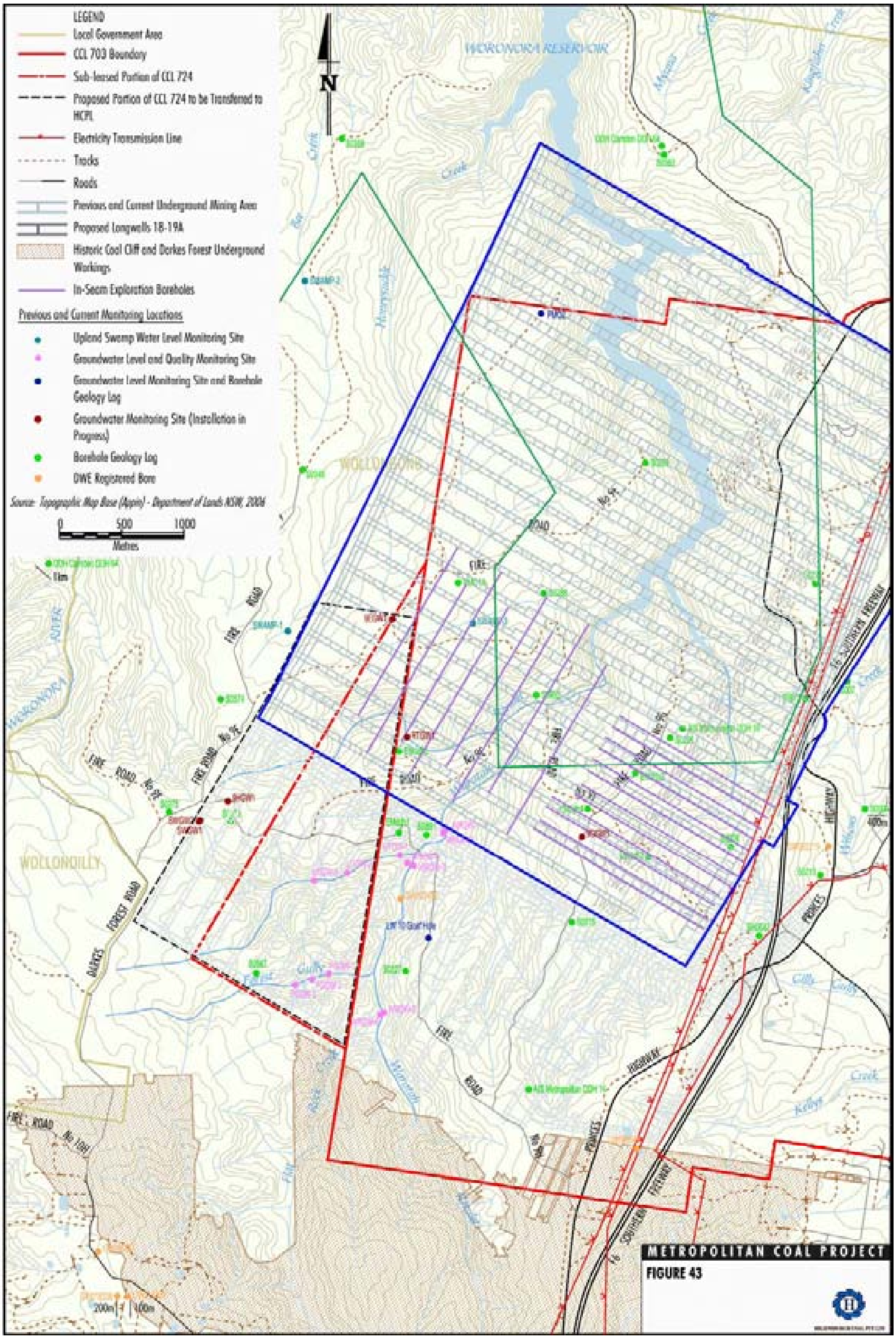
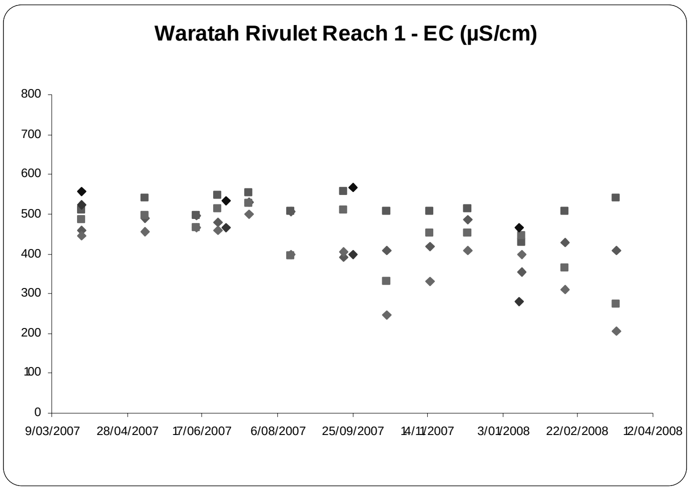
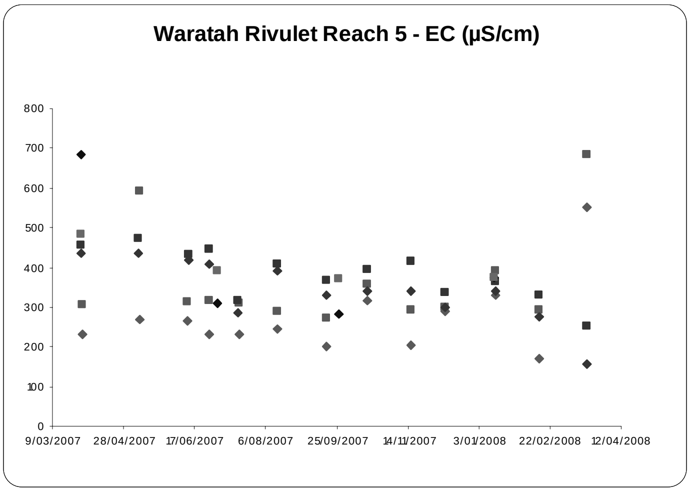


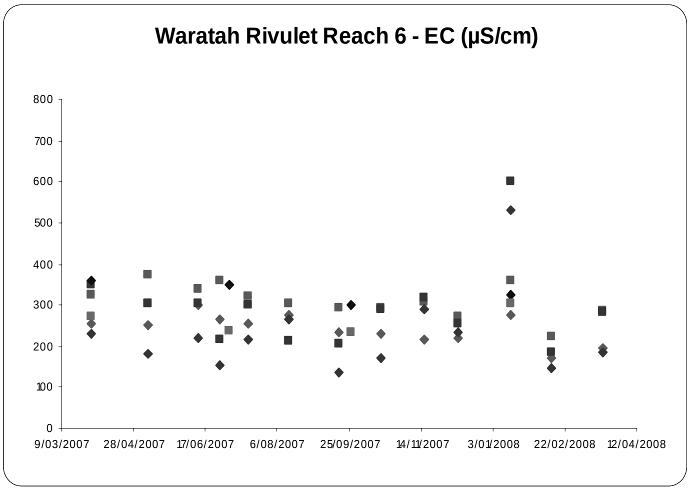
Figure 43. Locations of existing and proposed groundwater monitoring sites

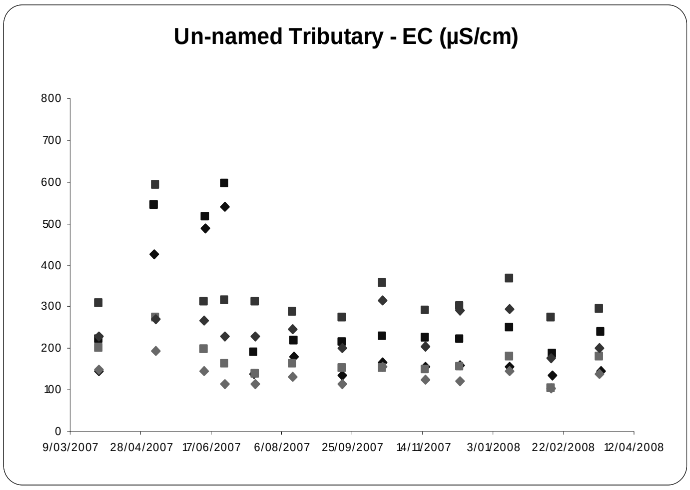
ATTACHMENT A

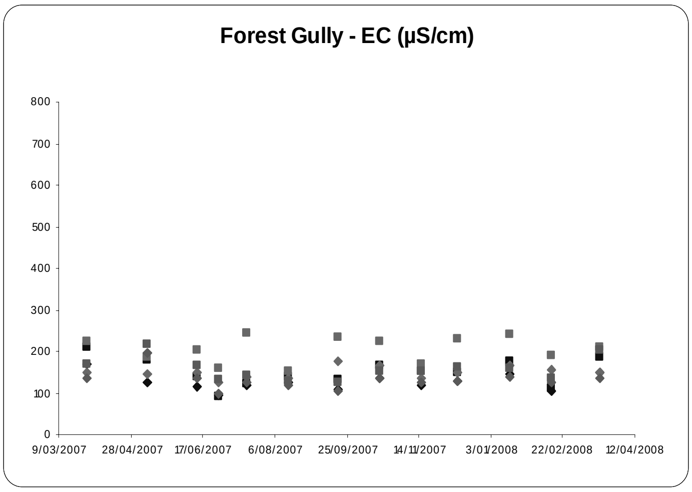
Groundwater Quality Monitoring Results



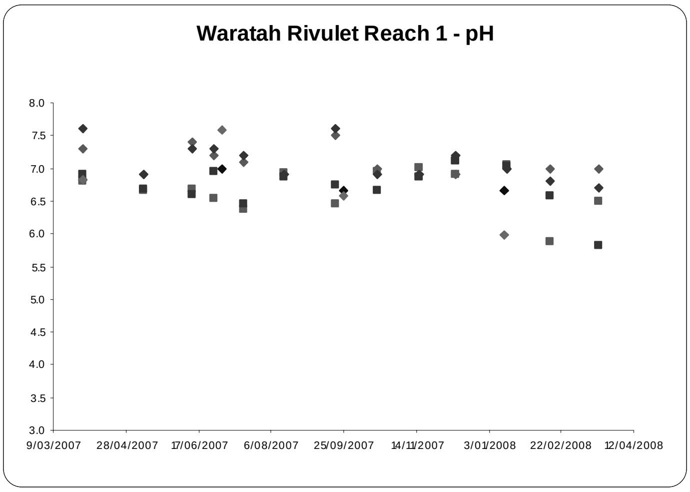


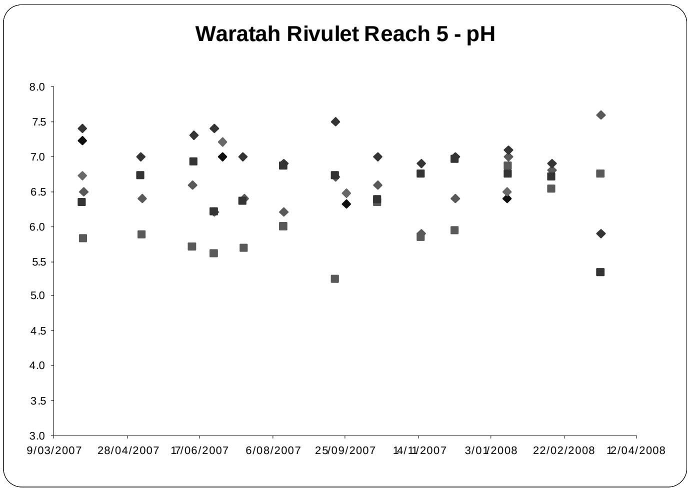


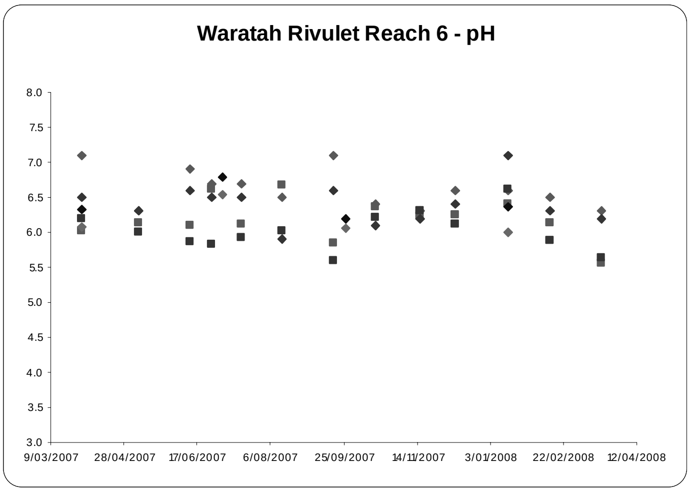


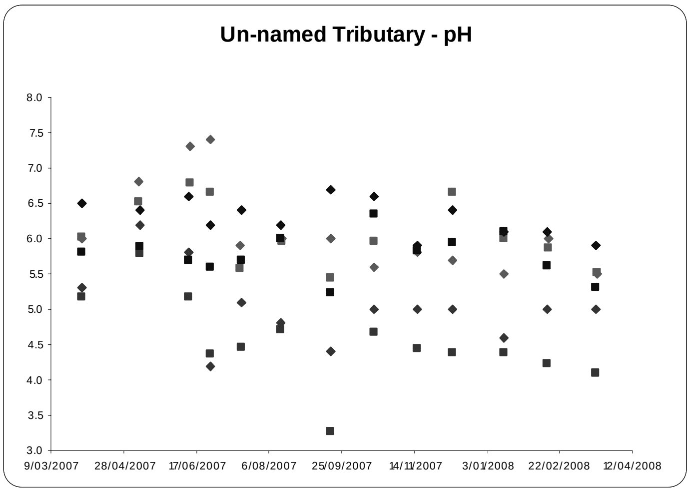


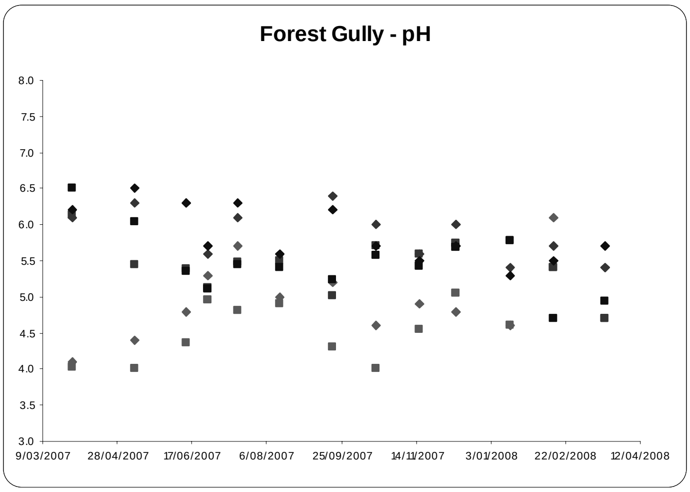
Attachment A1 **Observed Electrical Conductivity – Waratah Rivulet, Un-named Tributary and Forest Gully Groundwater.**



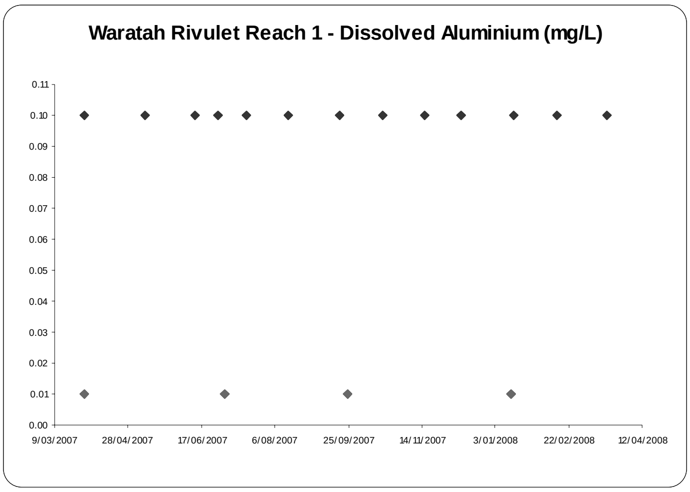


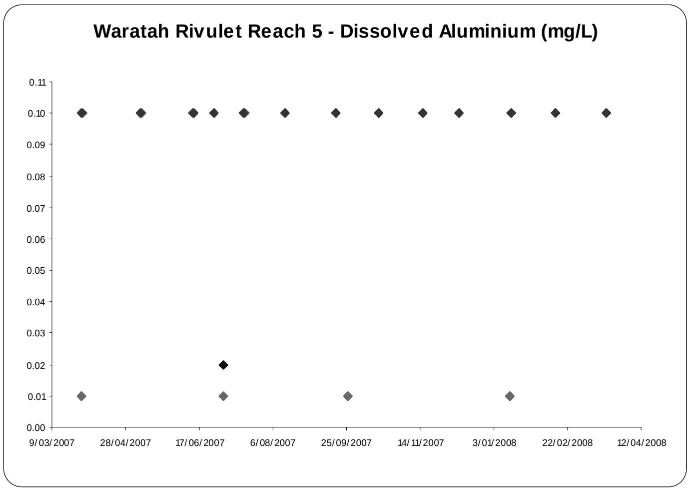


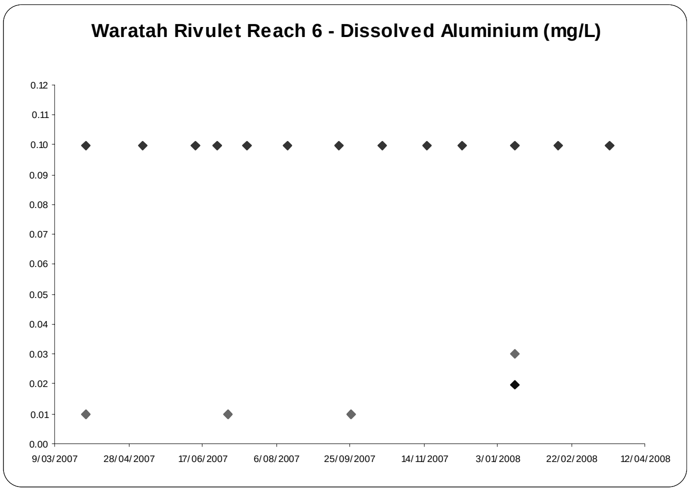


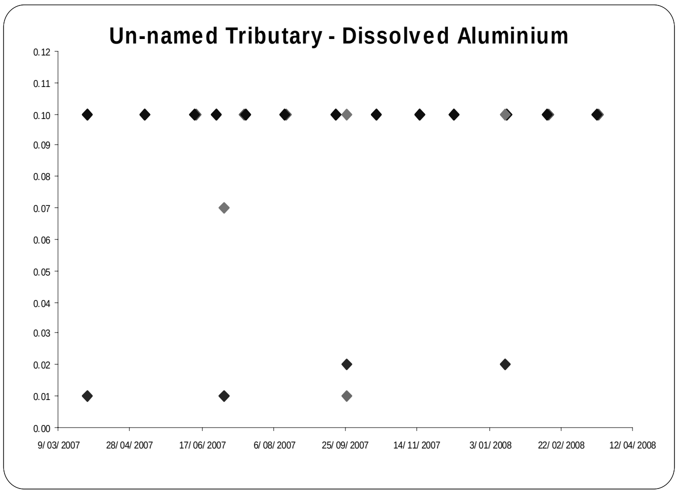


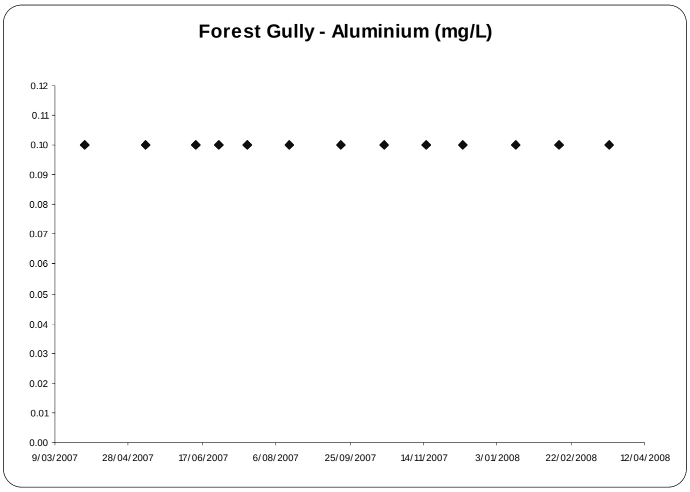
Attachment A2 Observed pH – Waratah Rivulet, Un-named Tributary and Forest Gully Groundwater.



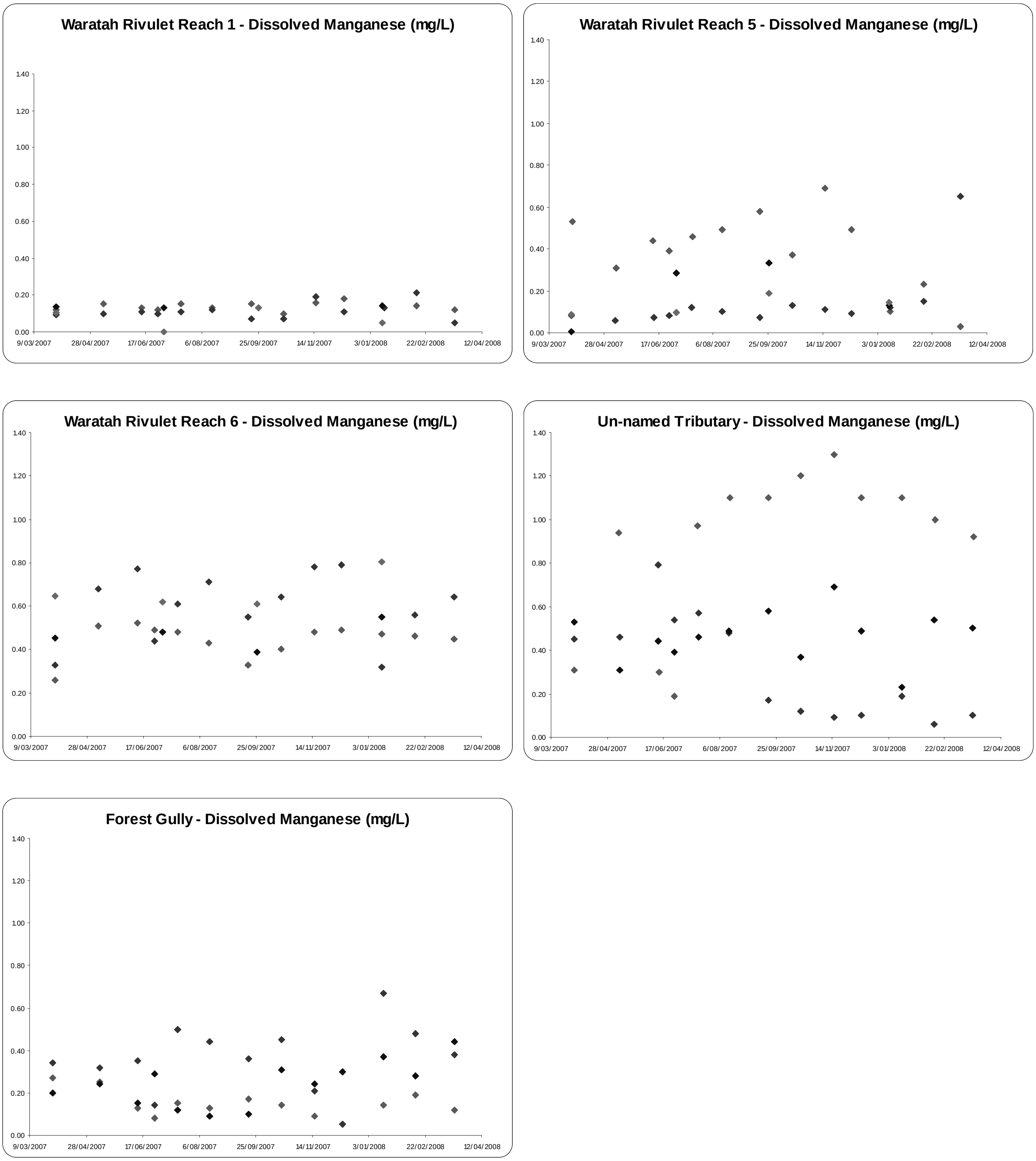




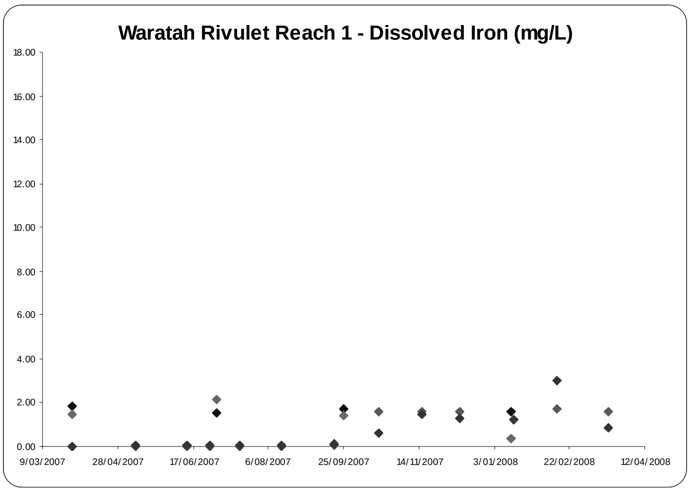


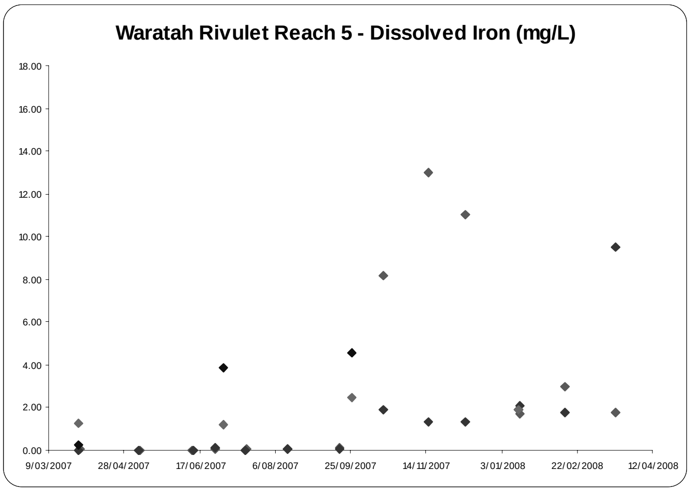


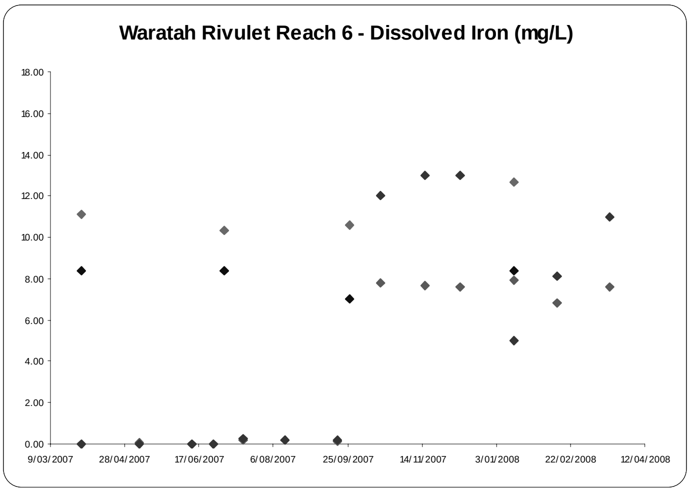
Attachment A3 Observed Dissolved Aluminium Concentrations – Waratah Rivulet, Un-named Tributary and Forest Gully Groundwater.

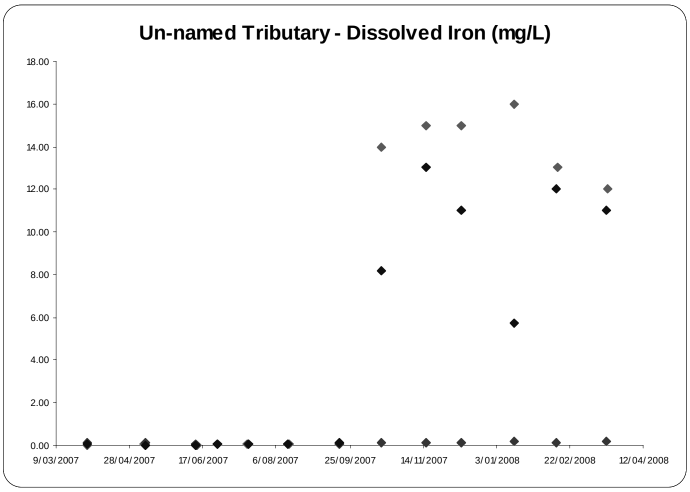


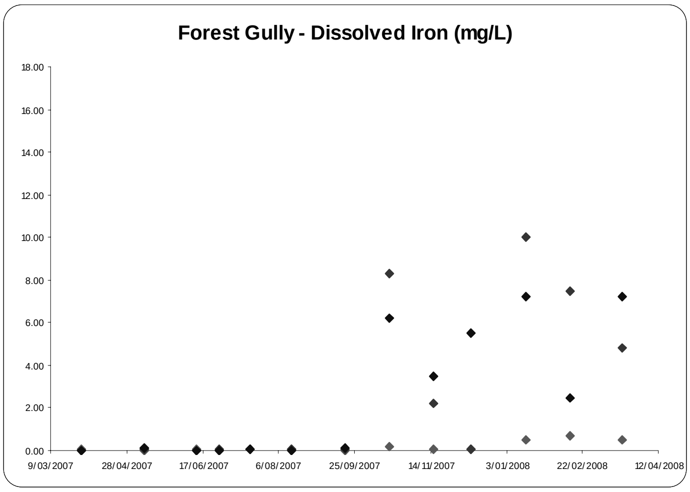
Attachment A4 **Observed Dissolved Manganese Concentrations – Waratah Rivulet, Un-named Tributary and Forest Gully Groundwater.**











Attachment A5 Observed Dissolved Iron Concentrations – Waratah Rivulet, Un-named Tributary and Forest Gully Groundwater.