BULLI SEAM OPERATIONS

APPENDIX B

GROUNDWATER ASSESSMENT

ILLAWARRACOAL
Pride, passion, performance

bhpbilliton
resourcing the future

BULLI SEAM OPERATIONS

GROUNDWATER ASSESSMENT

A HYDROGEOLOGICAL ASSESSMENT IN SUPPORT OF THE BULLI SEAM OPERATIONS ENVIRONMENTAL ASSESSMENT

FOR

ILLAWARRA COAL HOLDINGS PTY LIMITED

By

Dr N. P. Merrick

Heritage Computing

Project Number: BHPIC-07-01

Report HC2009/5

Date: July 2009

DOCUMENT REGISTER

REVISION	DESCRIPTION	DATE	AUTHOR
A	FIRST DRAFT	24 MARCH 2009	NPM
B	SECOND DRAFT	17 APRIL 2009	NPM
C	THIRD DRAFT	12 JUNE 2009	NPM
D	FOURTH DRAFT	5 JULY 2009	NPM
E	FINAL DRAFT (INCORPORATING KALF & ASSOCIATES REVIEW COMMENTS)	28 JULY 2009	NPM

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF ATTACHMENTS

1.0 INTRODUCTION

This report has been prepared for Illawarra Coal Holdings Pty Limited (ICHPL), a wholly owned subsidiary of BHP Billiton Pty Ltd. The report provides a hydrogeological assessment of proposed longwall mining at the Bulli Seam Operations (the Project) located within the Southern Coalfield in New South Wales (NSW).

ICHPL owns and operates the longwall mining operations at the Appin Mine and West Cliff Colliery. The operations at the current underground mining areas are supported by three pit tops (i.e. West Cliff, Appin East and Appin West) (Figure 1). The existing Appin East and West Cliff pit tops are located off Appin Road to the south-east of Appin village, while the Appin West pit top is located off Douglas Park Drive approximately 4 kilometres (km) south of Douglas Park township (Figure 1). The extent of previous mine development areas is shown on Figure 2.

The Project would involve the continuation of underground mining operations at the Appin Mine and West Cliff Colliery including West Cliff Area 5, Appin Area 7, Appin West (Area 9), Appin Area 8, Appin Areas 2 and 3 Extended and North Cliff. The area of proposed underground mining is shown on Figure 2.

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

1.1 SCOPE OF WORK

The key tasks for this assessment are:

- Characterisation of the existing groundwater environment including identification of potential groundwater dependent ecosystems in consultation with other relevant specialists.
- Collation and review of baseline groundwater data including:
    - existing ICHPL exploration programme piezometer data;
    - existing mine water management records; and
    - additional data (from other mining operations and government agencies e.g. NSW Department of Water and Energy [DWE] and Sydney Catchment Authority [SCA]).
- Development of a conceptual groundwater model and refinement through analysis of data collated to develop and calibrate a numerical groundwater model to predict potential impacts of underground mining and mine development on the groundwater regime.
- Preparation of a Groundwater Assessment report for inclusion in the EA that includes the following:
    - qualitative and quantitative assessment of underground mine groundwater impacts and cumulative impacts with other existing and approved mines in the area; and
    - assessment of post-mining groundwater impacts (recovery of groundwater levels).
- Development of measures to avoid, mitigate and/or remediate potential impacts on groundwater resources and recommend groundwater monitoring to measure potential impacts on groundwater resources.

In accordance with the NSW Government Department of Planning (DoP) 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 (NSW Department of Land and Water Conservation [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 Commission Groundwater Quality. Sampling Guidelines. Technical Report No 3 (MDBC); and
- Murray-Darling Basin Commission. Groundwater Flow Modelling Guideline (MDBC).

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 all significant watercourses; and
- Site water balance, 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 prepared by Gilbert & Associates (Appendix C of the EA).

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. Table 1 summaries the key issues that were raised in the Southern Coalfield Inquiry Report in relation to groundwater and provides references to the relevant sections in this report which address these issues.

Table 1. Issues Raised in the Southern Coalfield Inquiry Report

Issue	Quote	Section Reference
Appropriate Model Code	*…the Panel recommends the use of 3D groundwater numerical modelling which surprisingly, has hitherto not been utilised in the Southern Coalfield even though this type of predictive analysis has been employed in the Hunter and Western Coalfields for many years…The Panel notes it is especially important to ensure that the adopted model code can adequately address high contrasts in hydraulic properties and steep hydraulic gradients that are typically associated with underground mining operations.* [Section 4.3.4.3, pg 84]	Section 4.1
Hydrogeological Data	*…the density and duration of observations appear to be limited, especially with respect to redirected surface flows and regional strata depressurisation.* [Section 4.3.4.3, pg 84]	Sections 2.11, 2.12 and 3.2
Baseline Data	*Coal mining companies should provide a minimum of two years of baseline environmental data, collected at appropriate frequency and scale, to support any application under either Part 3A of the* Environmental Planning and Assessment Act 1979 *or for approval of a Subsidence Management Plan.* [Section 7, pg 124]	Sections 2.11, 2.12 and 3.2
Groundwater Monitoring	*Monitoring regimes should be based on:*	
	• *shallow piezometer installations for the monitoring of groundwater levels/pressures within significant upland swamps, drainages and any connected alluvium. Piezometers should have sufficient distribution so as to be able to characterise the aquifer in swamps S76, S77 and S92 with a high level of confidence in potentially affected areas. Water level measurements should be automated with daily or more frequent recording;*	Sections 2.11, 2.12 and 6.2.1
	• *groundwater quality classification through regular sampling and analyses at installed piezometers. Candidate analytes must facilitate the discrimination of mining related impacts and in particular, any ionic species that might be attributed to new water/rock interactions;*	Sections 2.11, 2.12 and 6.2.2
	• *deep piezometer installations for the monitoring of pore pressures within the natural rock strata. Piezometers should have sufficient distribution so as to be able to describe the distribution of deep aquifer pressures with a high level of confidence. Pore pressure measurements should be automated with daily or more frequent recording;*	Sections 2.11, 2.12 and 6.2.3
	• *strata hydraulic property measurements to facilitate calculation of subsurface flows. While such properties (porosity and permeability) are unlikely to change naturally over time and hence regular monitoring is not required, a properties database is required for impacts assessment and in this context, such measurement is considered to constitute baseline data. Techniques for the measurement of hydraulic properties are well established and include packer testing, variable head testing, test pumping, core analyses (matrix properties and defects inspections) and geophysical logging where appropriate; and*	Sections 2.11, 2.12, 6.2.4 and 6.3
	• *mine water balance for existing and extended operations is considered by the Panel to be an especially important part of baseline data measurements. It provides a means of confirming the groundwater transmission characteristics of the coal seam, overburden, and the drainage characteristics of goaves and the overlying failure regimes. It also provides a first indication of potentially anomalous mine water seepage that may be initiated by faulting or fractured with igneous intrusions and increased connectivity to surface drainage systems. The water balance for future operations should take into account all water imported to an underground operation or part thereof, and all water exported from that same operation including pumped water, coal moisture increases (allowing for inherent moisture), ventilation moisture and any other exports;…* [Section 4.4.2.3, pp 87-88]	Sections 6.2.5 and Appendix C of the EA

This report also considers the findings and recommendations of the Planning Assessment Commission (2009) in the "Metropolitan Coal Project Review Report". Table 2 summarises the key issues that were raised in the Metropolitan Coal Project Review Report in relation to groundwater and provides references to the relevant sections in this report which address these issues.

Table 2. Issues Raised by the Planning Assessment Commission in the Metropolitan Coal Project Review Report

Issue	Quote	Section Reference
Appropriate Model Simulation	*The Panel questioned the usefulness of steady state simulation of what is obviously a non-steady state flow domain.* [Section 8.4, pg 68]	Section 4.4
Appropriate Model Code	*The Panel also questioned the adoption of the Modflow code which has a number of limitations that can affect the accuracy of simulating mining operations.* [Section 8.4, pg 68] *…it is especially important to ensure that the adopted model code can adequately address high contrasts in hydraulic properties and steep hydraulic gradients that are typically associated with underground mining operations. In addition, the code must be able to simulate unsaturated and perched conditions that nearly always prevail above longwall panels or beneath upland headwater swamps.* [Section 8.5, pg 72]	Section 4.1
Use of Modelling as a Management Tool	*Aquifer numerical modelling to be used as a management tool for the ongoing prediction of impacts attributed to longwall extraction* [Section 19.6, pg 140]	Section 8.0
Consideration of Structural Features	*…the Panel considers that there remains a possibility albeit slim, that a structural feature (fault, dyke etc) could provide a leakage conduit from surface to depths below the identified aquitards like the Bald Hill Claystone. A number of candidate linear features have been identified from aerial photography (Geosensing 2008) and these may need to be considered as part of future exploration activity conducted by HCPL.* [Section 8.4, pg 69] *The Panel understands that HCPL propose to undertake in seam long hole drilling for gas drainage purposes. These holes should be used to identify the presence of any significant structures (faults) that may act as flow conduits – possibly from surface. If any such features are intercepted, then an appropriate strategy needs to be invoked that will characterise the structure and determine the magnitude and extent of leakage.* [Section 8.5, pp 71-72]	Sections 2.7 and 9.0 Sections 6.3 and 8.0
Mine Water Management System	*The Panel sought clarification with respect to the capacity of the mine water management system to manage increased contributions from underground operations…The Panel is of the view that neither the information on mine water make, nor the Proponent's general assurances as to appropriate responses should the substantial predicted increases occur, are adequate.* [Section 8.4, pp 69-70]	Sections 5.1, 5.7 and 6.2.5 and Appendix C of the EA
Baseline Environmental Data	*limited duration of groundwater monitoring – less than 2 years;* [Section 8.5, pg 70]	Sections 2.11, 2.12 and 3.2
Baseline Hydraulic Property Data	*…extremely limited measurement of strata hydraulic properties – one borehole, located outside the project area, with depth testing to about 70% of depth of cover;* [Section 8.5, pg 70]	Section 3.2
Baseline Swamp Data	*…extremely limited measurement of the hydrology of swamp lands – 3 boreholes, only one of which is located within the project area. No associated piezometers have been installed to verify perching and to monitor the underlying hardrock water table;* [Section 8.5, pg 70]	Section 6.2.7 and Appendix O of the EA

Table 2 (Cont.). Issues Raised by the Planning Assessment Commission in the Metropolitan Coal Project Review Report

Issue	Quote	Section Reference
Baseline Hydrogeological Data	*Future analyses and prediction of impacts of mining on groundwater either by the Proponent or by other mining companies in the region, give more focused consideration to:*	
	- *data assessments – the use of airborne laser survey for detailed topographic mapping, GIS of groundwater systems assessment and management, and consideration of data generated by other mine sites is encouraged.*	Sections 2.2 and 3.0
	- *wireline geophysical logging – to improve interpolation of measured hydraulic properties like permeability and porosity. Useful logs might include natural gamma; density (neutron), resistivity, sonic, acoustic scanner;* [Section 8.5, pg 72]	Sections 3.2, 6.2.4 and 6.3
Groundwater Monitoring	*In areas where natural conditions could change as a result of mining, specific monitoring regimes need to be tailored to the mine plans presented in the PPR and to address aquifer definition(s) and interactions, strata hydraulic properties, pore pressure distributions, and groundwater qualities.* [Section 19.6, pg 139]	Section 6.2
	The Panel recommends that…Groundwater monitoring regimes proposed by the SCI are incorporated into HCPL approval conditions, including requirements for:	
	- *shallow piezometer installations for the monitoring of groundwater levels/pressures within significant upland swamps, drainages and any connected alluvium. Piezometers should have sufficient distribution so as to be able to characterise the aquifer in swamps S76, S77 and S92 with a high level of confidence in potentially affected areas. Water level measurements should be automated with daily or more frequent recording.*	Sections 2.11, 2.12 and 6.2.1
	- *groundwater quality classification through regular sampling and analyses at installed piezometers. Candidate analytes must facilitate the discrimination of mining related impacts and in particular, any ionic species that might be attributed to new water/rock interactions;*	Sections 2.11, 2.12 and 6.2.2
	- *deep piezometer installations for the monitoring of pore pressures within the natural rock strata. Future piezometers should have sufficient distribution so as to be able to describe the distribution of deep aquifer pressures with a high level of confidence. Pore pressure measurements should be automated with daily or more frequent recording;*	Sections 2.11, 2.12 and 6.2.3
	- *strata hydraulic property measurements to facilitate calculation of subsurface flows. While such properties (porosity and permeability) are unlikely to change naturally over time and hence regular monitoring is not required, a properties database is required for impacts assessment and in this context, such measurement is considered to constitute baseline data. Additional core sampling and testing is recommended to confirm the presence and continuity of aquitards beneath Woronora Dam;*	Sections 2.11, 2.12, 6.2.4 and 6.3
	- *mine water balance for existing and extended operations this is an especially important part of baseline data measurements. It provides a means of confirming the groundwater transmission characteristics of the coal seam, overburden, and the drainage characteristics of goaves and the overlying failure regimes. It also provides a first indication of potentially anomalous mine water seepage that may be initiated by faulting or fracturing associated with igneous intrusions, and increased connectivity to surface drainage systems. The water balance for future operations should take into account all water imported to the underground operations or parts thereof, and all water exported from that same operations including pumped water, coal moisture increases (allowing for inherent moisture), ventilation moisture and any other exports;…* [Section 8.5, pg 71]	Section 6.2.5 and Appendix C of the EA

1.2 PROPOSED MINE DEVELOPMENT

The Project would extend the current operations at the Appin Mine and West Cliff Colliery by approximately 30 years. The main activities associated with the development of the Project would include:

- ☐ continued development of underground mining operations within existing coal leases and new mining leases to facilitate a total run-of-mine (ROM) coal production rate of up to 10.5 million tonnes per annum;
- ☐ ongoing exploration activities within existing exploration tenements;
- ☐ upgrade of the existing West Cliff Washery to support the increased ROM coal production;
- ☐ continued mine gas drainage and capture for beneficial utilisation at the West Cliff Ventilation Air Methane Project and Appin-Tower Power Project;
- ☐ continued generation of electricity by the existing Appin-Tower Power Project (owned and operated by Energy Development Limited utilising coal bed methane drained from the Bulli Seam;
- ☐ upgrade of existing surface facilities and supporting infrastructure (e.g. service boreholes, ventilation shafts, gas drainage equipment, waste water treatment and waste water disposal);
- ☐ continued and expanded placement of coal wash at the West Cliff Coal Wash Emplacement;
- ☐ continued road transport of ROM coal from the Appin East pit top to the West Cliff Washery;
- ☐ continued road transport from Appin East pit top and West Cliff pit top via the public road network of ROM coal to the Dendrobium Washery at Port Kembla;
- ☐ continued road transport of product coal from the West Cliff Washery via the public road network to BlueScope Steelworks, Port Kembla Coal Terminal, Corrimal and Coalcliff Coke Works and other customers;
- ☐ ongoing surface monitoring and rehabilitation (including rehabilitation of mine related infrastructure areas that are no longer required) and remediation of subsidence effects; 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 EA.

2.0 HYDROGEOLOGICAL SETTING

2.1 RAINFALL AND EVAPORATION

The general Project area experiences a wet temperate climate. Rainfall at Douglas Park, Wedderburn, Cataract Dam and Darkes Forest, the closest Bureau of Meteorology (BoM) rainfall gauges with reliable long-term statistics, has averaged between 758 millimetres (mm) and 1,419 mm per year (Table 3), with rainfall decreasing from east to west across the general Project area (Figure 3). Potential (pan) evaporation (based on the station at Wollongong University) is some 1,283 mm per year (Table 3). The average monthly rainfall and potential evaporation statistics from these stations are summarised in Table 3 below.

Table 3. Monthly Average Rainfall and Evaporation (mm)

Month	**Average Rainfall (mm)**				**Average Pan Evaporation (mm)**
	Douglas Park[1]	**Wedderburn[2]**	**Cataract Dam[3]**	**Darkes Forest[4]**	**Wollongong University[5]**
Jan	68	80	95	135	152
Feb	93	84	115	160	120
Mar	85	90	110	152	105
Apr	65	73	98	125	84
May	61	59	96	132	71
Jun	64	92	113	143	63
Jul	42	42	75	99	74
Aug	47	70	71	94	90
Sep	44	44	56	77	108
Oct	60	81	78	92	127
Nov	74	80	79	104	129
Dec	56	59	78	106	158
Annual Average	758	853	1,063	1,419	1,283

Source: BoM (2009).

[1] Douglas Park Station Record 1974 - 2008. BoM Site 068200.

[2] Wedderburn Station Record 1964 - 2008. BoM Site 068159.

[3] Cataract Dam Station Record 1904 - 2008. BoM Site 068016.

[4] Darkes Forest Station Record 1894 – 2008. BoM Site 068024.

[5] Wollongong University Station Record 1970 – 2008. BoM Site 068188.

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, dynamic 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 1894 is shown in Figure 4. The behaviour of the RMC for recent years is shown in more detail in subsequent Figures 19 to 21, where it is compared with groundwater hydrographic responses. There has been a pronounced dry period from 2002 to mid-2007, punctuated by minor wet periods in late 2004 and late 2005. A major wet period from June 2007 to February 2008 has been followed by another dry sequence.

2.2 TOPOGRAPHY AND DRAINAGE

There is significant topographic relief across the general Project area, and a relatively high drainage density. Surface elevations vary from approximately 100 metres (m) to 450 m Australian Height Datum (AHD) with ridgelines typically rising between 50 and 150 m above the drainage floor.

The general Project area spans the Woronora Plateau and the Cumberland Plain. The topography of the eastern part of the general Project area (i.e. on the Woronora Plateau) falls from elevations of up to 450 m AHD near Lake Cataract to elevations of 200 m AHD near the Woronora River to the north and 250 m AHD near Appin and Wilton to the north-west. The topography of the western part of the general Project area (i.e. the Cumberland Plain) slopes gently from approximately 250 m AHD in the Appin – Wilton area in the south along the Nepean Valley to 60 m AHD near Menangle Park to the north. Higher relief within the Cumberland Plain is found in the north-west of the general Project area in the vicinity of the Razorback Range, which reaches an elevation of 348 m AHD at Evelyn’s Ridge.

The topography on the Woronora Plateau consists of Hawkesbury Sandstone dip slopes falling to the north-west. The Wianamatta Group is the uppermost unit in the stratigraphic sequence across the general Project area; however on the Woronora Plateau, the Wianamatta Group occurs only infrequently as scattered remnant areas. The Wianamatta Group is predominantly found over the Cumberland Plain to the west of the general Project area (Figure 5).

Detailed topographic mapping is available across the Project extent of longwall mining area and was used in the development of the numerical model (Section 4.2). Topographic data was obtained using airborne laser scan methods across the majority of the Project extent of longwall mining area in 2005 with supplementary areas obtained in 2007.

2.3 LANDUSE

The proposed longwalls at North Cliff and Appin Areas 2 and 3 Extended are situated within a portion of the O’Hares Creek Special Area, the Woronora Special Area, and/or the Metropolitan Special Area which are owned and administered by the SCA. These three Special Areas are largely undeveloped and covered by bushland. The North Cliff longwalls are also located within portions of the Dharawal State Conservation Area.

The proposed longwalls in the western extent of the general Project area (i.e. West Cliff Area 5, Appin Area 7, Appin Area 8 and Appin West [Area 9]) are situated primarily within privately-owned lands used for residential and agricultural purposes.

Land Class 2 agricultural suitability is defined as (NSW Agriculture, 2002):

> "Arable land suitable for regular cultivation for crops, but not suited to continuous cultivation. It has a moderate to high suitability for agriculture but edaphic (soil factors) or environmental constraints reduce the overall level of production and may limit the cropping phase to a rotation with sown pastures."

The only Class 2 agricultural land located within the Project extent of longwall mining is located near the confluence of Foot Onslow Creek with the Nepean River in the north of Appin Area 7 (after NSW Department of Primary Industries [DPI] -Agriculture, 2008). There is no Class 1 agricultural land located within the Project area. The potential impacts on groundwater users located on Class 2 land is discussed in Section 6.1.4.

2.4 UPLAND SWAMPS

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

The eastern part of the Woronora Plateau has a favourable climate for upland swamp formation. Average rainfall exceeds average evaporation in most months of the year (Young, 1986). In more dissected catchments, such as parts of the O'Hares Creek catchment within the study area, the swamps are confined largely to headwater tributaries (Young, 1986). Hawkesbury Sandstone provides a low permeability base on which the swamp sediments and organic matter rest. Hawkesbury Sandstone is also the predominant source of sediment for the upland swamps (*ibid.*). Erosion of the sandstone surface of the plateau supplies largely medium-coarse sand to the valleys in which the swamps lie.

The sandy sediment accumulation in the swamps along with the dense hydrophidic vegetation and associated decaying organic matter, traps rainfall infiltration, seepage and low-flow runoff. Rainfall infiltrates the accumulating swamp material with drainage impeded by low floor slope, the low permeability sandstone base and the dense swamp vegetation. Partially decayed organic matter accumulates in the sediments, further increasing their water-holding capacity (Young, 1986).

There is a number of ways to define or categorise the upland swamps of the Woronora Plateau (Young, 1986 and NPWS, 2003). In this case it is useful to categorise the swamps on the basis of broad geomorphological features and landscape position as these inform the assessment of the types and magnitude of subsidence movements that would be experienced at the swamp as well as how the swamp processes may be impacted by these movements. Broadly, upland swamps can be classified as headwater upland swamps and in-valley upland swamps (also called in-stream, in valley or valley floor swamps). Some characteristics overlap between headwater upland swamps and in-valley upland swamps resulting in larger swamps transitioning from headwater in one part to in-valley in another and making some swamps difficult to classify definitively (Planning and Assessment Commission, 2009).

Headwater upland swamps (Figure 6a) 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. The water levels within the swamps fluctuate seasonally with climatic conditions, as rain adds to soil moisture and evapotranspiration slowly removes moisture from storage (Figure 6b). Excess rainfall produces a perched water table within the sediments that is independent of the regional water table in the underlying Hawkesbury Sandstone. During rain events, some stream flow and runoff along indistinct braided channels occurs.

The growth of dense vegetation and the low land gradient generally prevent the formation of an open drainage channel that would otherwise transport water and sediments. Due to gentle gradients, only the largest upland swamps have open channels near the downstream end, sometimes with a series of discontinuous elongated pools in the valley axes further upstream. In some headwater upland swamps, there is likely to be minor groundwater seepage from outcropping sandstone at the edges of the swamp or from any nearby hillslope aquifers.

In-valley upland swamps have multiple sources of water and are primarily sustained by stream flow (including a groundwater derived baseflow component) along distinct channels, supplemented by rain infiltration. In-valley swamps 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 the proximity of the eastern mining domains (i.e. North Cliff and Appin Areas 2 and 3 Extended), a number of upland swamps have been identified (FloraSearch, 2009). The characteristics of these swamps are provided in Appendix O of the EA (Upland Swamp Risk Assessment) and a figure showing the location of these swamps is presented in Appendix E of the EA (Terrestrial Flora 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;
- Baseflows in streams;
- Aquifer and cave ecosystems; and
- Wetlands.

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

The potential impacts of the Project on groundwater dependent ecosystems that may occur within the general Project area are described in Appendix C (surface water assessment), Appendix D (aquatic ecology assessment), Appendix E (terrestrial flora assessment) and Appendix F (terrestrial vertebrate fauna assessment) of the EA.

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 7). At the top of the sequence in the area of interest is the Hawkesbury Sandstone overlain by the Wianamatta Group (Figure 5).

The majority of mining in the Southern Coalfield extracts coal from the Bulli or Wongawilli Seams, with some mining also occurring in the Balgownie Seam (DoP, 2008). The coal seams generally deepen from south to north, with mining activities in the south extracting coal from around 100 m below the surface. In the north, mining is more than 500 m below the surface (*ibid*.). Mining depths would be up 800 m in the north-west of the extent of the Project longwall mining area.

A summary of the lithology as described in records held by the ICHPL Resource and Exploration Department is provided below. A geological cross section of the general Project area is shown on Figure 8. A number of exploration, service and related boreholes have been drilled across the general Project area as shown on Figure 9. Registered bores within the Project area are shown on Figures 10a to 10d.

Wianamatta Group (variable thickness) - is the uppermost unit in the stratigraphic sequence in the west of the general Project area (i.e. the Cumberland Plain). The Wianamatta Group is prominent in the West Cliff Area 5, Appin Area 7, Appin Area 8 and Appin Area West [Area 9] domains. This unit supports the agricultural activities that cover most of Appin Area 7. The Wianamatta Group only occurs as scattered remnant areas in the east of the general Project area (i.e. North Cliff and Appin Areas 2 and 3 Extended).

Hawkesbury Sandstone (169 m median thickness) - is the uppermost unit in the stratigraphic sequence in the eastern extent of the general Project area (i.e. North Cliff and Appin Areas 2 and 3 Extended) associated with the Woronora Plateau and consists of thickly bedded or massive quartzose sandstone (with grey shale lenses up to several metres thick).

Narrabeen Group (311 m median thickness) – the sequence 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 extent of longwall mining area. The Narrabeen Group consists of the Newport, Garie, Bald Hill Claystone, Bulgo Sandstone, Stanwell Park Claystone, Scarborough Sandstone, Wombarra Claystone and Coal Cliff Sandstone, which are described below.

Newport Formation (13 m median thickness) - the uppermost stratum of the Narrabeen Group and consists of interbedded grey shales and sandstones. The Newport Formation varies in thickness across the extent of longwall mining area, from 12 m at North Cliff and Appin Areas 2 and 3 Extended to 24 m in Appin Area 7.

Garie Formation (3 m median thickness) - consists of cream to brown, massive, characteristically oolitic claystone. The Garie Formation has a near constant thickness of 3 m across the general Project area.

Bald Hill Claystone (25 m median thickness) - consists of brownish-red coloured "chocolate shale", a 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 and across the Project area (Section 2.8). It has an average thickness of 26 m, with standard deviation 16 m, and a minimum recorded thickness of 8 m from 373 recordings.

Bulgo Sandstone (173 m median thickness) - consists of strong, thickly bedded, medium to coarse-grained lithic sandstone with occasional beds of conglomerate or shale. The unit thickens north-westerly from 161 m at North Cliff and Appin Areas 2 and 3 Extended to 220 m at Appin Area 7.

Stanwell Park Claystone (17 m median thickness) - consists of greenish-grey mudstones and sandstones. The claystone thickens north-westerly from 6 m at North Cliff and Appin Areas 2 and 3 Extended to 20 m at Appin Area 7.

Scarborough Sandstone (33 m median thickness) - consists mainly of thickly bedded sandstone with shale and sandy shale lenses up to several metres thick.

Wombarra Claystone (32 m median thickness) - has similar properties to the Stanwell Park Claystone. The claystone thickens south-easterly from 30 m at Appin Area 7 to 41 m at North Cliff and Appin Areas 2 and 3 Extended.

Coal Cliff Sandstone (16 m median thickness) - consists of basal shales and mudstones that are contiguous with the underlying Bulli Coal seam. In the coastal region of the Coalfield the Coal Cliff Sandstone is a strong quartzose sandstone. Westward, away from the coast, dominance of the sandstone diminishes and in many areas the roof strata of the Bulli Seam, a shale/mudstone unit (which can become laminated in places), is prominent. The sandstone is common as erosive channels across Appin Area 7 and has completely eroded the mudstone unit in several areas and in some instances into the Bulli Seam.

Illawarra Coal Measures - consist of interbedded shales, mudstones, lithic sandstones and coals, including the Bulli Seam, Loddon Sandstone, Lawrence Sandstone, Eckersley Formation, Wongawilli Coal and Kembla Sandstone. The Bulli Coal seam is described below.

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 the Appin Mine and West Cliff Colliery and would continue to be mined as part of the Project.

2.7 STRUCTURAL GEOLOGY

Within the Project extent of the longwall mining area, the Bulli Seam is located between approximately 300 m (in the south-east) and 850 m (in the north-west) below the surface and is the uppermost seam of the Illawarra Coal Measures. It has a regional dip to the north-west of about 1 in 30 and reflects the synclinal structure of the Douglas Park and Camden Synclines within the general Project area. The strata around the Bulli Seam provides good conditions for longwall mining and in particular the floor is hard and competent (Moffitt, 2000). The immediate roof can range from mudstone, interbedded siltstone and sandstone, to sandstone (*ibid.*).

A review of exploration data in the ICHPL Resource and Exploration Department records (ICHPL, 2009) was undertaken across the general Project area and surrounds.

There are a number of known major structures (e.g. faults or fault systems) in the vicinity of the Project underground mining areas including the following:

- Nepean Fault Zone;
- O’Hares Fault;
- J-Line Fault;
- Area 7 series (A7F6 to A7F13);
- Stokes Fault System;
- Hakea Fault System;
- Scarborough Fault;
- Dahlia Fault;
- Pig Farm Fault; and
- Cobbong Fault.

The locations of the known major structures listed above are provided in Appendix A of the EA (Subsidence Assessment). Extensive surface based exploration is used to define major faulting and potential longwall domains between the structures. The surface exploration utilises techniques including 2D and 3D seismic, magnetic surveys, lineament analysis, vertical boreholes and ‘surface to in-seam’ (MRD) boreholes. The exploration techniques are used within the constraints imposed by the topography, surface development and the property access.

In addition to the surface based exploration, the underground mining operations at Appin Mine and West Cliff Colliery undertake in-seam drilling in advance of all development underground. In-seam drilling is undertaken in order to identify minor geological structures and drain the gas from the Bulli Seam (and adjacent strata). The in-seam drilling has been undertaken since the 1970s to prevent outbursts (gas driven ejection of coal from the active mining face) which have caused fatalities in the Southern Coalfield. The in-seam drilling is undertaken in advance of all development roadways and has the effect of draining the water and gas in advance of the workings. In-seam drilling is very effective at detecting any hydraulically charged geological structure because the drilling is undertaken from beneath the potential feature and the head would drive the water out of the hole making it readily apparent to the drill operator. Since the drilling commenced in the 1970s no hydraulically charged structures have been intersected at West Cliff Colliery or Appin Mine.

In the year ending June 2009, Appin Mine and West Cliff Colliery had drilled 194,819m (89,634m and 105,185m respectively) of in-seam holes and this is typical of the level of drilling undertaken each year in advance of ICHPL's operations. As a result of the surface and in-seam drilling there is negligible risk of intersecting hydraulically charged geological structures in the workings. The longwalls are designed around geological structures, where the displacement is greater than ~5 m.

The exploration activities described above are also used to identify intrusions. Few intrusions of significance are known within the extent of longwall mining area. There is a tendency for intrusions to be associated with synclinal structures (e.g. the Douglas Park and Camden Synclines). Igneous dykes and sills have been mapped on the surface at various sites across the general Project area. No diatremes have been identified within the extent of longwall mining area (after ICHPL, 2009).

Faults and dykes have the potential to adversely affect underground longwall mine development and extraction and would require specific management measures (e.g. dyke extraction by road header and installation of additional ground support as required). Due to the uncertainty in location and persistence of such structures throughout the Project area, they have not been included in the numerical model simulation (Section 9.0).

2.8 HYDROGEOLOGY

Apart from coal seam aquifers at depths of greater than 300 m (Figures 11 and 12), the recognised aquifers in the stratigraphic sequence at the Project are the Hawkesbury Sandstone and the sandstones of the Narrabeen Group. Whilst of low permeability, the Hawkesbury Sandstone has the relatively higher permeability (Section 3.2) compared to other units and is 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. Due to alternation of sheet and massive facies, groundwater flow is primarily horizontal with minor vertical leakage. Perched water tables (i.e. hydraulically disconnected from the regional aquifer) can be expected in elevated sandstone areas, adjacent to cliff faces and within upland swamps.

The Wianamatta Group outcrops in the western area of interest in the form of the Cumberland Plain, as shown in Figure 5. Vertical flow continuity within the Wianamatta Group is retarded by the Ashfield Shale. This is consistent with SCA's findings in the Upper Nepean (Kangaloon) Borefield Project Environmental Assessment (KBR, 2008) which states:

> *The Ashfield Shale and Mittagong Formation (where present) impede the vertical flow of groundwater because they behave as aquitards.*

The Ashfield Shale is thought to occasionally have a temporary or perched water table zone, with deeper water tables (if present) leaking to the underlying aquifer, in this case the Hawkesbury Sandstone (KBR, 2008). Permeability in the Ashfield Shale is mostly associated with bedding plane separations (*ibid*.).

Vertical continuity of Hawkesbury Sandstone with the underlying Narrabeen Group aquifer is interrupted by a major aquitard, the Bald Hill Claystone. The thickness of the Bald Hill Claystone is generally consistent and continuous across the general Project area (ICHPL, 2009) (Figure 8). The continuity and consistency of the Bald Hill Claystone across the Project area was confirmed by comparing the thickness based on observations of 373 geological logs. 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).

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 13). In the vicinity of the Project, the salinity is generally in the range 1,000-3,000 milligrams per litre (mg/L) (refer to Section 2.13).

The Project lies within three groundwater flow systems (GFS) as defined by Grey and Ross (2003): (a) GFS5 Hawkesbury Sandstone – South-East; (b) GFS6 Hawkesbury Sandstone – Confined; and (c) GFS16 Wianamatta Shale – Sydney.

GFS5, in the eastern part of the general Project area, 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 just 55 megalitres per year (ML/year). This contrasts with a sustainable yield estimate of 58,000 ML/year (58 gigalitres per year [GL/year]) (Grey and Ross, 2003). There are no high yield bores (>6 litres per second [L/s]) identified within the GFS.

GFS6 in the western part of the general Project area consists of Hawkesbury Sandstone where it is capped by shale. Groundwater development is moderate, with 1008 bores at a density of 0.4 bores per square kilometre (km^2). Total entitlements of 3.5 GL/year are much less than the sustainable yield estimate of 49 GL/year (Grey and Ross, 2003). About 2% of bores have reported yields in excess of 6 L/s.

GFS16 comprises Wianamatta Shale, Ashfield Shale and Mittagong Formation. Groundwater development is low, given low yields (<2 L/s) and brackish to saline water quality.

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 where yields are in the order of 1-3 L/s. High yields (~30 L/s) have been found in the Kangaloon and Leonay-Wallacia 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. However, the Project sits in a relatively undisturbed area, suitable for longwall mining, and does not have any substantial commercial groundwater production from the Hawkesbury Sandstone.

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 very low permeability of the Narrabeen Group lithologies is substantiated by the common experience of “dry mines” in the Southern Coalfield. However, in the Blue Mountains to the north-west of the general Project area, the Narrabeen Group yields water for domestic and garden use. Very little is known of groundwater quality in the Narrabeen Group. In mid-upper levels (Bulgo Sandstone), KBR (2008) notes total dissolved solids (TDS) as <1500 mg/L. In lower levels (Scarborough Sandstone) Short et al. (2007) measured the electrical conductivity (EC) of six samples as 850 ± 96 microSiemens per centimeter (μS/cm).

2.9 GROUNDWATER BORE CENSUS

As of June 2009, according to the Natural Resources Atlas (http://test.nratlas.nsw.gov.au) there are 190 registered bores in the vicinity of the Project. The bore locations are shown on Figure 10a, and bore details are summarised in Attachment A.

Some of the bores do not have reported/surveyed surface collar levels; therefore groundwater elevations are estimated from approximate ground levels. The majority of historical data from DWE bores is limited to notes on levels and salinity records taken at the time of installation.

2.10 GROUNDWATER EMBARGO ZONES

The DWE confirmed the existence of groundwater zones where an embargo on any further applications for sub-surface water licences applies in the Southern Coalfield (ordered under section 113A of the Water Act, 1912), including:

- ☐ Nepean Sandstone Water Shortage Zone GWMA 607 (gazetted 8 June 2007); and
- ☐ NSW Southern Highlands (gazetted 21 May 2004 and 16 December 2005).

The Nepean Sandstone Water Shortage Zone GWMA 607 is the nearest groundwater zone where an embargo applies, located approximately 5 km north-west of the Project extent of longwall mining area. Due to the large separation distances, the predicted depressurisation as a result of the Project longwall mining operations (Section 6.1.2) would not have any effect on these groundwater zones.

2.11 GROUNDWATER MONITORING

Groundwater quality sampling and water level monitoring in the general Project area has historically been undertaken by ICHPL and DWE in accordance with the National Water Quality Management Strategy Guidelines for Groundwater Protection in Australia (ARMCANZ/ANZECC, 1995). Groundwater quality sampling by ICHPL has been primarily focused on the areas of the Georges, Cataract and Nepean Rivers, and is associated with areas of proposed or recently completed mining.

Groundwater levels are recorded by ICHPL from shallow piezometers in the Georges, Cataract and Nepean Rivers, and from deep piezometers in the Bulli Seam, spread over the general Project area. ICHPL have also recently installed multi-level piezometers in the Appin Area 7 and Appin West (Area 9) areas.

Groundwater monitoring programmes are currently active in the Longwalls 29 to 36, 409 and 701 to 710 areas. Data is typically reported following completion of each longwall panel. Details of the current monitoring programme for these areas are summarised in Table 4. Groundwater monitoring locations are shown on Figures 10a to 10d.

Table 4. Previous and Existing Monitoring Programmes

Parameters	Monitoring Site	Frequency
- Shallow groundwater levels[1].	- GR01-GR39. - GR49-GR55, GR57, GR58. - GR59-GR64 - GR65-GR67.	- Weekly. - Weekly. - Continuous. - Weekly.
- Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Dissolved Oxygen concentration (DOC), Chemical Oxygen Demand (COD), Biological Oxygen Demand (BOD), Total Organic Carbon (TOC). - pH. - SO_4. P_{tot}. - Ca. Mg. Na. K. Fe. Fe_{tot}. Al. As. Cu. Mn. Ni. Pb. Se. Zn. Al_{tot}. $Mn_{tot.}$ Ba. Cs. Li. Rb. Cl. Fl. Br. I. B. - Hydroxide as OH, Carbonate as $CaCO_3$, Bicarbonate as $CaCO_3$, Alkalinity as $CaCO_3$, Ammonia as N, Nitrite as N, Nitrite and Nitrate as N, Total Kjeldahl Nitrogen as N (TKN), Total Nitrogen as N, Total Cations, Total Anions, Actual (Anion/Cation) Diff, Allowed (Anion/Cation) Diff, Ionic Difference %.	- GR 27, GR 29.	- Three water quality samples taken (12, 6 and 1 month) before mining to form a baseline. - Three water quality samples taken (1, 6 and 12 months) after mining to form a basis for comparison.
- Shallow Groundwater Levels[3]. - Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Dissolved Oxygen concentration (DOC), Methane (CH_4), Ethane (C_2H_6), Trace Phenols, Sulphide. - pH. - SO_4. P_{tot}. - Ca. Mg. Na. K. Fe. Fe_{tot}. Al. As. Cu. Mn. Ni. Pb. Se. Zn. Al_{tot}. $Mn_{tot.}$ Cl. Br. I. - Total Alkalinity, TKN, Ammonia as N, Nitrite and Nitrate as N, Dissolved Phosphorous (FRP).	- NGW3, NGW4, NGW5, NGW6, NGW7, NGW9, NGW10, NGW11.	- Monthly water levels. - Water quality tested prior to extraction of an underlying longwall or adjacent longwall and following the incremental subsidence of each longwall that is likely to impact on the bore.
- Shallow Groundwater Levels[4]. - Electrical Conductivity (EC), Temperature, Total Dissolved Solids (TDS). - pH. - SO_4. P_{tot}. - Ca. Na. K. Fe. Fe_{tot}. Al. As. Cu. Mn. Ni. Pb. Se. Sr. Zn. Al_{tot}. $Mn_{tot.}$ Ba. Cs. Li. Rb. Cl. F. - Total Alkalinity, TKN, Total Ammonia (NH3-N), Total Nitrite and Nitrate nitrogen (NOx).	- NGW3, NGW4, NGW5, NGW6, NGW7, NGW9, NGW10, NGW11.	- Standing water levels measured (hourly) and data logged twice daily in the baseline, impact and post-mining period. - Water quality tested at least once from each piezometer in the pre-mining phase. - Water quality test repeated at the end of mining Longwalls 702, 703 and 704 (or if trigger reached during mining).
- Shallow Groundwater Levels[5]. - Electrical Conductivity (EC), Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Dissolved Oxygen concentration (DOC). - pH. - SO_4. P_{tot}. N_{tot}. - Ca. Mg. Na. K. Fe. Fe_{tot}. Al. As. Cu. Mn. Ni. Pb. Se. Zn. Ba. Sb. Sr. Al_{tot}. $Mn_{tot.}$ F. Cl. Br. I. - Total Alkalinity, TKN, Ammonia as N, Nitrite and Nitrate as N, Ammonia as N, Total Cations, Total Anions.	- A3GW1, A3GW2, A3GW3, A3GW4, A3GW5, A3GW6, A3GW7, A3GW8.[6]	- Continuous water level data logged hourly. - Three water quality samples taken from each piezometer in the pre-mining phase. - Three water quality samples taken from each piezometer at the end of mining Longwalls 301, 301A and 302.

1 West Cliff Area 5 Longwalls 31 to 33 (pt) – Monitoring Programme (ICHPL, 2005a).
2 West Cliff Area 5 Longwalls 34 to 36 Subsidence Management Plan Application (Cardno Forbes Rigby, 2008a).
3 Appin Area 7 Longwalls 705 to 710 Subsidence Management Plan Application (Cardno Forbes Rigby, 2008b).
4 Douglas Area 7 Longwalls 701 to 704 Groundwater Assessment (GeoTerra, 2006).
5 Appin Area 3 Subsidence Monitoring Programme (ICHPL, 2005b).
6 Each site has three boreholes with the exception of A3GW4 which has two boreholes.

Data from selected DWE registered bores is also recorded in the vicinity of the current mining areas, as shown in Table 5 and Figure 10a.

Table 5. DWE/Private Bore Monitoring

Parameters	Monitoring Site	Frequency
• Shallow Groundwater Levels[1]. • Electrical Conductivity (EC), Temperature, Total Dissolved Solids (TDS). • pH. • SO_4. P_{tot}. • Ca. Na. K. Fe. Fe_{tot}. Al. As. Cu. Mn. Ni. Pb. Se. Sr. Zn. Al_{tot}. $Mn_{tot.}$ Ba. Cs. Li. Rb. Cl. F. • Total Alkalinity, Total Kjeldahl (TKN), Total Ammonia (NH3-N), Total Nitrite and Nitrate nitrogen (NOx).	• GW101437, GW104154, GW034425, GW102584, GW103161, GW104602, GW104661, GW102043, GW102798, GW104068, Lot1, Lot24/25.	• Standing water levels measured at least once before the area is mined under in all available private bores, as well as at least once after each bore is mined under. • Water quality tested at least once from each private bore in the pre-mining phase.

1 Douglas Area 7 Longwalls 701 to 704 Groundwater Assessment (GeoTerra, 2006).

In addition to the above, pool levels are monitored at a number of surface water locations discussed in Gilbert & Associates (2009).

The groundwater quality data acquired from shallow piezometers are documented in Attachment B. Analysis of groundwater levels recorded across the general Project area is provided in Section 2.12.2.

Piezometers in the Bulli Seam (i.e. shown as Deep Piezometers on Figure 10a) have been used to contour the Bulli Seam water level shown in Figure 14. Deep piezometers in the Bulli Seam have been monitored by ICHPL since 2004. Actual measurements are supplemented by Bulli Seam floor levels to the east (in previously mined areas) where there are no measurements to date.

Multi-level piezometers installed at four locations (i.e. EAW5, EAW7, EAW9 and EAW18) in the Appin Area 7 and Appin West (Area 9) areas (Figure 10a) have been acquiring data since 2008. The bores are drilled over areas yet to be mined. Information provided by these deep holes is discussed in Section 2.12.3. An additional three holes (S1993, S1996, S1997; Figure 10a) were established in 2009 but time series data were not available in time to incorporate into the numerical model in this assessment.

Bore EAW5 reached a depth of 559.50 m from a collar elevation of 117.04 mAHD. Data has been collected from EAW5 since May 2008.

Bore EAW7 reached a depth of 556.10 m from a collar elevation of 148.14 mAHD. Data has been collected from EAW7 since September 2008.

Bore EAW9 reached a depth of 596.00 m from a collar elevation of 146.82 mAHD. Data has been collected from EAW9 since October 2008.

Bore EAW18 reached a depth of 742.90 m from a collar elevation of 309.99 mAHD. Data has been collected from EAW18 since December 2008.

Bores S1993, S1996 and S1997 were drilled to depths of 516 m, 491 m and 578 m, respectively, from collar elevations of 164.39, 381.65 and 370.17 m AHD, respectively.

The density, duration and scale of the groundwater monitoring data were considered adequate to inform the development of the numerical groundwater model and to conduct an assessment of potential hydrogeological impacts. A proposed groundwater monitoring programme and geological investigation programme is provided in Sections 6.2 and 6.3, respectively, to address the issues raised in the Southern Coalfield Inquiry Report (DoP, 2008) and by the Planning Assessment Commission in the Metropolitan Coal Project Review Report (Planning Assessment Commission, 2009).

2.11.1 Bulgo Sandstone Injection Trial

Mine water injection into the Bulgo Sandstone was trialled at Appin Mine between November 1997 and November 2006 as a method of discharging excess saline mine water. The injection trial was licensed by the NSW Department of Environment and Climate Change (DECC) (under Environment Protection Licence [EPL] No. 758) and designed to ensure that the water was injected into the target Bulgo Sandstone. Saline minewater continued to be discharged via water injection into the Bulgo Sandstone until June 2006, when saline minewaters were transferred and treated at the Appin West Water Filtration Plant, under EPL No. 398. Water injection of mildly saline surface waters continued until 14th April 2008, when the injection lines and pump were decommissioned.

Water was discharged to the injection boreholes by two pipelines known as Line 1 and Line 2. Line 1 serviced boreholes Appin 45, Appin 47 and Appin 84 and Line 2 serviced boreholes Appin 33, Appin 34, Appin 35, Appin 41, Appin 65, Appin 103 and Appin 104 (Figure 10d). The first boreholes utilised were all drilled prior to extraction in the area. Their original purpose was to allow gas drainage from the Bulgo Sandstone strata to the surface. Boreholes Appin 65, Appin 84, Appin 103 and Appin 104 were purpose designed and drilled for the strata injection.

Injection into the drilled boreholes ranged from very limited capacity in some holes (i.e. Appin 45) to up to 450 litres per minute (L/min) into Appin 47 (after ICHPL, 2002; 2005c). Injection of water into the Bulgo sandstone was achieved at rates up to approximately 2 megalitres per day (ML/day) (after ICHPL, 2002; 2005c). Each injection borehole was equipped with a vibrating wire piezometer and data logger to measure potentiometric head, and strata properties including transmissivity, virgin porosity and salinity were also recorded. The hydraulic properties observed during the trial are consistent with the values used in the numerical model (Section 3.2).

2.12 BASELINE GROUNDWATER LEVEL DATA

2.12.1 Shallow and Deep Spatial Groundwater Levels

Natural groundwater levels are sustained by rainfall infiltration and are controlled by ground surface topography, geology 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 find expression in the shape of the water table, and will influence the hydraulic gradients that drive vertical groundwater flow near the ground surface. 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 at DWE bores or measured from shallow piezometers near the Nepean, Cataract and Georges Rivers (Figure 15). The dataset has been supplemented with surface water levels in no-data areas, assuming equivalence between surface water and groundwater levels along drainage lines.

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 the same groundwater flow pattern. As groundwater will flow perpendicular to the contours, in general (except for discrete fracture flow), the groundwater in the upper part of the Hawkesbury Sandstone will flow from the ridges to the natural surface drainages. The Nepean River is a prominent groundwater discharge feature.

Of significance is that the direction of groundwater flow has not reversed as a result of mining in nearby areas (e.g. previous mining in the Appin area, and recent mining at Metropolitan Colliery). At Appin, groundwater maintains a flow direction from elevated land in the south-east towards the Nepean River to the north-west. At the Metropolitan mine, the shallowest piezometer at the LW10 goaf hole has a total head that is well above the water level in the Waratah Rivulet (Heritage Computing, 2008). This high gradient will maintain horizontal flow through the Hawkesbury Sandstone to the Waratah Rivulet (*ibid*.).

The magnitude of the flow is controlled by the horizontal hydraulic conductivity of the sandstone. 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.

2.12.2 Temporal Shallow Groundwater Levels

In the Southern Coalfield, shallow groundwater levels show a variable response to deep mining. At many places there is no effect at all. Elsewhere, there are clear effects. Whether or not there is a response seems to depend on the randomness of surficial cracks or bedding plane separations.

For example, there is compelling evidence at bore DDH34 at Dendrobium Colliery to the south of the Project area that shows no change in water table elevation as longwall mining passes by (as “LW Chainage” approaches zero) (Figure 16), 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 at this location, there is clear isolation between the two aquifer zones.

Similarly, long-term pumping trials beneath Stockyard Swamp (Figure 17) and Butlers Swamp (Figure 18) at the planned Kangaloon Borefield near Robertson (about 40 km south-west) 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 a deeper formation is depressurised.

In the Project area, shallow groundwater levels are being monitored in proximity to three rivers at locations shown in Figure 10a:

- ☐ Georges River (Figure 10b): 58 piezometers at 58 sites;
- ☐ Nepean River (Figure 10c): 8 piezometers at 8 sites; and
- ☐ Cataract River (Figure 10d): 23 piezometers at 8 sites;

Georges River

The monitoring bores adjacent to the Georges River (Figure 10b) are based in Hawkesbury Sandstone at depths ranging from 10 m to 51 m, with average 19 m and median 16 m.

There is considerable documentation on the impacts of mining in 2000 to 2003 of Longwalls 5A1 (LW25) to 5A4 (LW28) on the Georges River in the vicinity of Jutts Crossing and Marhnyes Hole, and subsequent remediation (BHP Billiton, 2006). That material will not be repeated here. However, one hydrograph from the affected area is given in Figure 19a for Bore GR20 (depth 30 m) to show that responsiveness to rainfall in recent years has restored groundwater levels to near-normal. This bore lies over Longwall 5A3 (LW27), and appears to have been affected by the passage of Longwall 5A4 (LW28) in October 2002 (Figure 10b).

Figure 19b shows an unexpected rising water level trend at Bore GR24 (depth 12 m), about 800 m east of Longwall 31 and 400 m east of the river (Figure 10b). It is responsive to rainfall events, but the water level continues to rise during drier periods. This suggests an alternate source of water, or enhanced recharge potential from rainfall perhaps due to surficial cracks induced by valley closure.

Longwall 33 is currently being mined (Figure 10b). Figure 19c shows hydrographic responses at bores in the vicinity of recent mining of Longwalls 29-33. There is a clear mining effect at Bore GR23 (depth 36 m) which lies over the eastern end of Longwall 29; water level dropped initially by 7 m and then settled 5 m lower; readings have not been taken since late 2004. Bore GR25 (depth 25 m) lies at the south-eastern corner of Longwall 31a; there is no apparent mining effect, but there is a general correlation with rainfall trends. Bore GR67 is a shallow bore (depth 10 m) adjacent to Pool 34 at the north-eastern corner of Longwall 31a; this bore is very responsive to rainfall events but as water level appears to be often lower than river level, the river must be losing water to shallow groundwater storage. Regionally, however, away from the river, groundwater levels are much higher than river levels. This indicates that the river system (comprising surface flow and underflow) is a gaining system in the sense of receiving regional groundwater discharge.

Nepean River

The NGW bores (Figure 10c) range in depth from 66.7 to 77.7 m depth, with bottom elevations a little below river bed elevation. Representative hydrographs for the Nepean River bores from 2004 are shown on Figures 20a to 20c. Bore NGW9 lies 1.3 km to the east of the eastern end of Longwall 702, and is far from any prior mining (Figure 10c). Its hydrograph (Figure 20a) shows a very strong correlation with rainfall trends implicit in the rain residual mass curve from 2004 to early 2008, after which time water levels have remained high despite declining rainfall.

Figure 20b shows the hydrographs for Bore NGW4 lying over Longwall 702 and Bores NGW5 and NGW6 between Longwall 702 and the river (Figure 10c). Longwall 702 commenced in September 2008 and finished in April 2009, working from east to west. Prior to mining, there was a mild correlation with rainfall, with a natural variation of 2 m amplitude at NGW4. There is no apparent correlation with river stage, apart from a spiked response at NGW6 in June 2007. The period of rising water level during 2005-2006 at NGW6 coincides with the commencement of development headings in April 2005, at a distance of 1.2 km to the south-south-east of NGW6. The headings passed by NGW6 in August 2006, after which time the water levels stabilised. The responses are not due to longwall mining as they post-date the nearest mining at Tower Longwall 20 from May to November 2002.

There is a clear response at each Bore to the passage of Longwall 702, with initially increased water levels followed by a sharp water level decline, with recovery to normal levels at the completion of the panel. This can be explained as an initial impulse at the nearest bores (NGW4 and NGW6), followed by increased permeability from probable bed separation due to differential subsidence as mining passes underneath, and restoration of permeability as dilation settles down. The temporary permeability changes are expected to be localised. Although the water level at NGW4 drops well below river level (by about 6 m), the water levels at NGW5 and NGW6 remain higher than river level, although NGW6 is almost coincident at times. There is likely to be reduced baseflow from the aquifer to the river from November 2008 to March 2009, with the distinct possibility of minor leakage from the river to the aquifer during this period where mining comes closest to the river.

Figure 20c shows the hydrographs for Bores NGW7, NGW10 and NGW11 adjacent to development headings at the eastern end of Longwall 702 (Figure 10c). NGW10 differs from the other two quiescent responses in that it has a large decline (total 11 m) originating at April 2005 and July 2006. The reason for this response is unknown. The development headings commenced in April 2005, at a distance of 1.8 km to the south of NGW10. The headings passed by NGW10 in February 2007, after which time the water levels stabilized (except for a sampling episode in December 2007). NGW7 is not similarly affected, although it is just as close to the development headings which passed by in July 2006. However, there are mild responses that could be caused by the development headings. Both NGW7 and NGW11 show mild declines at the commencement of Longwall 702. Rainfall responses are barely perceptible. As all groundwater levels are substantially above river level (about 61 mAHD), permanent groundwater discharge to the river is assured.

The passage of the northerly development headings on the eastern side of Longwalls 701-703 has had a relatively large effect on the water levels at NGW6 and NGW10 (Figures 20b and 20c, respectively). As NGW6 rises, NGW10 falls. As the direction of the headings parallels a near-linear reach of the Nepean River, it is possible that fault control is complicating the groundwater responses.

Cataract River

The monitoring bore cluster near the Cataract River lies 1 to 3 km east of Broughtons Pass Weir (Figure 10d). Bores A3GW2,3,5 are positioned over extracted Longwalls 301 and 302; A3GW7 is adjacent to headings to the north-west of these longwalls; A3GW1 is on open ground 500 m west of Longwall 301; and Bores A3GW4,6,8 are south of the river over longwalls to be mined as part of this Project. Most sites have three multi-level piezometers labeled A (deepest, 20-60 m depth), B (15 to 20 m depth) and C (shallowest, 10 m depth). Representative hydrographs for bores A3GW2 (Longwall 301) and A3GW5 (Longwall 302) from 2006 are shown in Figures 21a and 21b, respectively. Pronounced head differences of 45-60 m between the C and A piezometers, and different dynamic patterns, suggest a sequence of perched water tables through the Hawkesbury Sandstone at shallow depths. As all water levels are above river level, continuous baseflow would occur.

A3GW2 (Figure 21a) shows a rise in water level of about 3 m at the A level due to the passage of Longwall 301 and a mild decline when mining passes by in adjacent Longwall 302; the upper B and C levels seem unaffected by Longwall 301 mining directly beneath, but they do respond to adjacent mining in October 2007; rainfall correlation is mild but is best developed at the uppermost C level. Water levels have been fairly stable during the dry period from March 2008 to March 2009, with only a small decline at upper levels C and B, and a small rise at deepest level A.

A3GW5 (Figure 21b) shows a decline in water level of about 2 m at the deepest A level due to the passage of adjacent Longwall 301 and a mild rise followed by a large decline (14 m) when Longwall 302 mining passes underneath; in March 2008, the depleted water level at A rises sharply (by 6 m) and returns to normal levels after heavy rain; the upper B and C levels seem unaffected by Longwall 302 mining directly beneath, and seem to have responded selectively to the heavy rainfall event in June 2007 but not to other events. Water levels have been fairly stable during the dry period from March 2008 to March 2009, except for a 2 m decline at uppermost level C.

A3GW3 (over Longwall 302) has similar mining effects at the A level to what has been observed at A3GW5, but there are clear mining responses at B and C levels also. Bores south of the river have very flat responses with very little rainfall contribution.

The observed variable responses at the three sites over the two longwalls suggest that water level changes are induced by bedding plane separation of limited extent. There is no clear evidence to suggest connective vertical fractures between the aquifers because a substantial head difference is maintained between the piezometers, irrespective of mining.

2.12.3 Deep Groundwater Piezometric Analysis

Four surface-to-seam multi-piezometer holes have been acquiring continuous data since May 2008 (EAW5 at Appin Area 7), September 2008 (EAW7 at Appin Area 7), November 2008 (EAW9 at Appin West Area 9) and January 2009 (EAW18 at Appin West Area 9). Additional surface-to-seam multi-piezometer holes are recently been established (S1993 at Appin Area 7; S1996 at Appin Area 2 Extended; and S1997 at North Cliff). To the east of the Project area, the Metropolitan mine is also establishing a network of surface-to-seam multi-piezometer holes. The data for two of those holes (LW10 goaf, PM02) have been made available for this study. All bore locations are shown in Figure 10a.

Vertical Gradients

Representative vertical hydraulic gradient profiles are shown in Figures 22 to 28. In the western part of the general Project area, away from mining, groundwater heads at depth tend to be higher than those observed in the Hawkesbury Sandstone. In the east, heads are fairly uniform with depth, but decline with depth in areas close to mining.

At EAW5 (Figure 22), head declines linearly in the Hawkesbury Sandstone. Beneath the Bald Hill Claystone, the heads become artesian (at or above ground level), except for a slightly lower head in the Bulli Seam. There is a clear difference in the behavior of groundwater pressures above and below the Bald Hill Claystone, which is evidence of the contiguous nature of the claystone across the general Project area, and evidence of the pre-mining separation between shallow and deep aquifer heads. Figure 22 also indicates the potential vertical groundwater flow directions, according to the polarities of the vertical head gradients. The actual flow magnitude depends on the vertical hydraulic conductivities of the strata.

Figure 23 (EAW7) shows a very similar pattern but the deeper heads are sub-artesian, although still generally higher than the Hawkesbury Sandstone levels. This hole is the closest of the four holes to current longwall mining in the Bulli Seam; Longwall 702 (completed 30 April 2009) is 1.3 km to the south.

EAW9 (Figure 24) also has similar features, but now there is a mixture of sub-artesian heads at mid-depths and artesian heads in the two deep coal seams.

EAW18 (Figure 25) differs in that there are seven piezometers within the shales and sandstones of the Wianamatta Group, five piezometers within the Hawkesbury Sandstone, and one piezometer at depth in the Bulli Seam. The lack of pressure in the shallow piezometers suggests a series of perched water tables with intervening unsaturated zones. A regional water table does not establish until the upper Hawkesbury Sandstone is reached. Again, the Bulli Seam head is much higher than the heads in the Hawkesbury Sandstone but conditions are not artesian.

Initial head measurements taken in June 2009 are available for two of the three newly established surface-to-seam multi-piezometer holes. Although S1993 (Figure 26) is adjacent to historical mining, the head in the Scarborough Sandstone is still quite high (about 55 m AHD, compared to about 100 m AHD at EAW7). No data is available for the Bulli Seam in S1993. S1997 (Figure 27) is located close to current mining at Metropolitan Colliery and historical mining at Darkes Forest, indicates a clear mining effect on recorded groundwater heads. There is a fairly uniform vertical hydraulic gradient down to the Bulli Seam (apart from one anomaly in the mid Scarborough Sandstone).

The vertical hydraulic gradients at the two Metropolitan Colliery sites are illustrated in Figure 28. The holes have drilled depths of 327 m (LW10 goaf hole) and 575 m (PM02) at mined (LW10 goaf) and unmined (PM02) locations. The LW10 goaf hole terminated about 130 m above the mined seam at the top of the inferred fractured zone.

At the LW10 goaf hole, apart from the Bald Hill Claystone, there is a systematic reduction in total head with depth down to the depth of the Bulgo Sandstone (Figure 28). Hence, there is a potential for downwards groundwater flow in response to a vertical hydraulic gradient. This contrasts with groundwater heads at similar depths in the PM02 hole, where the potential for vertical flow has not been enhanced by mining. The formations being monitored at the LW10 goaf hole 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. The head in the lower Bulgo Sandstone is about 60 m lower than observed at the new S1997 hole about 2.5 km to the west.

At PM02, apart from a pronounced high water level in the shallowest piezometer indicative of a perched water table, the piezometers show little variation from each other and all cluster around the approximate elevation of Lake Woronora, about 500 m to the east. There is a clear lateral hydraulic gradient for shallow groundwater flow towards the lake. At most depths there is a mild propensity for downward groundwater flow; two exceptions suggest that the Bald Hill Claystone and the Stanwell Park Claystone are acting as strong aquitards that confine the underlying sandstone formations (Bulgo and Scarborough) and put them under increased pressure.

Time Series

Variations with time of potentiometric heads at the four Project sites are shown in Figures 29 to 32. Some graphs show an initial period of stabilisation after grouting of the vibrating wire piezometers.

Figure 29 (EAW5) shows substantially lower heads in the Hawkesbury Sandstone (HBSS) in the bottom three curves, and a slight decay with time. There is no clear correlation with rainfall at any level. The curves are fairly stable with minor fluctuations of a few metres. There is no evidence of any mining effect, but the Bulli Seam curve where an effect might be noticed has only recently stabilised.

EAW7, on the other hand, does show a probable mining effect due to Longwall 702 at 1.3 km to the south (Figure 30). There is a sudden drop of about 10 m in the Bulli Seam head in January 2009. This response is very similar to that of shallow piezometer NGW4 directly over Longwall 702, as shown in Figure 20b. As most higher-elevation piezometers at EAW7 have a declining trend from January 2009, some mining-induced reduction in pressure could be occurring. Middle and lower Hawkesbury Sandstone heads decline with time, but this is probably unrelated to mining and is due either to dry conditions or active groundwater pumping.

Figure 31 (EAW9) shows a rising head in the Bulli Seam (BUCO) and the deeper Wongawilli Seam (WWCO), punctuated by a temporary decline in the Bulli Seam head of about 16 m. This appears to be a mining effect, but the nearest mining is 3 km away, and immediate recovery at distance would not be expected. The responses in the overburden are very stable.

EAW18 piezometers (Figure 32) would be expected to be more responsive to rainfall as the lower permeability Wianamatta Group, in which seven of the piezometers are placed, will amplify responses to rain recharge. However, there is a mixture of stable, rising and falling trends in March 2009 in response to 68 mm rain in February and 23 mm in March. This could reflect a time lag for infiltration to percolate through the variably saturated surficial formations. The piezometer at 273 m depth in the upper Hawkesbury Sandstone gives inconsistent heads compared to adjacent piezometers early in the monitoring period and a large (anomalous) change later in the monitoring period (which indicates that the data is unreliable).

2.13 BASELINE GROUNDWATER CHEMISTRY DATA

Table 6 summarises the chemical attributes of all groundwater samples from January 1998 to March 2008 taken at the shallow monitoring sites shown in Figures 10a to 10d by ICHPL.

Table 6. Chemical Data Summary at Groundwater Monitoring Sites

Analyte	Unit	Median	Minimum	Maximum	Average
pH	-	6.01	3.31	12.60	6.85
Dissolved Oxygen	% Saturation	32.0	4.4	98.5	34.5
EC	µS/cm	559	45	10,100	2,746
TDS	mg/L	1,003	92	5,560	1,700
Iron (Total)	mg/L	1.58	<0.01	105.00	3.65
Aluminium	mg/L	0.05	<0.01	4.82	0.73
Magnesium	mg/L	10.00	0.02	358.00	87.16
Calcium	mg/L	28.0	<1.0	464.0	74.0
Sodium	mg/L	104.0	7.0	1,450.0	481.9
Chloride	mg/L	153.0	10.8	3050.0	935.2
Sulphate	mg/L	25.0	<1.0	283.0	80.9

Source: ICHPL (2009).

The groundwater is slightly brackish, as indicated by a median salinity (TDS) of about 1,000 mg/L and a median EC of about 560 µS/cm. The occurrence of half the samples with less than 1,000 mg/L salinity is evidence of good stream-aquifer interaction, as groundwater is likely to be recharged by fresh river water during times of high flow.

Although there are no deep groundwater samples available, the salinity of deeper waters is expected to be much higher in accordance with the regional pattern in Figure 13. This view is supported by two samples of Bulgo Sandstone water taken during the trial of mine water injection into the Bulgo Sandstone (Section 2.11.1) which had ECs of 4,240 and 5,510 µS/cm. Higher salinity at depth indicates separation of deeper groundwater from shallow groundwater, and longer residence time of the deeper groundwater.

The groundwater data are shown graphically in Attachment B.

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 8);
- ☐ relevant data from the DWE register on the Natural Resources Atlas (http://test.nratlas.nsw.gov.au);
- ☐ geological and hydrogeological assessments undertaken for the Appin Mine and West Cliff Colliery and other Southern Coalfield mine operations;
- ☐ piezometric monitoring and geological information from the Multi-level piezometers EAW5, EAW7, EAW9 and EAW18;
- ☐ 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 the nearby 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 & Associates (2009) (Appendix C of the EA) have been considered.

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

- ☐ Perched groundwater system - associated with swamps, elevated sandstone and shales;
- ☐ Shallow groundwater system; and
- ☐ Deep groundwater system.

The three separate groundwater systems are illustrated in the conceptual model of the region in Figure 33.

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 topography, geology and surface water levels. A local groundwater mound develops beneath 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 the ground surface within upland swamps and outcropping sandstone/shales.

During short events of high surface flow, streams can lose water to the aquifers that host the streams, but during recession the aquifer will discharge water slowly back into the stream from bank storage. In gaining streams, baseflow is caused by slow drainage of groundwater from the surrounding rock strata or alluvium. Groundwater also discharges naturally to cliff faces and ultimately to the sea, east of the Project area. 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 by collapse above the caved zone and by stress relaxation below the caved zone. Hence, aquifer properties will change with time. The overlying rocks in the fractured zone will have a higher vertical permeability and enhanced horizontal 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 mediate the connectivity between shallow and deep aquifers. At the substantial depths of cover at the Project (Figure 11), 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.

Stream beds can experience cracking in response to subsidence to a depth of 10-20 metres. There will be no 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.

As inferred from the monitoring bores near the Cataract River (Section 2.12.2), horizontal bed separation can occur at shallow depths in sandstone and this will occasion changes in perched or shallow groundwater levels. Of all the shallow monitoring wells close to the Nepean and Cataract Rivers, there is only one instance of a mining-induced reduction in groundwater level to lower than river level. In that case, the groundwater level recovered soon afterwards, and has remained above river level. Well-documented reductions in groundwater level below river level occurred when the Georges River was undermined. This occasioned a remediation programme to restore relative water levels. In recent years, the natural gaining status of the rivers in the Project area has been maintained during mining.

Topographic relief control the hydraulic gradients that 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.

3.1 FRACTURED ZONE

The drilling of the LW10 goaf hole at Metropolitan Colliery indicated that the fractured zone extends in the order of 130 m above the mined coal seam, in the vicinity of the Stanwell Park Claystone (Figure 28). As longwall panel widths are relatively narrow (133-163 m) at Metropolitan, while depth of cover is substantial (400 to 560 m), it is expected that the fractured zone for this Project will extend to a higher altitude, likely into the Lower Bulgo Sandstone (as indicated in Figure 33).

The concept of a fractured zone has a vague definition. Booth (2002), in his review of mostly American and English mining, defined four zones in these terms:

I) “a caved zone, typically two to eight times the height of the workings, in which roof material collapses directly into the mined-out longwall area.

II) a heavily fractured zone, typically thirty to forty times the height of the workings, in which the strata break by vertical fractures and horizontal bedding-plane separations.

III) above that, a continuous deformation zone which subsides coherently with little extensive fracturing.

IV) a zone of well-defined and open fracturing at the ground surface and in the shallow strata, which can move more freely than the deeper strata.”

For Australian conditions, Forster and Enever (1992) and Forster (1995) applied the following terms to the same deformation zones, with thickness multiples of the mined thickness (t) representative of the Newcastle Coalfield:

I) Caved or Collapsed Zone (5t to 10t);

II) Disturbed or Fractured Zone (21t to 33t);

III) Constrained or Aquiclude Zone (>12t advisable); and

IV) Surface Zone.

Mine Subsidence Engineering Consultants (MSEC) (2009) (Appendix A of the EA) have conducted a literature review of definitions for the deformation zones. They describe a Fractured Zone as comprising "in-situ material lying immediately above the caved zone which have sagged downwards and consequently suffered significant bending, fracturing, joint opening and bed separation".

Descriptions of the fractured zone are necessarily qualitative. This report considers the fractured zone to be that highly permeable zone above a mined coal panel that is dominated by vertical fracturing and has gradational depressurisation down to zero pressure towards its base. This implies that the water pressures are negative or zero in the lower part of the fractured zone, and the material in that zone is unsaturated. This description carries the implication that the zone is not always amenable to direct measurement by standard piezometers. Although a piezometer placed within a future fractured zone will show diagnostic declining water pressure as mining approaches, the piezometer could be destroyed by shearing. Piezometers emplaced after mining when the strata have had time to settle will be limited as to depth of investigation, if fracture openings are substantial.

It will be possible, however, to infer the altitude of a fractured zone from surviving piezometers placed above a fractured zone or adjacent to one. Water pressures at those piezometers will decline in a diagnostic manner. Numerical model calibration of adjacent piezometer water pressures can give the altitude of a fractured zone that is consistent with those external measurements (to the resolution of adopted model layer thicknesses).

3.2 HYDRAULIC PROPERTIES

Thirteen (13) layers are conceptualised in Figure 34 for the purpose of numerical modelling. The three major sandstone formations (Hawkesbury, Bulgo and Scarborough) are split into multiple layers in recognition of natural or mining-induced vertical hydraulic gradients.

Indicative permeabilities for the various stratigraphic units, summarised in Table 7, are informed by SCA pumping tests, model calibration at Kangaloon (KBR, 2008), model calibration at Mangrove Mountain (Alkhatib and Merrick, 2006), model estimates at Dendrobium Mine (GHD Geotechnics, 2007), and core measurements with model calibration at Metropolitan Colliery (Heritage Computing, 2008). At Metropolitan, core measurements were made on Hawkesbury Sandstone, Bald Hill Claystone and Bulgo Sandstone samples.

Table 7. Indicative Hydraulic Properties of Stratigraphic Units

Unit	Hydrogeological Description	Horizontal Permeability Kx [m/d]	Vertical Permeability Kz [m/d]
Wianamatta Group	Unconfined, perched	0.01-0.1	-
Hawkesbury Sandstone	Unconfined Aquifer	0.01 - 1	0.0005 – 0.5
Bald Hill Claystone	Aquitard	$1x10^{-5}$	$1x10^{-6}$
Bulgo Sandstone	Leaky Confined Aquifer	$4x10^{-4}$ – 0.07	$3x10^{-4}$ – 0.007
Stanwell Park Claystone	Aquitard	$1x10^{-4}$	-
Scarborough Sandstone	Leaky Confined Aquifer	0.01 – 0.04	-
Wombarra Claystone	Aquitard	$1x10^{-4}$	-
Coal Cliff Sandstone	Leaky Confined Aquifer	$1x10^{-4}$ – 0.02	-
Bulli Coal Seam	Aquifer	0.04	-
Loddon Sandstone	Confined Aquifer	$1x10^{-4}$	-

After: GHD Geotechnics (2007); KBR (2008); Alkhatib and Merrick (2006).
m/d = metres per day.

The Wianamatta Group unit in Table 7 includes Ashfield Shale, Minchinbury Sandstone and Bringelly Shale.

In addition for the Project, packer tests have been conducted at hole EAW5 to the base of the Scarborough Sandstone; readings varied from 10^{-9} metres per second (m/s) (~10^{-4} m/d) to 10^{-6} m/s (~0.1 m/d) in the Hawkesbury Sandstone, with one outlier of 10^{-3} m/s (~100 m/d); in the Narrabeen Group readings ranged from 10^{-9} m/s (~10^{-4} m/d) to $2x10^{-8}$ m/s (~0.002 m/d), with one outlier of 10^{-7} m/s (~0.01 m/d).

The hydraulic property data available was considered adequate to inform the development of the numerical groundwater model and to obtain initial permeability values. However, given the Planning Assessment Commission (2009) in the Metropolitan Coal Project Review Report recommended wireline geophysical logging, this technology should be considered as part of future investigations. A proposed geological investigation programme is provided in Section 6.3, and if required the results of future geological investigations should inform progressive development of the numerical model (Section 8.0). The performance of the calibrated numerical model is discussed in Section 4.5.

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

Table 8. Initial Permeabilities in the Numerical Model

Unit	Relative Depth	Horizontal Permeability Kx [m/d]	Vertical Permeability Kz [m/d]	Kx/Kz
Alluvium	Surficial	10	1	10
Wianamatta Group	Surficial	0.01	0.05	2
Hawkesbury Sandstone	Superficial Upper Lower	0.2 0.1 0.01	0.1 0.05 0.005	2 2 2
Bald Hill Claystone		$1x10^{-5}$	$2x10^{-6}$	5
Bulgo Sandstone	Upper Lower	0.001 $1x10^{-4}$	$2x10^{-4}$ $2x10^{-5}$	5 5
Stanwell Park Claystone		$3x10^{-5}$	$6x10^{-6}$	5
Scarborough Sandstone	Upper Lower	0.01 0.01	$5x10^{-3}$ $5x10^{-3}$	2 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

Groundwater modelling has been conducted in accordance with the Murray-Darling Basin Commission Groundwater Flow Modelling Guideline (MDBC, 2001). Under the modelling guidelines, the model is best categorised as an Impact Assessment Model of medium complexity. The guide (MDBC, 2001) describes this model type as follows:

"Impact Assessment model - a moderate complexity model, requiring more data and a better understanding of the groundwater system dynamics, and suitable for predicting the impacts of proposed developments or management policies."

Numerical modelling has been undertaken using the Groundwater Vistas (Version 5.33) software interface (Environmental Simulations Inc, 2009) in conjunction with MODFLOW-SURFACT (Version 3) distributed commercially by Hydrogeologic, Inc. (Virginia, USA). MODFLOW-SURFACT is an advanced version of the popular MODFLOW code developed by the United States Geological Survey (McDonald and Harbaugh, 1988). MODFLOW is the most widely used code for groundwater modelling and is presently considered an industry standard. However, it has deficiencies in proper simulation of the near-field effects of underground mining; that is, those effects that occur close to the mine workings.

MODFLOW-SURFACT is a three-dimensional model able to simulate variably saturated flow and can handle desaturation and resaturation of multiple aquifers without the "dry cell" problems of Standard-MODFLOW. This is pertinent to the depressurisation that occurs in the caved zone and fractured zone above mined coal panels, and to possible dewatering of the uppermost model layer(s). Standard-MODFLOW can handle depressurisation to some extent, but model cells that are dewatered (reduced below atmospheric pressure) are replaced by "dry cells".

To handle the observed vertical changes in groundwater head within a given formation, and expected goaf fracturing, 13 model layers represent the stratigraphic section (Figure 34). The Wianamatta Group and Hawkesbury Sandstone sequence is represented by three layers. The Bulgo Sandstone and Scarborough Sandstone in the Narrabeen Group are each divided into two layers. The model complexity used is considered adequate to simulate contrasts in hydraulic properties and hydraulic gradients that may be associated with changes to the groundwater system as a result of the Project.

4.2 MODEL GEOMETRY

The model domain is discretised into 1,201,200 cells arranged into 13 layers comprising 220 rows and 420 columns. The dimensions of the model cells are uniformly 100 m in both directions. The model extent as shown in Figure 35 is 42 km from west to east and 22 km from south to north, covering an area of approximately 924 km^2.

The south-eastern corner of the model extent crosses the Illawarra Escarpment and reaches the sea (Figures 35 and 36). This allows the inclusion of a significant natural boundary condition at regional scale. Figure 35 also shows the drainage network and surface topography incorporated in the model.

The extent of longwall mining area outlines are shown in Figure 35 and Figure 37 for Appin Mine, West Cliff Colliery and Tower Colliery historical workings, for Longwalls 1-17, 18-19A and 20-44 at Metropolitan Colliery; for old workings at Darkes Forest and Helensburgh; for existing workings at Bellambi West (NRE No.1) and Tahmoor Colliery; and old Bulli workings.

Representative model cross sections are displayed in Figure 36 for Easting 285,950 (model column 100) and northing 6,206,050 (row 200); see Figure 35 for section locations. The elevation of the base of the Bulli Coal Seam (Figure 12) is well defined over most of the model extent. The interface elevations for other layers were derived from this base using measured thicknesses where available, and an extensive database of formation intersections, supplemented by median thicknesses outside the Project Area (as listed in Figure 34).

4.3 MODEL STRESSES AND BOUNDARY CONDITIONS

Rainfall infiltration has been imposed as fractions of long-term average rainfall across five zones, in accordance with the spatial rainfall distribution in Figure 3:

- ☐ Eastern Hawkesbury Sandstone (rain > 1,200 mm): 5%;
- ☐ Central Hawkesbury Sandstone (900 < rain < 1,200 mm): 5%;
- ☐ Western Hawkesbury Sandstone (rain < 900 mm): 5%;
- ☐ Wianamatta Shale: 7.5%; and
- ☐ Alluvium: 20%.

In the first four zones, the values were initially double those of the final calibrated values.

The main streams in the area, denoted in Figure 37[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 square metres per day (m^2/day). Minor drainage lines were established as “drain” cells in the model using the MODFLOW DRN package (shown in orange in Figure 37[a]). This allows groundwater to discharge to the drainage lines as baseflow. The drain conductances were set at 2.5 m^2/day.

Specified heads were set at the major dams and 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 were given invert levels equal to the top of the Bulli Coal Seam to represent flooded workings at atmospheric pressure. These are shown in Figure 37[b]. Historical and current mining at the Appin Mine (including Tower) and West Cliff Colliery, Metropolitan/Helensburgh, Bellambi West and Tahmoor Colliery was simulated by invert levels set at the bottom of the coal seam plus 0.5m. The initial drain conductance was set at 10 m^2/day.

4.4 MODEL VARIANTS

Both steady state and transient models have been developed:

- ❑ Steady state model of current conditions: Metropolitan Longwalls 1-19 (with fractured zone); current Tahmoor longwalls; and all old workings and first workings (Appin Mine [including Tower] and West Cliff old workings, Darkes Forest, Helensburgh/ Metropolitan, and Bellambi West old workings). Calibration against EAW5, EAW7, EAW9, LW10 and PM02 multi-level piezometers and also against 220 groundwater level targets distributed over the model domain and located mainly in Hawkesbury Sandstone and Bulli Seam aquifer systems.
- ❑ Transient model on a yearly basis for 30 years (with fractured zone changes every 2 years) to estimate the mine inflow for underground mining operations at the Appin Mine and West Cliff Colliery and also for 25 years at Metropolitan Longwalls 20-44. Appin Mine and West Cliff Colliery include West Cliff Area 5, Appin Area 7, Appin West (Area 9), Appin Area 8, Appin Areas 2 and 3 Extended and North Cliff.
- ❑ Recovery model run for 100 years after the end of Appin Mine and West Cliff Colliery underground mining.

4.5 CALIBRATION

The model was set up and initially run in steady state mode, to represent long-term average aquifer conditions. The objective was to undertake a comprehensive simulation of old and current mine workings to give a set of aquifer heads that replicate recent groundwater levels, illustrated by the spatial patterns in Figures 14 and 15 for Bulli Seam pressures and the regional water table, respectively.

The steady state calibration was initially achieved with sequential model runs by manually adjusting the horizontal (Kx) and vertical hydraulic conductivity (Kz) and recharge values until the best fit between the simulated water levels and field-based water levels was obtained. Then the calibration was finalised automatically using PEST software and zoned regions. Each layer was assumed uniform laterally except for the superficial aquifer (layer 1) and the fractured zone above and below the underground mining operations, where different Kx and Kz values were permitted in layers 6 to 13 (Lower Bulgo Sandstone down to the layer below the Bulli Seam).

PEST was run in a single step with simultaneous calibration of Kx and Kz for layers 1 to 13. The fracture zones for layers 6 to 13 were then adjusted accordingly to the host value calibrated from PEST. The horizontal hydraulic conductivity for the fractured zone was assumed to be higher than the host value by a factor of 2, while the fractured zone vertical conductivity was taken to be greater than the host by a factor of 10. A constrained zone was defined in Upper Bulgo Sandstone above the fractured zone. The horizontal hydraulic conductivity for this zone was set at five times greater than the host value while the vertical hydraulic conductivity was defined equal to the host value.

Table 9 summarises the hydraulic properties for the stratigraphic section, and for the constrained and fractured zones.

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

Aquifer/Aquitard	Host Kx	Host Kz	Fracture Kx	Fracture Kz	Constrained Kx
Superficial Aquifer (Alluvium,Shale,Sandstone)	10, 0.1, 0.1	1, 0.05, 0.01	-	-	-
Upper Hawkesbury Sandstone	5.0E-03	8.5E-04	-	-	-
Lower Hawkesbury Sandstone	9.3E-04	8.1E-05	-	-	-
Bald Hill Claystone	1.2E-05	3.1E-06	-	-	-
Upper Bulgo Sandstone	2.8E-03	9.4E-05	-	-	1.4E-02
Lower Bulgo Sandstone	6.6E-05	1.0E-05	1.3E-04	1.0E-04	-
Stanwell Park Claystone	3.7E-04	3.0E-06	7.4E-04	3.0E-05	-
Upper Scarborough Sandstone	8.2E-04	1.1E-04	1.6E-03	1.1E-03	-
Lower Scarborough Sandstone	1.60E-03	5.9E-05	3.2E-03	5.9E-04	-
Wombarra Claystone	1.3E-04	6.0E-07	2.7E-04	6.0E-06	-
Coal Cliff Sandstone	5.1E-05	3.5E-07	1.0E-04	3.5E-06	-
Bulli Coal Seam	1.0E-03	1.0E-04	10	10	-
Loddon Sandstone	1.0E-05	2.0E-06	2.0E-05	2.0E-05	-

The calibration performance is illustrated in Table 10. A reasonable steady state model calibration was obtained, demonstrated in quantitative and qualitative terms by the following measures:

- Scatter plots of modelled versus measured heads for 220 bores, showing good agreement between observed and computed heads across shallow and deep model layers, with a scaled root mean square (SRMS) error of 9.6% (within the target range of 5-10%), and coefficient of determination of 1.2 (Table 10 and Figure 38). The scaled RMS (SRMS) value (Table 10) is the RMS value divided by the range of heads across the site, and forms the main quantitative performance indicator. This result is consistent with the relevant groundwater modelling guideline listed in the EARs (MDBC, 2001) (Section 1.2).
- Contour plan of modelled heads for the regional water table (Figure 39) when compared with the inferred actual water table (Figure 15);
- Contour plan of modelled heads for the Bulli Seam (Figure 41[c]) when compared with measured heads (Figure 14) [with due allowance for different colour scales];
- Similarity of simulated and measured vertical head profiles at the five target multi-piezometer holes (Figures 42 and 43).

Table 10. Steady State Calibration Performance

Calibration Statistics	Value
Number of Data (n)	220
Root Mean Square (RMS) [m]	98.3
Scaled Root Mean Square (SRMS) [%]	9.6
Scaled Root Mean Fraction Square (RMFS) [%]	11.5
Coefficient of Determination (CD)	1.2

The very small water balance residual of 0.1% (Section 4.6) is an indication of acceptable run convergence.

Figure 39 shows the calibrated groundwater levels in the Hawkesbury Sandstone (Layer 2). Layer 1 shows the same pattern but many model cells are unsaturated along the ridgelines (as expected). There is very good agreement between observed and simulated patterns (Figures 15 and 39).

The groundwater heads in the Bald Hill Claystone (Figure 40[b]) preserve the pattern that occurs in overlying Hawkesbury Sandstone layers, with the exception of Tahmoor in the south-western corner. Beneath the Bald Hill Claystone, the groundwater heads start to show responses to mining (Figure 40[c]). Figure 41 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 40 and Figure 41.]

Figures 42 and 43 illustrate the ability of the steady state model to replicate the observed vertical groundwater head profiles at the five deep holes (EAW5, EAW7, EAW9, LW10 goaf hole and PM02). Although the vertical gradient at PM02 is mild, it does appear that some influence from past mining has propagated to this location.

4.6 WATER BALANCE

The steady state water balance across the entire model area is summarised in Table 11. The total inflow (recharge) to the aquifer system is 165 ML/day, comprising mainly rainfall recharge (about 83%), and leakage from streams into the aquifer (about 12%). The stream leakage is simulated to be about 20 ML/day.

Table 11. Simulated Water Balance for the Steady State Calibration Model

Component	Groundwater Inflow (Recharge) (ML/day)	Groundwater Outflow (Discharge) (ML/day)
Rainfall Recharge	137	-
Evapotranspiration (ET)	-	98.4
Rivers	20.4	56.7
Minor Creeks "Drains"	-	4.89
Sea "Constant Head"	0.048	0.084
Cataract Reservoir and Lake Woronora "Constant Head"	7.45	1.73
Mine Old Workings	-	3.16
TOTAL	**165**	**165**
Discrepancy (%)	**-0.11**	

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 Metropolitan Longwalls 1-19 (at the time of model calibration). It is assumed that any water carried by ephemeral streams would have a negligible contribution to groundwater recharge through leakage.

The total groundwater outflow across the Appin Model is 165 ML/day. Evapotranspiration represents the major outflow of about 60%. Baseflow to the streams accounts for about 34% of the total discharge under steady state conditions, with minor creeks accepting about 3%. Modelling suggests that the old and current workings (Appin, Metropolitan Longwalls 1-19, Darkes Forest, Helensburgh, Bellambi West and Tahmoor) are receiving about 3.2 ML/day (about 2% of the total outflow). This suggests that all old and current mine workings have caused negligible changes in groundwater discharge to natural features.

4.7 SENSITIVITY ANALYSIS

Analysis has been carried out to assess the sensitivity of the model calibration to the assumed input parameters and boundary conditions. The sensitivity analysis was carried out by first decreasing and then increasing one input parameter or boundary condition at a time, and evaluating the impacts of the changes on the calibration statistics. Any parameter change that resulted in a change to the SRMS statistic by a significant amount was identified as a sensitive parameter in the model. The base SRMS value for these runs was 9.61%.

Sensitivity analysis was carried out on:

- Hydraulic conductivity (horizontal and vertical);
- Recharge; and
- River-bed conductance.

Table 12 summarises the parameters and the spatial zones that were tested during the sensitivity analysis. The calibrated model aquifer hydraulic parameter values and zones are listed in Table 12.

Table 12. Parameters, Zones and Multipliers Tested in the Sensitivity Analysis Process

Parameter	Zone	Calibrated Value	Layer	Multiplier
Horizontal Hydraulic Conductivity	1	1.00E-01 m/d	1	0.5, 2
	2	4.95E-03 m/d	2	0.5, 2
	3	9.28E-04 m/d	3	0.5, 2
	4	1.18E-05 m/d	4	0.5, 2
	5	2.81E-03 m/d	5	0.5, 2
	6	6.60E-05 m/d	6	0.5, 2
	7	3.72E-04 m/d	7	0.5, 2
	8	8.20E-04 m/d	8	0.5, 2
	9	1.58E-03 m/d	9	0.5, 2
	10	1.34E-04 m/d	10	0.5, 2
	11	5.14E-05 m/d	11	0.5, 2
	12	1.00E-03 m/d	12	0.5, 2
	13	1.00E-05 m/d	13	0.5, 2
	24	1.00E+01 m/d	1 [alluvium]	0.5, 2
	25	1.00E-01 m/d	1 [shale]	0.5, 2
Vertical Hydraulic Conductivity	1	1.00E-02 m/d	1	0.1, 10
	2	8.51E-04 m/d	2	0.1, 10
	3	8.11E-05 m/d	3	0.1, 10
	4	3.13E-06 m/d	4	0.1, 10
	5	9.41E-05 m/d	5	0.1, 10
	6	1.00E-05 m/d	6	0.1, 10
	7	3.03E-06 m/d	7	0.5, 2
	8	1.10E-04 m/d	8	0.1, 10
	9	5.920E-05 m/d	9	0.1, 10
	10	6.04E-07 m/d	10	0.1, 10
	11	3.51E-07 m/d	11	0.1, 10
	12	1.00E-04 m/d	12	0.1, 10
	13	2.00E-06 m/d	13	0.1, 10
	24	1.00E+00 m/d	1 [alluvium]	0.1, 10
	25	5.00E-02 m/d	1 [shale]	0.1, 10
Recharge	5	20%	Applied to the Highest Active Layer	0.5, 2
	6	5%	Applied to the Highest Active Layer	0.5, 2
	7	5%	Applied to the Highest Active Layer	0.5, 2
	8	5%	Applied to the Highest Active Layer	0.5, 2
	9	7.5%	Applied to the Highest Active Layer	0.5, 2
River Bed Conductance	**All River Reaches in the Model**			0.1, 10

4.7.1 Hydraulic Conductivity

Hydraulic conductivity zones in the model were tested by applying factors to the horizontal hydraulic conductivity of 0.5 (decrease) and 2 (increase) to the calibrated model values, whereas the vertical hydraulic conductivity was changed by factors of 0.1 and 10. The results for the horizontal hydraulic conductivity (Kx) and vertical hydraulic conductivity (Kz) sensitivity analysis are summarised in Table 13.

Table 13. Sensitivity Analysis of Horizontal and Vertical Hydraulic Conductivity Values

Horizontal Hydraulic Conductivity (m/d)						**Vertical Hydraulic Conductivity (m/d)**					
Zone	**Calibrated Value**	**Layer**	**Multiplier**	**SRMS (%)**	**% Change**	**Zone**	**Calibrated Value**	**Layer**	**Multiplier**	**SRMS (%)**	**% Change**
			0.5	9.61	0.00%				0.1	9.61	0.00%
1	1.00E-01	1	**1**	**9.61**	-	1	1.00E-02	1	**1**	**9.61**	-
			2	9.61	0.00%				10	9.61	0.00%
			0.5	9.60	0.10%				0.1	9.70	-0.94%
2	4.95E-03	2	**1**	**9.61**	-	2	8.51E-04	2	**1**	**9.61**	-
			2	9.62	-0.10%				10	9.61	0.00%
			0.5	9.61	0.00%				0.1	9.84	-2.39%
3	9.28E-04	3	**1**	**9.61**	-	3	8.11E-05	3	**1**	**9.61**	-
			2	9.61	0.00%				10	9.59	0.21%
			0.5	9.61	0.00%				0.1	11.66	**-21.3%**
4	1.18E-05	4	**1**	**9.61**	-	4	3.13E-06	4	**1**	**9.61**	-
			2	9.61	0.00%				10	9.48	1.35%
			0.5	9.60	0.10%				0.1	9.69	-0.83%
5	2.81E-03	5	**1**	**9.61**	-	5	9.41E-05	5	**1**	**9.61**	-
			2	9.60	0.10%				10	9.60	0.10%
			0.5	9.61	0.00%				0.1	10.08	-4.89%
6	6.60E-05	6	**1**	**9.61**	-	6	1.00E-05	6	**1**	**9.61**	-
			2	9.61	0.00%				10	9.55	0.62%
			0.5	9.60	0.10%				0.1	9.84	-2.39%
7	3.72E-04	7	**1**	**9.61**	-	7	3.03E-06	7	**1**	**9.61**	-
			2	9.61	0.00%				10	9.58	0.31%
			0.5	9.60	0.10%				0.1	9.61	0.00%
8	8.20E-04	8	**1**	**9.61**	-	8	1.10E-04	8	**1**	**9.61**	-
			2	9.61	0.00%				10	9.61	0.00%
			0.5	9.60	0.10%				0.1	9.62	-0.10%
9	1.58E-03	9	**1**	**9.61**	-	9	5.92E-05	9	**1**	**9.61**	-
			2	9.62	-0.10%				10	9.61	0.00%
			0.5	9.58	0.31%				0.1	11.50	**-19.7%**

Table 13 (Cont.). Sensitivity Analysis of Horizontal and Vertical Hydraulic Conductivity Values

Horizontal Hydraulic Conductivity (m/d)						Vertical Hydraulic Conductivity (m/d)					
Zone	Calibrated Value	Layer	Multiplier	SRMS (%)	% Change	Zone	Calibrated Value	Layer	Multiplier	SRMS (%)	% Change
			0.5	9.61	0.00%				0.1	9.61	0.00%
10	1.34E-04	10	**1**	**9.61**	-	10	6.04E-07	10	**1**	**9.61**	-
			2	9.64	-0.31%				10	9.54	0.73%
			0.5	9.58	0.31%				0.1	11.30	**-17.6%**
11	5.14E-05	11	**1**	**9.61**	-	11	3.51E-07	11	**1**	**9.61**	-
			2	9.66	-0.52%				10	9.58	0.31%
			0.5	9.58	0.31%				0.1	9.61	0.00%
12	1.00E-03	12	**1**	**9.61**	-	12	1.00E-04	12	**1**	**9.61**	-
			2	9.91	**-3.12%**				10	9.61	0.00%
			0.5	9.56	0.52%				0.1	9.59	0.21%
13	1.00E-05	13	**1**	**9.61**	-	13	2.00E-06	13	**1**	**9.61**	-
			2	9.69	-0.83%				10	9.60	0.10%
			0.5	9.60	0.10%				0.1	9.61	0.00%
24	1.00E+01	1	**1**	**9.61**	-	24	1.00E+00	1	**1**	**9.61**	-
			2	9.61	0.00%				10	9.61	0.00%
			0.5	9.59	0.21%				0.1	9.61	0.00%
25	1.00E-01	1	**1**	**9.61**	-	25	5.00E-02	1	**1**	**9.61**	-
			2	9.63	-0.21%				10	9.61	0.00%

Sensitivity analysis for Kx was carried out for 15 zones defined over 13 model layers. The sensitivity analysis results showed that the maximum change in SRMS was 3% in Zone 12 in Layer 12 (Bulli Seam) when the base case value (0.001 m/d) was increased by a factor of 2. These results reveal that the horizontal hydraulic conductivity is not a sensitive parameter in this model.

Of the 15 zones of Kz tested, Zone 4 in Layer 4 (Bald Hill Claystone), Zone 10 in Layer 10 (Wombarra Claystone) and Zone 11 in Layer 11 (Coal Cliff Sandstone) were the most sensitive, giving 21.3%, 19.7% and 17.6% change in SRMS respectively when the base case values for these zones decreased by a factor of 10. Generally, however, the adopted calibration values of the vertical hydraulic conductivity zones are considered the optimal values, as the calibration statistic is generally the best for this set of parameters.

4.7.2 Recharge

Recharge zones were examined by changing their values by factors of 0.5 and 2. The results of the recharge sensitivity analysis are presented in Table 14.

Five zones representing low and high recharge rates were tested, and the results show that the model is insensitive to halving or doubling of the calibration recharge rates in all recharge zones.

Table 14. Sensitivity Analysis of Recharge, River Bed Conductance, Storage Coefficient and Specific Yield Values

Sensitivity to Recharge					
Zone	Calibrated Value	Layer	Multiplier	SRMS (%)	% Change
			0.5	9.61	0.00%
5	20%	Applied to Highest Active Layer	1	**9.61**	-
			2	9.60	0.10%
			0.5	9.60	0.10%
6	5%	Applied to Highest Active Layer	1	**9.61**	-
			2	9.61	0.00%
			0.5	9.61	0.00%
7	5%	Applied to Highest Active Layer	1	**9.61**	-
			2	9.60	0.10%
			0.5	9.62	-0.10%
8	5%	Applied to Highest Active Layer	1	**9.61**	-
			2	9.60	0.10%
			0.5	9.64	-0.31%
9	7.5%	Applied to Highest Active Layer	1	**9.61**	-
			2	9.58	0.31%
Sensitivity to River Conductance (m^2/d)					
Reach	**Calibrated Value**	**Layer**	**Multiplier**	**SRMS (%)**	**% Change**
			0.1	9.59	0.21%
All	2.5, 5, 10, 20 and 50	All	1	**9.61**	-
			10	9.61	0.00%

4.7.3 River and Drain Bed Conductance

River and drain-bed conductance values for all reaches in the model were tested by multiplying by 0.1 and 10. Sensitivity was evaluated in relation to groundwater levels via the SRMS statistic, and also to predicted mine inflow and river baseflow. The SRMS results of the sensitivity analysis are shown in Table 14, and reveal that the model is insensitive to multiplying the calibration river bed conductance values by either 0.1 or 10, in all river reaches.

The sensitivity to the river bed conductance parameter was also evaluated in terms of effects on the computed baseflow for the main streams in the model area (Table 15). The results show that the maximum baseflow change was about 0.4 ML/day in Cataract River and O'Hares Creek when the river and drain-bed conductances in the model were decreased by a factor of 10. But when the river and drain-bed conductances were increased by a factor of 10, the maximum baseflow change was about 0.2 ML/day in O'Hares Creek (Table 15).

Table 15. Sensitivity Analysis of River and Drain Bed Conductance on Baseflow for the Main Streams

Stream	Catchment Area (km^2)	Simulated Baseflow [ML/day]			Baseflow Change (ML/day) 0.1 x Basecase Cond	Baseflow Change (ML/day) 10 x Basecase Cond
		Basecase Cond	0.1 x Basecase Cond	10 x Basecase Cond		
Cataract Reservoir	130.0	0.381	0.384	0.424	-0.003	-0.043
Cataract River	92.5	2.842	2.442	2.935	0.400	-0.093
Georges River	26.8	1.140	1.257	1.281	-0.117	-0.141
Nepean River	1305.0	5.332	5.339	5.499	-0.007	-0.167
O'Hares Creek	73.0	3.322	2.909	3.548	0.414	-0.225
Woronora Reservoir	75.0	0.857	0.863	0.983	-0.007	-0.126
Woronora River	14.0	0.559	0.742	0.585	-0.183	-0.026

Sensitivity analysis was also performed on the mine drain conductance parameter by varying the assumed value over two orders of magnitude (1 – 100 m^2/day). The sensitivity results (Table 16) show that the maximum mine inflow change was about 0.04 ML/day (40 kilolitres per day [kL/day]) at Helensburgh when the drain bed conductance reduced from 10 m^2/day to 1 m^2/day. Table 16 reveals that the historical and current mine inflows are insensitive to multiplying the drain bed conductance values by either 0.1 or 10.

Table 16. Sensitivity Analysis for Drain Conductance

Name	Reach	Simulated Mine Inflow [ML/day]			Mine Inflow Change (ML/day) 0.1 x Basecase Cond	Mine Inflow Change (ML/day) 10 x Basecase Cond
		Basecase Cond	0.1 x Basecase Cond	10 x Basecase Cond		
Helensburgh Workings	30	0.368	0.327	0.388	0.040	-0.021
Darkes Forest Workings	40	0.206	0.205	0.206	0.000	0.000
Appin Mine	50	1.246	1.246	1.248	-0.001	-0.002
Metropolitan (Longwall 1-14)	60	0.306	0.339	0.298	-0.033	0.008
Bellambi West (NRE No.1)	70	0.218	0.217	0.218	0.000	0.000
Tahmoor Colliery	80	0.787	0.787	0.787	0.000	0.000
Metropolitan Colliery (Longwall 15-19)	90	0.028	0.034	0.016	-0.006	0.012

5.0 SCENARIO ANALYSIS

In order to assess the potential impacts of progressive mining, a transient model simulation has been conducted. The model was based on the mine development schedule provided in Section 2 of the Main Report of the EA and tracked the progressive mining of all longwalls through to mine completion. The old mine workings were assumed also to remain active sinks at atmospheric pressure until the completion of future mining.

The transient model was based on hydraulic properties derived from steady state calibration, with a pervasive time-varying fractured zone over all longwalls. Storage coefficient was set at 10^{-5} in sandstones and 10^{-6} in claystones and shale; specific yield was set at 0.1 in alluvium, 0.005 in sandstones and 0.001 in claystones and shale.

The underground mining and dewatering activity is defined in the model using drain cells within the mined coal seams, with modelled drain elevations set to 0.5m above the base of the Bulli Seam coal layer (Layer 12). These drain cells were applied wherever workings occur, and were progressed through annual increments in a transient model set-up. The set-up involved changing the parameters with time in the goaf and overlying fractured zones directly after mining of each longwall panel, whilst simultaneously activating drain cells along all development headings. Although the coal seam void should be dominated by the drain mechanism, the horizontal and vertical permeabilities were raised to 10 m/d but the storage properties were unchanged.

Figures 44 and 45 show the simulated groundwater head contours in Layers 3, 4 and 5 (Figure 44), and Layers 6, 9 and 12 (Figure 45) at the completion of mining (Year 30). These figures should be compared with corresponding Figures 40 and 41 at the end of all historical and current mining operations (steady state model Year 0).

The groundwater heads in the Lower Hawkesbury Sandstone preserve the Year 0 pattern (Layer 3; Figure 44[a]), but there is a perceptible reduction in heads in the Bald Hill Claystone (Layer 4; Figure 44[b]), particularly across Appin Area 7. Beneath the Bald Hill Claystone, the groundwater heads 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 45). [Note the change in colour scale between Figure 44 and Figure 45.]

5.1 MINE SCHEDULE

In order to simulate the change in hydraulic properties that occurs during the mining operations, it is necessary to be able to change the hydraulic properties of the model cells. For underground mining, model cells for the Bulli Seam initially have coal seam properties, then progressively void properties as mining develops. Likewise, the material overlying (Layers 5 to 11) and underlying (Layer 13) the coal seam initially has *in-situ* rock properties, which change with time to represent the goaf and overlying subsidence zones.

The horizontal and vertical hydraulic conductivity parameters were changed in Layer 12 (Bulli Coal Seam), and in the overlying Layers 5 to 11, and underlying Layer 13 to represent the constrained and fractured zones for all underground mining operations (Appin, Metropolitan, Darkes Forest, Helensburgh, Bellambi West and Tahmoor).

MODFLOW-SURFACT does not allow changing of hydraulic conductivity parameters with time during a single simulation. However, the use of ‘time-slices’ of short duration (generally two years) has allowed parameters to be changed periodically in specific areas to represent underground mining, and the expansion of the subsidence failure zone as underground mining progresses. Fifteen time slices were used to represent the 30 year mine life of this Project.

Table 17 outlines the model stress period set-up for the prediction model runs. A stress period is the timeframe in the model when all hydrological stresses (e.g. recharge, mine dewatering) remain constant.

Mining operations at the Appin Mine and West Cliff Colliery and Metropolitan Longwall 20 have been assumed to commence simultaneously in year 2010. The simulated time of historical and future mining at the Appin Mine and West Cliff Colliery, Metropolitan, Darkes Forest, Bellambi West and Tahmoor are also shown in Table 17.

The mine drain cells for the historical and future underground mining at Metropolitan Colliery were retained up to the end of Year 25. However, the mine drain cells for Appin Mine and West Cliff Colliery historical and future underground mining were kept active up to the end of model Year 30.

Figure 46 shows indicative snapshots of progressive mine development, as simulated in the model, in increments of five stress periods. Development headings are activated in advance of longwall panels.

Figure 47 shows the pattern of model cells activated in the fractured zone at the end of mining simulation (year 30). Effective chain pillar cells are maintained in the Project Area and in the future Metropolitan mine.

5.1.1 Historical Workings

The predicted dewatering rates for all historical underground mining operations (Appin Mine [including Tower] and West Cliff Colliery, Metropolitan, Darkes Forest, Bellambi West and Tahmoor) were simulated on a yearly basis from Year 0 (steady state model) up to Year 30 at the end of Project underground mining (transient model). The predicted mine inflows for each mining area in the model are presented in Table 18.

The predicted mine inflow in historical workings and current workings at the Appin Mine and West Cliff Colliery is about 1.25 ML/day at Year 0. This amount reduces gradually to 0.86 ML/day at Year 30 (Table 18). This is due to reduced hydraulic gradients in this area as the future underground mining operation moves progressively from Year 1 to 30 to cover West Cliff Area 5, Appin Area 7, Appin Area 8, Appin West (Area 9), Appin Area 2 and 3 Extended, and North Cliff.

The average inflows at external mines are estimated to be about 1.1 ML/day at Metropolitan Colliery, 0.2 ML/day at Bellambi West and 0.8 ML/day at Tahmoor Colliery (Table 18). The predicted inflow to Metropolitan Longwalls 20-44 (0.6 ML/day) is consistent with the latest low-inflow variant of the Metropolitan model (0.4 ML/day) (Heritage Computing, 2009). As discussed in Section 2.8, mines in the Southern Coalfield are commonly “dry”, which is reflected in modelled mine inflows (Table 18). Water balance data for Bellambi West from October 2005 to June 2009 showed mine inflows ranged from 0.05 ML/day to 1 ML/day with an average of 0.6 ML/day (Gujarat NRE Minerals Limited, 2009). This is in general agreement with the modelled mine inflows in Table 18 (average 0.21 ML/day).

Table 17. Model Stress Period Setup

Model	Stress Period	Time Slice	Year	Days	Timing of Operations													Mine Year
CALIBRATION	Steady State				Darkes Forest	Metropolitan Historic Workings (Helensburgh)	Metropolitan Longwalls 1-19	Bellambi West	Tahmoor	Appin/West Cliff/Tower (Historic Workings & Current)								0
PREDICTION	1	1	2010	365		▨	Metropolitan Longwalls 20-44	▨	▨	▨	Appin Area 7					West Cliff Area 5		1
	2	1	2011	365		▨	▨	▨	▨	▨	▨					▨		2
	3	2	2012	365		▨	▨	▨	▨	▨	▨	Appin West Area 9				▨		3
	4	2	2013	365		▨	▨	▨	▨	▨	▨	▨						4
	5	3	2014	365		▨	▨	▨	▨	▨	▨	▨						5
	6	3	2015	365		▨	▨	▨	▨	▨	▨	▨						6
	7	4	2016	365		▨	▨	▨	▨	▨	▨	▨						7
	8	4	2017	365		▨	▨	▨	▨	▨	▨	▨						8
	9	5	2018	365		▨	▨	▨	▨	▨	▨	▨						9
	10	5	2019	365		▨	▨	▨	▨	▨	▨	▨						10
	11	6	2020	365		▨	▨	▨	▨	▨	▨	▨						11
	12	6	2021	365		▨	▨	▨	▨	▨	▨	▨	Appin Area 8					12
	13	7	2022	365		▨	▨	▨	▨	▨	▨		▨					13
	14	7	2023	365		▨	▨	▨	▨	▨	▨		▨					14
	15	8	2024	365		▨	▨	▨	▨	▨			▨	Appin Area 2 Extended				15
	16	8	2025	365		▨	▨	▨	▨	▨			▨	▨				16
	17	9	2026	365		▨	▨	▨	▨	▨			▨	▨				17
	18	9	2027	365		▨	▨	▨	▨	▨			▨	▨				18
	19	10	2028	365		▨	▨	▨	▨	▨			▨		Appin Area 2 Extended			19
	20	10	2029	365		▨	▨	▨	▨	▨			▨		▨			20
	21	11	2030	365		▨	▨	▨	▨	▨			▨		▨			21
	22	11	2031	365		▨	▨	▨	▨	▨			▨		▨		North Cliff	22
	23	12	2032	365		▨	▨	▨	▨	▨					▨		▨	23
	24	12	2033	365		▨	▨	▨	▨	▨							▨	24
	25	13	2034	365		▨	▨	▨	▨	▨							▨	25
	26	13	2035	365				▨	▨	▨							▨	26
	27	14	2036	365				▨	▨	▨							▨	27
	28	14	2037	365				▨	▨	▨							▨	28
	29	15	2038	365				▨	▨	▨							▨	29
	30	15	2039	365				▨	▨	▨							▨	30
	31	16	2139	36525	Post-mining Recovery													

Table 18. Predicted Mine Inflow Rates (ML/day) for Historical, Current and Future Underground Workings

Year	Appin/West Cliff/Tower	Metropolitan			Darkes Forest	Bellambi West	Tahmoor
	Historical Workings and Current	Historical Workings	Longwall 1-19	Longwall 20-44	Historical Workings		
0	1.25	0.37	0.33	-	0.21	0.22	0.79
1	1.23	0.48	0.37	0.01	-	0.22	0.79
2	1.22	0.50	0.38	0.02	-	0.22	0.79
3	1.13	0.46	0.02	0.47	-	0.22	0.79
4	1.11	0.46	0.02	0.47	-	0.22	0.79
5	1.11	0.42	0.01	0.55	-	0.22	0.79
6	1.10	0.42	0.01	0.55	-	0.22	0.79
7	1.09	0.42	0.01	0.59	-	0.22	0.79
8	1.09	0.42	0.01	0.59	-	0.22	0.79
9	1.09	0.41	0.01	0.63	-	0.22	0.79
10	1.09	0.41	0.01	0.63	-	0.22	0.79
11	1.08	0.41	0.01	0.66	-	0.22	0.79
12	1.08	0.41	0.01	0.66	-	0.22	0.79
13	1.07	0.41	0.01	0.69	-	0.22	0.79
14	1.07	0.41	0.01	0.70	-	0.22	0.79
15	0.95	0.41	0.01	0.74	-	0.22	0.79
16	0.94	0.40	0.01	0.74	-	0.22	0.79
17	0.94	0.48	0.01	0.61	-	0.21	0.79
18	0.93	0.48	0.01	0.62	-	0.21	0.79
19	0.92	0.48	0.01	0.66	-	0.21	0.79
20	0.92	0.47	0.01	0.66	-	0.21	0.79
21	0.91	0.47	0.01	0.70	-	0.20	0.79
22	0.91	0.47	0.01	0.70	-	0.20	0.79
23	0.90	0.47	0.01	0.79	-	0.20	0.79
24	0.89	0.47	0.01	0.79	-	0.20	0.79
25	0.89	0.47	0.01	0.79	-	0.20	0.78
26	0.87	-	-	-	-	0.19	0.78
27	0.87	-	-	-	-	0.19	0.78
28	0.86	-	-	-	-	0.19	0.78
29	0.86	-	-	-	-	0.19	0.78
30	0.86	-	-	-	-	0.19	0.78
Min (Year 1 -30)	**0.86**	**0.40**	**0.01**	**0.01**	**-**	**0.19**	**0.78**
Max (Year 1-30)	**1.23**	**0.50**	**0.38**	**0.79**	**-**	**0.22**	**0.79**
Ave (Year 1-30)	**1.00**	**0.44**	**0.04**	**0.60**	**-**	**0.21**	**0.79**

5.1.2 West Cliff Area 5

The underground mining operations in West Cliff Area 5 commence in model Year 1 in continuity with current operations. Based on the mine development schedule, the mining operations in West Cliff Area 5 are assumed to complete within three years from the start of the simulation.

The predicted mine inflow in West Cliff Area 5 ranges from about 0.06 ML/day to about 0.32 ML/day with an average of 0.28 ML/day over the life of the Project (Table 19).

Table 19. Predicted Mine Inflow (ML/day) at the End of each Mine Year

Model Year	West Cliff Area 5	Appin Area 7	Appin West Area 9	Appin Area 8	Appin Area 2 Extended	Appin Area 3 Extended	North Cliff	Total*
1	0.06	0.04	-	-	-	-	-	0.10
2	0.06	0.07	-	-	-	-	-	0.13
3	0.31	0.19	0.02	-	-	-	-	0.52
4	0.29	0.21	0.05	-	-	-	-	0.55
5	0.32	0.32	0.15	-	-	-	-	0.79
6	0.31	0.32	0.16	-	-	-	-	0.78
7	0.31	0.42	0.30	-	-	-	-	1.03
8	0.31	0.43	0.31	-	-	-	-	1.05
9	0.30	0.55	0.41	-	-	-	-	1.27
10	0.30	0.54	0.42	-	-	-	-	1.27
11	0.30	0.64	0.53	-	-	-	-	1.46
12	0.30	0.63	0.52	0.03	-	-	-	1.47
13	0.30	0.74	0.58	0.08	-	-	-	1.70
14	0.30	0.72	0.57	0.12	-	-	-	1.71
15	0.30	0.92	0.56	0.26	0.05	-	-	2.08
16	0.30	0.91	0.56	0.27	0.06	-	-	2.09
17	0.30	0.90	0.55	0.39	0.20	-	-	2.34
18	0.30	0.90	0.54	0.42	0.19	-	-	2.34
19	0.30	0.90	0.53	0.56	0.28	0.04	-	2.62
20	0.30	0.90	0.53	0.56	0.27	0.06	-	2.61
21	0.30	0.89	0.52	0.71	0.26	0.20	-	2.89
22	0.30	0.89	0.52	0.71	0.26	0.19	0.04	2.90
23	0.30	0.89	0.51	0.84	0.26	0.33	0.07	3.20
24	0.29	0.89	0.51	0.82	0.26	0.31	0.13	3.21
25	0.29	0.89	0.51	0.81	0.28	0.37	0.35	3.50
26	0.29	0.89	0.51	0.81	0.27	0.36	0.36	3.49
27	0.29	0.89	0.51	0.80	0.27	0.36	0.66	3.78
28	0.29	0.89	0.51	0.80	0.27	0.36	0.67	3.79
29	0.29	0.89	0.51	0.80	0.26	0.36	0.86	3.97
30	0.29	0.89	0.51	0.80	0.26	0.36	0.83	3.94
Min (Year 1-30)	**0.06**	**0.04**	**0.02**	**0.03**	**0.05**	**0.04**	**0.04**	**0.10**
Max (Year 1-30)	**0.32**	**0.92**	**0.58**	**0.84**	**0.28**	**0.37**	**0.86**	**3.97**
Ave (Year 1-30)	**0.28**	**0.67**	**0.44**	**0.56**	**0.23**	**0.27**	**0.44**	**2.09**

* Total inflow values have been rounded.

5.1.3 Appin Area 7

The underground mining operations in Appin Area 7 also start in model Year 1 (i.e. contiguous with the current operations) and proceed to the north (Figure 2). Mining at Appin Area 7 is assumed to take 14 years to reach completion from the start of the simulation, based on the mine development schedule.

The predicted mine inflow in Appin Area 7 increases from 0.04 ML/day at Year 1 to about 0.92 ML/day over the life of the Project with an average inflow rate of 0.67 ML/day (Table 19).

5.1.4 Appin West (Area 9)

The mining operation in Appin West (Area 9) is assumed to commence in model Year 3 and ends in model Year 12. The predicted mine inflow for Appin West (Area 9) ranges from 0.02 ML/day at the commencement of mining within the domain to about 0.58 ML/day over the life of the Project with an average predicted mine inflow of about 0.44 ML/day (Table 19).

5.1.5 Appin Area 8

The mining operation in Appin Area 8 is assumed to start in model Year 12 and ends in Year 22. The predicted average mine inflow in Appin Area 8 is about 0.56 ML/day with minimum inflow of 0.03 ML/day at the commencement of mining within the domain and a predicted maximum inflow of 0.84 ML/day over the life of the Project (Table 19).

5.1.6 Appin Areas 2 and 3 Extended

The Appin Area 2 Extended mining operation is assumed to start in model Year 15 and ends in model Year 18. The mining operations in Appin Area 3 Extended are assumed to commence directly after the completion of mining in Appin Area 2 Extended and are completed in Year 23.

The average predicted mine inflow in Appin Area 2 Extended is about 0.23 ML/day with minimum inflow of about 0.05 ML/day at the commencement of mining within the domain and maximum inflow of about 0.28 ML/day over the life of the Project (Table 19). The predicted mine inflow in Appin Area 3 Extended ranges from around 0.04 ML/day to 0.37 ML/day over the life of the Project, with an average predicted mine inflow rate of 0.27 ML/day (Table 19).

5.1.7 North Cliff

The North Cliff underground mining operations are assumed to commence in model Year 22 with low mine inflow of about 0.035 ML/day at the commencement of mining within the domain. The predicted mine inflow increases gradually to reach a maximum of about 0.86 ML/day. The average mine inflow over the mining period within the domain is about 0.44 ML/day (Table 19).

The predicted mine inflows described in the above sections generally apply to each domain despite the timing or order in which the mine development schedule is implemented (e.g. should the North Cliff domain actually be developed in Year 10 of the Project, the predicted mine inflows would be expected to be generally within the same range).

5.2 PREDICTED BASEFLOW CHANGES

Predicted changes in baseflow on the main streams in the model area have been assessed by comparing the stream baseflow results from the base case (Steady State Model) with the results of the predictive model run (Transient Model). Table 20 illustrates these streams, their catchment areas and their baseflow changes as ML/day and megalitres per day per square kilometre (ML/day/km^2).

Table 20. Predicted Baseflow at End of Mining

Stream	Catchment Area (km^2)	Simulated Baseflow [ML/day]		Baseflow Change Since Steady State [ML/day]	Baseflow Change Since Steady State [ML/day/km^2]
		Steady State	After 30 Years of Mining		
Cataract Reservoir	130.0	0.381	0.351	0.030	0.000
Cataract River	92.5	2.842	2.737	0.105	0.001
Georges River	26.8	1.140	1.099	0.040	0.002
Nepean River	1305.0	5.332	5.119	0.213	0.000
O'Hares Creek	73.0	3.322	3.266	0.056	0.001
Woronora Reservoir	75.0	0.857	0.854	0.002	0.000
Woronora River	14.0	0.559	0.558	0.001	0.000

Baseflow changes have been assessed for these streams through the 30 year mining period and the subsequent 100 year recovery period.

The model results as shown in Table 20 reveal that the proposed underground mining operation has a negligible impact on stream baseflow. The results show that the maximum predicted reduction in groundwater baseflow over 30 years of mining operations is 0.21 ML/day in Nepean River; this value converts to 0.0002 ML/day/km^2 when the size of the catchment is taken into consideration (Table 20); hence, the impact is considered negligible.

The model has assumed a uniformly fractured zone above the entire mined seam across all longwall panels, without recognition of the reduction in fractured zone above the chain pillars. As a result, the model is being conservative with respect to environmental impacts by over-predicting the likely magnitude of depressurisation effects. Notwithstanding, the groundwater model calculates only a negligible reduction in baseflow for all streams. This is consistent with the findings of the Southern Coalfield Inquiry (DoP, 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."

The findings of the Metropolitan Coal Project Review Report are also in agreement with the conclusions of this assessment and the Southern Coalfield Inquiry (Planning Assessment Commission, 2009):

> "…the Panel's view is that the risk of any significant loss is very low unless a major geological discontinuity is encountered during mining that provides a direct hydraulic connection between the surface and the mine workings. This is considered unlikely."

In addition, this finding is consistent with the conclusions of separate hydrological studies undertaken by Gilbert & Associates (Appendix C of the EA) 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 WATER PRESSURE HEAD CROSS- SECTION

The effect of mining on water pressure at depth is best illustrated by representative cross-sections of the pressure head, shown in Figure 48 for west-east and south-north sections. The zero contour marks the line of atmospheric pressure. Negative pressures denote an unsaturated zone.

Figure 48 shows that the unsaturated zone is limited to the mined coal seam and the underlying layer. Although the model assumes the fractured zone extends midway between the Bald Hill Claystone and the Stanwell Park Claystone, in the middle of the Bulgo Sandstone, the line of zero pressure does not extend to this height. However, there is a clear reduction in pressure directly above the mined seam across the extent of the fractured zone. There is also partial depressurisation up to and above the Bald Hill Claystone.

5.4 RECOVERY SIMULATION

The recovery simulation deactivates all mine drain cells (new and old workings), and commences with simulated heads at the end of North Cliff underground mining, i.e. conditions at the end of Year 30, as the initial conditions. The model is run in transient mode for 100 years. Recovery is monitored at the five multi-level piezometer holes (EAW5, EAW7 and EAW9 in the Appin area and PM02 and LW10 in the Metropolitan area).

The rate of recovery is very sensitive to the adopted storage properties. The base case recovery simulation has storage coefficient set at 10^{-5} in sandstones and coal, 10^{-6} in claystones and shale. Specific yield was set at 0.1 in alluvium, 0.005 in sandstones and coal, and 0.001 in claystones and shale. Sensitivity to these values is addressed in Section 5.5.

The resulting hydrographs for the base case are shown in Figures 49 and 50. It is noted that the Hawkesbury Sandstone head is not perceptibly altered by the mining history beneath.

At the EAW5 and EAW9 holes, the Lower Bulgo Sandstone and the Lower Scarborough Sandstone and the deepest formation, represented by the Loddon Sandstone (model layer 13), recover by 100% after about 10 years.

Recovery at the EAW7 hole is more rapid, with the Lower Bulgo Sandstone and the Lower Scarborough Sandstone and the Loddon Sandstone all recovering by 100% after about six years.

However, the Loddon Sandstone achieves 100% recovery at the LW10 goaf hole immediately after Metropolitan mining ceases, and after about seven years at the PM02 hole.

At the end of the 100 year recovery period, water levels in all the main hydrogeological units had recovered to at least, and often to higher than, the levels recorded at the start of mining (Year 1). The higher water levels observed after the recovery period are due to the fact that the starting heads include some residual impacts of historical dewatering at the Appin Mine and West Cliff Colliery, Metropolitan, Darkes Forest, Bellambi West and Tahmoor Colliery. These mines are completely deactivated during the recovery period.

The water level patterns in six of the model layers, shown in Figures 51 and 52, support full recovery at the end of the simulation period (130 years from commencement of mining). The two depressions in the central north of Figure 52[c] are due to current gas wells which are unlikely to remain active far into the future.

5.5 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 by a factor of 10. Therefore, the specific yield increased to 0.05 and storage coefficient 0.0001 for the sandstone and the coal seam layers, and the specific yield and storage coefficient increased to 0.01 and 0.00001 respectively in claystone, shale and the deepest formation. The results for the EAW5, EAW7, and EAW9 holes are displayed in Figure 53.

A comparison of full-recovery times is given in Table 21. The recovery times in EAW5, EAW7 and EAW9 are about 7-10 times longer with a higher storage coefficient. At the EAW5 hole, the deepest formation [Loddon Sandstone] would achieve 100% recovery in 100 years after mining ceases. However, EAW7 and EAW9 responses are faster than EAW5; the groundwater level would recover in these holes in about 50 and 70 years respectively after mining completion.

Table 21. Time Required for 100% Recovery (years)

Formation	EAW5		EAW7		EAW9		LW10		PM02	
	Baseline S	S by Factor of 10	Baseline S	S by Factor of 10	Baseline S	S by Factor of 10	Baseline S	S by Factor of 10	Baseline S	S by Factor of 10
Lower Bulgo Sandstone	10	100	6	47	10	69	1.5	-	7.5	-
Lower Scarborough Sandstone	10	100	6	47	10	69	1	-	6	-
Loddon Sandstone	10	100	6	47	10	69	0.5	-	7	-

The sensitivity results for LW10 goaf hole and PM02 hole, located in the Metropolitan mine area, were unreliable because underground mining ceases in mine year 25, so much of the recovery occurs before the storage changes after year 30.

Spatial water level patterns through the stratigraphic section are presented in Figures 54 and 55. The deepest layer shows incomplete recovery in the central north area, but this is exacerbated by two active gas wells that would in reality be inactive.

Simulations with the specific yield of coal seam voids set at high values approaching unity revealed that the recovery at all monitored sites would be in excess of 100 years. A recovery of 50% can be expected after about 50 years (assuming goaf specific yield 10% and goaf permeability 1,000 m/day).

5.6 POST MINING BASEFLOW

The baseflow for the main streams in the model area has been re-assessed at 100 years after mining completion. The predicted changes in baseflow for these streams are illustrated in Table 22 as ML/day and ML/day/km^2.

Table 22. Predicted Baseflow after 100 Years of Recovery

Stream	Catchment Area (km^2)	Simulated Baseflow [ML/day]		Baseflow Change Since Steady State [ML/day]	Baseflow Change Since Steady State [ML/day/km^2]
		Steady State	After 130 Years of Mining		
Cataract Reservoir	130.0	0.381	0.433	-0.053	0.000
Cataract River	92.5	2.842	2.993	-0.151	-0.002
Georges River	26.8	1.140	1.220	-0.080	-0.003
Nepean River	1305.0	5.332	5.409	-0.077	0.000
O'Hares Creek	73.0	3.322	3.385	-0.062	-0.001
Woronora Reservoir	75.0	0.857	0.869	-0.012	0.000
Woronora River	14.0	0.559	0.578	-0.020	-0.001

The results show that for all streams the baseflow at the end of the recovery model run (Year 130) is fully re-established at above 100% of the steady state level (Year 0), due to the steady state model being affected by past and current dewatering activities at Appin, Metropolitan, Darkes Forest, Bellambi West and Tahmoor underground workings. The maximum baseflow change at the end of the recovery period is predicted to be higher than the steady state level by 0.15 ML/day at Cataract River (Table 22).

5.7 WATER BALANCE

Table 23 documents the water balance for the recovery model and for earlier model variants. The model suggests a total mine inflow of about 4 ML/day for the Project longwalls at the end of mining, and less than 2 ML/day for historical and current workings.

The anticipated mine inflows for this Project would account for about 2.4% of the water budget discharges, with a total of 3.5% for all mines when all old workings are included.

Table 23. Simulated Water Balance for Prediction Model

Component	Simulated Flow Rate (ML/day)			Change Since Steady State (%)	
	Steady State (Year 0)	At the End of the Prediction Period (Year 30)	At the End of the Recovery Period (Year 130)	At the End of the Prediction Period (Year 30)	At the End of the Recovery Period (Year 130)
Recharge					
Rain	137.00	136.94	136.88	0.05%	0.08%
Rivers	20.40	20.37	20.33	0.15%	0.33%
Cataract Reservoir and Lake Woronora ("Constant Head ")	7.50	7.53	7.48	-0.39%	0.21%
Storage	-	0.12	0.00	-	-
TOTAL	164.90	164.96	164.70	-0.04%	0.12%
Discharge					
ET	98.40	96.56	100.56	1.87%	-2.19%
Rivers	56.70	55.81	57.41	1.58%	-1.26%
Minor Creeks ("drains")	4.89	4.74	5.02	3.03%	-2.59%
SEA, Cataract Reservoir and Lake Woronora ("Constant Head ")	1.81	1.79	1.87	1.08%	-3.11%
Old Workings	3.16	1.83	0.00	42.06%	100.00%
Appin Future Longwalls	-	3.95	0.00	-	-
Storage	-	0.48	0.00	-	-
TOTAL	164.96	165.16	164.86	-0.12%	0.06%

6.0 SUBSIDENCE IMPACTS ON THE GROUNDWATER RESOURCE

6.1 POTENTIAL IMPACTS OF LONGWALL MINING

6.1.1 Subsidence Mechanism

The Project extent of the longwall mining area is shown in Figure 2. The prediction of subsidence parameters and the assessment of mine subsidence impacts are documented separately in a report by MSEC (2009) included as Appendix A of the EA.

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 mining of the proposed longwalls. Above goaf zones changes would 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 would 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 would 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.

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 would 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 groundwater levels and pressures must accompany changes in hydraulic gradients. However, pronounced changes in groundwater levels can occur without any significant drainage into a mine.

The most pronounced changes in formation properties would take place in the fractured zone above mined longwall panels. A detailed discussion on the fractured zone is provided separately in a report by MSEC (2009) included as Appendix A of the EA.

6.1.1.3 Changes in Groundwater Flow

MSEC (2009) 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.

At some of the monitoring bores adjacent to the Cataract River, substantial short-term changes in water levels have been observed in those bores overlying mined longwalls that are screened close to river level. The variability in observed responses suggests that water level changes are induced by bedding plane separation of limited extent, with no clear evidence of connective vertical fractures, and no interruption to baseflow.

Modelling suggests minimal alteration of groundwater spatial patterns and flow directions in the Hawkesbury Sandstone. Consequently, no appreciable change is expected for groundwater flow at the level of the regional water table. During mining, however, there would be changes in groundwater flow directions in the strata of the Narrabeen Group, with a slight increase in velocity as water is drawn towards mining sinks.

6.1.2 Drainage Mechanism

Above goaf zones there would 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 would 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 Appin Mine and West Cliff Colliery.

6.1.2.1 Mine Inflows

The formation of a fractured zone above the goaf would encourage additional mine inflow as mining progresses. The fractured zone is essentially free draining, and is the primary source of the water that enters the mine. Mines in the Appin area are regarded as “dry mines”. Numerical modelling estimates the inflow for current and historical workings at about 1.2 ML/day. The inflow for the Project is estimated to peak at about 4 ML/day, with an average over 30 years of about 2 ML/day each year.

6.1.2.2 Depressurisation

Although a substantial depth of cover offers protection against connective cracking throughout the stratigraphic section, a necessary consequence is significant depressurisation within the overburden, most pronounced in the caved zone and the fractured zone. Numerical modelling has been used to show the spatial extent of depressurisation in each layer at the end of mining, and the degree of recovery after cessation of mining. Conversion of modelled heads to pore pressures suggests that unconfined and unsaturated conditions are localised to the mined coal seam and the underlying formation, even though the fractured zone is assumed to extend from the coal seam up to the level of the Lower Bulgo Sandstone (see Section 5.3 and Figure 48).

Possible depressurisation in the Hawkesbury Sandstone is expressed in terms of drawdown; that is, the drop in water level from its current position to the levels anticipated at the end of mining. Drawdown of a substantial degree can affect access to water in registered production bores by landowners, and could result in stream baseflow reductions. The numerical modelling confirms that the Bald Hill Claystone protects the Hawkesbury Sandstone from significant changes in head. 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. Potential impacts on production bores are described in Section 6.1.4.

The groundwater pressures in the depressurised zone immediately above a goaf zone would 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. The Narrabeen Group in this region are not known to support any groundwater dependent ecosystems.

6.1.3 Potential Impacts on Shallow Groundwater Systems

There would be an intermediate (constrained) zone in the overburden that maintains its integrity, and mediates the connectivity between 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, and that the Hawkesbury Sandstone is protected from severe reductions in groundwater levels.

Near-surface fracturing can occur from horizontal tension at the edges of a subsidence trough. At some of the monitoring bores adjacent to the Cataract River, substantial short-term changes in water levels have been observed in those bores overlying mined longwalls that are screened close to river level. The variability in observed responses suggests that water level changes are induced by bedding plane separation of limited extent, with no clear evidence of connective vertical fractures.

At the shallow monitoring bores adjacent to the Cataract River, there is some evidence of prolonged mining-induced changes in groundwater levels. A longer period of record is required to verify that the changes are not permanent. The changes appear to be localised, and hence do not have consequential effects on streams and ecosystems.

6.1.4 Potential Impacts on Registered Production Bores

While there would be an impact on the structure of the Narrabeen Group aquifers, the effects are of no consequence as the Narrabeen sandstone aquifers are not in productive use and are not high-yielding. Hawkesbury Sandstone aquifers are being used for consumptive purposes, but the substantial depth of cover and the presence of thick aquitards protect the shallow aquifers from damage.

Of the 190 registered production bores in the model area, 165 (87%) have a reported drilled depth in the database held by the DWE, and 68 bores have a reported yield at the time of construction (36%). This information has been used to infer the likely formation that is yielding water for consumptive purposes, but it is not known how many bores are in productive use:

- Model Layer 1: Upper Hawkesbury Sandstone/Wianamatta Shale/Alluvium – 44 bores (23.2%);
- Model Layer 2: Middle Hawkesbury Sandstone – 72 bores (37.9%);
- Model Layer 3: Lower Hawkesbury Sandstone – 40 bores (21.1%);
- Model Layer 5: Bulgo Sandstone – 9 bores (4.7%);
- Unknown formation – 24 bores (12.6%); and
- Backfilled – 1 bore (0.5%).

There would be a negligible water access impact on shallow bores (model layer 1), as the predicted drawdown after 30 years of mining is no more than 1 m anywhere. Bores in the middle Hawkesbury Sandstone are expected to see a drawdown (over 30 years) that would range up to 12 m as shown in Figure 56. Individual bores likely to be affected are listed in Table 24.

Table 24. Predicted Drawdown at Registered Production Bores

Middle Hawkesbury Sandstone		Lower Hawkesbury Sandstone		Bulgo Sandstone		Unknown Formation	
Bore ID	Predicted Drawdown (m)	Bore ID	Predicted Drawdown (m)	Bore ID	Predicted Drawdown (m)	Bore ID	Predicted Drawdown * (m)
105942	6	103437	23	Lot 24/25	85	072196	15
108193	6	105531	16	038059	60	106675	15
053980	3	108907	15	058832	55	106574	14
		102619	14	060886	50	107791	14
		105376	14	060887	50	072329	7
		105388	14	060888	50	106250	6
		105534	14	060889	50	106412	6
		105574	14	108322	50	107421	5
		102581	12	101942	30	107721	5
		105339	12			107718	3
		108312	12				
		104661	11				
		104602	10				
		104154	8				
		104025	7				
		104546	6				
		040953	4				
		040954	4				
		043690	4				
		067606	4				
		102043	4				
		104068	4				
		104558	4				
		104224	3				
		105207	3				

* Assuming bores are located in the Lower Hawkesbury Sandstone.

Production bores in the lower Hawkesbury Sandstone could experience drawdown to a maximum of 26 m as shown in Figure 57. The zone of maximum drawdown is located beneath the Razorback Range in Area 9 (Appin West), across Area 7 and in the northern half of Area 8. Individual bores in the lower Hawkesbury Sandstone that are likely to be affected are listed in Table 24.

Although there are nine bores that seem to bottom in the Bulgo Sandstone, it is not known whether they yield useful quantities of water. There would be substantial loss of pressure in this formation after 30 years of mining, with predicted water levels to be lowered by 30-85 m at the locations of known bores (see Figure 58 and Table 24).

For bores of unknown depth, Figure 59 shows that most bores are located away from the zone of maximum drawdown. Possibly impacted bores, on the assumption that they are based in the lower Hawkesbury Sandstone, are listed in Table 24.

For bores located directly above mined longwalls, there is a risk of damage to bore casing from subsidence related movements (discussed in Appendix A of the EA).

As described in Section 2.3, the only Class 2 agricultural land located within the Project extent of longwall mining is located near the confluence of Foot Onslow Creek with the Nepean River in the north of Appin Area 7. There are three registered bores (GW026473, GW026545 and GW026557) located within land mapped as Class 2. The three bores range in depth from 8.5 m to 28.4 m (Attachment A) and coincide with model layer 1. As a result, there is predicted to be negligible water access impacts to the registered bores within Class 2 agricultural land.

Section 8.0 describes management measures for potential impacts on groundwater users.

6.1.5 Potential Impacts on Surface Water Bodies

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. 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.

Potential impacts to the local ecosystem are separately assessed in Appendix C (Surface Water Assessment), Appendix D (Aquatic Ecology Assessment), Appendix E (Terrestrial Flora Assessment) and Appendix F (Terrestrial Fauna Assessment) of the EA.

Groundwater modelling suggests a negligible reduction in baseflow (Section 5.2). The maximum predicted reduction in groundwater baseflow over 30 years of mining operations is about 0.2 ML/day in Nepean River, which converts to 0.0002 ML/day/km^2 when the size of the catchment is taken into consideration. Hence, the impact is considered negligible.

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 from this source.

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 would 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 (Appendix C of the EA).

6.1.5.1 Changes in Water Quality

A summary of the groundwater quality monitoring results at the Appin Mine and West Cliff Colliery is provided in Attachment B.

Localised surface water quality impacts would occur in the form of reduced dissolved oxygen and increased salinity, iron oxides and manganese where diverted shallow groundwater re-emerges downstream of a subsidence affected (e.g. sandstone streambed cracking) 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.

Assessment of the potential surface water quality effects are provided in the Surface Water Assessment (Appendix C of the EA).

There are not expected to be any changes in the quality of groundwater as a consequence of mining, other than diverted underflow at streams affected by cracks in the bed of the stream. Such short-lived groundwater would pick up minerals from fresh rock faces prior to emergence downgradient as surface water as recognised in the Metropolitan PAC Report.

6.1.5.2 Changes in Water Balance

Numerical modelling has allowed quantification of the relative magnitudes of the major components of the water balance. Recharge is dominated by rainfall (83%) and stream leakage (12%). Discharge is dominated by evapotranspiration (60%) and baseflow (37%). Pre-Project discharge to existing mines is estimated to be about 2% of the water budget. The post-Project inflows are anticipated to amount to about 3.5% of all discharge in the water balance, with this Project contributing about 2.4% of the total. These figures suggest that the Project would have only a marginal effect on the water balance component relativities.

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. The simulation and assessment of near surface cracking effects is described in the Surface Water Assessment (Appendix C of the EA).

6.1.5.3 Effects on Surface Ecosystems

Excess rainfall produces a permanent perched water table within swamp sediments and outcropping sandstone that is independent of the regional water table in the Hawkesbury Sandstone. The growth of dense vegetation in upland swamps and the low ground gradient reduces the formation of open channels 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 (Section 2.4).

The Planning Assessment Commission Panel for the Metropolitan Coal Project identified three broad mechanisms by which subsidence could cause changes in swamp hydrology (Planning Assessment Commission, 2009):

> “1. The bedrock below the swamp cracks as a consequence of tensile strains and water drains into the fracture zone. If the fracture zone is large enough or connected to a source of escape (e.g. a deeper aquifer or bedding shear pathway to an open hillside) then it is possible for sufficient water to drain to alter the hydrologic balance of the swamp.

> “2. Tilting of sufficient magnitude occurs to either re-concentrate runoff leading to scour and erosion, potentially allowing water to escape from the swamp margins (possibly affecting the whole swamp) or to alter water distribution in parts of the swamp, thus favouring some flora species associations over others.
>
> “3. Buckling and bedding shear enhances fracture connectivity in the host bedrock which promotes vertical then lateral drainage of the swamp. This mechanism is similar to redirected surface flow observed in subsidence-upsidence affected creek beds.”

The substantial depth of cover and the presence of a thick aquitard protect the shallow aquifers in the Hawkesbury Sandstone, which are in connection with streams and ecosystems, from transmitted effects due to reduction in groundwater pressures. Based on the analysis of the conceptual groundwater system, and modelling results, there is no expected dewatering of swamps from depressurisation at depth. 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, 2007). This supports the argument that the regional aquifer is hydraulically disconnected from perched water in the upland swamps.

As the free-draining fractured zone that is to be expected above a goaf zone does not extend as high as the Bald Hill Claystone, the perched water in upland swamps would not be impacted directly by vertically connected cracking. The only possibilities for impact are through bed separation or superficial tensile cracking associated with a moving subsidence trough, and that is likely to be transitory or localised.

Very little drainage of water due to bed separation or superficial tensile cracking is expected from the perched water table in a 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 (MSEC, 2009). 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.

Some surface cracking is expected in the upland swamps. The sediments in the upland swamps are described by Young (1986) as “silty clays with very high organic contents” and “silty coarse-medium sands”. Consequently, there is a substantial volume of sediment available for sedimentation within the cracks that may potentially limit the redirection of surface flow. This mechanism has not been measured through focused studies, but may be similar to the observed self sealing of the Pool A rock bar at the Metropolitan Colliery (Gilbert & Associates, 2008).

An Upland Swamp Risk Assessment (Appendix O of the EA) was conducted which assesses the potential impacts and environmental consequences of subsidence effects on upland swamps as a result of the Project.

6.2 PROPOSED GROUNDWATER MONITORING PROGRAMME

The proposed groundwater monitoring programme for the Project is summarised in Table 25 and described below. The groundwater monitoring programme should augment the existing ICHPL groundwater monitoring programme and should expand the existing knowledge of groundwater systems in the Project area. The programme should comply with the Murray-Darling Basin Groundwater Quality Sampling Guidelines (MDBC, 1997).

The groundwater monitoring programme should monitor groundwater conditions for changes as a result of mining and should include consideration of aquifer definition and interactions, strata hydraulic properties, pore pressure distributions and groundwater quality. The programme should be tailored to the mine plan as the detailed design of longwall layouts are completed.

The results of the groundwater monitoring programme should be used to validate modelling predictions and should be used throughout the Subsidence Management Plan (SMP) process.

6.2.1 Shallow Piezometers

The existing ICPHL shallow piezometer network should be augmented to include new Project areas as mining progresses (Table 25). Shallow piezometers should be installed in the vicinity of representative streams that are third order or above and in the vicinity of significant upland swamps (defined in Appendix O of the EA) at least six months prior to mining being conducted underneath or near these areas. The network of shallow piezometers should be similar to the existing network near the Georges, Nepean and Cataract Rivers near previously mined areas (Figures 10a to 10d). The final location of shallow piezometers should be determined through the SMP process, and should include consideration of site characteristics, their location relevant to the mine plan, access and site inspection.

Water level measurements should be automated with daily or more frequent recordings and should continue for at least two years following mining.

6.2.2 Shallow Groundwater Quality

The ICHPL shallow piezometer monitoring network should also be sampled for water quality on a regular basis at least 6 months prior to mining being conducted underneath or near these areas, and for at least two years. The frequency of monitoring at each piezometer location should be determined as part of the SMP process and should include consideration of their location relevant to current mining and access. Water quality samples should also be taken during drilling of new multi-level piezometer bores (Section 6.2.3).

Groundwater quality monitoring should include, but not necessarily be limited to, analysis of the following parameters: pH, dissolved oxygen, EC, TDS, iron, aluminium, magnesium, calcium, sodium, chloride and sulphate. Analysis should be undertaken at a NATA accredited laboratory. Water quality data should be evaluated as part of the SMP and Annual Environmental Management Report (AEMR) processes and should aim to identify any potential mining related impacts, including the potential presence of new water/rock interactions.

Table 25. Proposed Groundwater Monitoring Programme

Parameter	**Appin Area 7**	**Appin West (Area 9)**	**Appin Area 8**	**Appin Area 3 Extended**	**Appin Area 2 Extended**	**North Cliff**	**West Cliff Area 5**
Shallow Piezometers	• Existing Nepean River shallow piezometers (Figure 10c). • New sites near Nepean River, Foot Onslow Creek, Navigation Creek and Harris Creek.	• New sites near Nepean River, Apps Gully, Harris Creek and Matahill Creek.	• New sites near Nepean River, Carriage Creek, Byrnes Creek, Allens Creek and Stringybark Creek.	• Existing Cataract River shallow piezometers (Figure 10d). • New sites near Cataract River, Lizard Creek, Wallandoola Creek, Cascade Creek and tributaries.	• New sites near Cataract River and tributaries and tributaries to Lake Cataract.	• New sites near Stokes Creek, O'Hares Creek, Dahlia Creek, Woronora River, Punchbowl Creek and tributaries.	• Existing Georges River shallow piezometers (Figure 10b).
Shallow Groundwater Quality	• At sites above.	• At sites above.	• At sites above.	• At sites above.	• At sites above.	• At sites above.	• At sites above.
Multi-Level Piezometers	• EAW5, EAW7, S1993.	• EAW9, EAW18.	• Two new sites in Appin Area 8.	• New site in west of Appin Area 3 extended.	• S1996.	• S1997. • Data augmented from Metropolitan Colliery.	• Data augmented from S1993 and other sites within Appin Area 7 and North Cliff.
Hydraulic Property Measurements (Core Sampling and Testing)	• Conducted during drilling of new multi-level piezometer and other drilling.	• Information utilised from other mining domains and other drilling.	• Conducted during drilling of new multi-level piezometers and other drilling.	• Conducted during drilling of new multi-level piezometer and other drilling.	• Information utilised from other mining domains and other drilling.	• Information utilised from other mining domains and other drilling.	• Conducted during drilling of new multi-level piezometer and other drilling.
Mine Water Balance	• Measurement of volumes of mine dewatering, pumped water, coal moisture, ventilation moisture, etc.						

6.2.3 Multi-Level Piezometers

A multi-level piezometer network should be used to monitor pore pressures within the natural rock strata to enable description of the distribution of deep aquifer pressures. The three existing multi-level piezometers used in the groundwater model should be augmented to include piezometers distributed across the Project domains. An additional three multi-level piezometers (S1993, S1996 and S1997 [Figure 10a]) have been installed and should be included in the monitoring programme, as well as additional piezometer locations (Table 25). Water quality measurements should be taken during the installation of new multi-level piezometer bores.

Water level measurements should be automated with daily or more frequent recordings. Monitoring at these locations should continue throughout the Project life and should be reported in the AEMR. Monitoring results from these multi-level piezometers should be used to refine the groundwater modelling results as part of the SMP process.

6.2.4 Hydraulic Property Measurements (Core Sampling and Testing)

Core sampling and testing should be conducted during the drilling of new multi-level piezometers and other appropriate ICHPL drilling within the Project area, where practicable, to determine aquifer properties within the natural rock strata (e.g. porosity and permeability). ICHPL should create a database of testing data throughout the Project area, which should be used to validate modelling prediction and future groundwater assessments undertaken as part of the SMP process.

6.2.5 Mine Water Balance

Monitoring should be conducted of water entering and leaving the workings, including mine dewatering, pumped water, coal moisture and ventilation moisture. Water balances should be conducted regularly accounting for all monitored volumes and should be reported in the AEMR.

The water balance should be regularly reviewed to confirm groundwater transmission characteristics and modelling predictions. Monitoring results which indicate anomalous mine water seepage should be investigated. If anomalous seepage is determined to be as a result of faulting or fracturing associated with igneous intrusions, ICHPL should notify and consult with DoP regarding further courses of action.

The Project water management system is discussed further in Appendix C of the EA.

6.2.6 Upland Swamps

The proposed monitoring programme for upland swamps is described in the Upland Swamp Risk Assessment (Appendix O of the EA) and includes groundwater monitoring and the collection of a minimum of 2 years baseline data.

6.3 PROPOSED GEOLOGICAL INVESTIGATION PROGRAMME

The existing geological investigation programme as described in Section 2.7 should continue and be progressively implemented for the life of the Project.

In addition to the proposed groundwater monitoring programme described in Section 6.2, the geological investigation programme should be used to manage the potential for unexpected groundwater related effects, including where available:

- surface mapping (ground-truthing) of geological characteristics; and
- further analysis of geomorphic expressions.

The above activities should focus on the identification of potential conduits (e.g. faults, dykes, joint systems)[1] and include extrapolation from areas external to the extent of the longwall mining area.

These data, in combination with surface exploration and underground mapping data, can be used to build robust and accurate geological models upon which detailed mine plans can be developed, including consideration of potential groundwater related effects.

---

[1] Consistent with Recommendation 18 of the Southern Coalfield Inquiry report (DoP, 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 of 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.

Annual rainfall is expected to change by -10% to +5% by 2030 (Pittock, 2003) in parts of south-eastern Australia. 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 for this assessment is to conduct steady state simulations at the completion of mining (Year 30) for two scenarios:

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

The Base Case (calibrated rainfall) includes only the proposed mining for this Project and the historical workings in the Appin Area. All external mines are excluded. Hence, the Base Case baseflows at key water bodies presented in Table 26 are higher than those for full model extent mining and transient simulation shown in Table 20.

The results of the climate change scenario analysis are summarised in Table 26 in terms of baseflow reductions expressed as rates and percentages. The simulated reductions in baseflow are due to reduced water table levels.

Table 26. Predicted Changes in Baseflow due to Climate Change

Stream	Simulated Baseflow (ML/day)			Baseflow Change (ML/day) 10% Less Rain	Baseflow Change (ML/day) 20% Less Rain
	Base Case	10% Less Rain	20% Less Rain		
Cataract Reservoir	0.380	0.375	0.327	1.3	14/0
Cataract River	3.65	3.26	3.03	10.7	16.9
Georges River	1.43	1.16	1.04	19.0	27.5
Nepean River	5.69	5.08	4.58	10.7	19.5
O'Hares Creek	3.56	3.15	2.82	11.4	20.8
Woronora Reservoir	0.99	0.82	0.76	16.9	23.3
Woronora River	0.90	0.74	0.64	17.3	28.8

On average, there is expected to be 12% reduction in baseflow for 10% reduction in rainfall infiltration, and 21% loss for 20% less recharge. Overall, the percentage reduction in baseflow is similar to the assumed reduction in rain infiltration. Individual effects range from 1% to 19% loss for 10% reduced recharge, and 14% to 29% loss for 20% reduced recharge. Cataract Reservoir is the water body least susceptible to the effects of climate change, while Georges River and Woronora River are the most susceptible (due to their smaller catchments). The anticipated climate change effects on baseflow across the general Project area are greater than the expected changes in baseflow induced by mining (which on average is 3%).

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 minor incremental effect on baseflow in streams. 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

ICHPL should implement the proposed groundwater monitoring programme and geological investigation programme outlined in Sections 6.2 and 6.3, respectively.

The numerical model developed as part of this hydrogeological assessment should be used as a management tool for the prediction of groundwater impacts throughout the Project life. The results of the groundwater monitoring programme (Section 6.2) and geological investigation programme (Section 6.3) should inform progressive development of the numerical model. Revised outputs from the numerical model should be reported in the relevant Extraction Plan(s) over the life of the Project.

8.1.1 Streams

Stream impact minimisation criteria, provided in Section 2 in the Main Report of the EA, have been applied to a number of streams in the Project area. Implementation of the criteria would result in longwall layouts that do not directly undermine particular stream reaches and in some cases include setbacks so as to avoid significant fracturing of rock bars and draining of associated pools. Other potential management measures (e.g. grouting of rock bar fractures) are discussed in the Stream Risk Assessment (Appendix P of the EA) and the proposed surface water monitoring programme is described in the Surface Water Assessment (Appendix C of the EA).

8.1.2 Upland Swamps

A number of management measures are available to minimize potential impacts on swamps such as avoidance, restriction of ground movement and maintenance responses such as knick point control, water spreading, sealing of bedrock fractures and injection grouting. Potential management measures and the proposed swamp monitoring programme are discussed in the Upland Swamp Risk Assessment (Appendix O of the EA).

8.1.3 Groundwater Users

Over the Project life, ICHPL should:

- confirm, where the landholders consent, the location of landowner bores and report these details in Property Subsidence Management Plans;
- develop a comprehensive groundwater monitoring programme (Section 6.2) to measure the actual groundwater effects of the Project (including triggers for investigation);
- monitor the spread of groundwater depressurisation effects;
- if, in the event groundwater monitoring and investigation determines that an adverse Project-induced effect on the productive yield of a landowner’s bore is occurring, implement appropriate contingency measures, for the period during which such effects continue (determined in consultation with the affected landowner), which could include:
    - lowering of the pumps in the landowner’s affected bore;
    - deepening of the landowner’s affected bore;
    - development of a new bore(s);

    - provision of an alternative water supply (i.e. of at least the same standard of quality and quantity as the landowner's bore had prior to the land being affected by the Project), the nature of which would depend on the location of the affected landowner and the availability of nearby sources; or
    - if the above measures can not be implemented, provision of compensation to the affected landowner for any loss of bore productivity arising from the Project-induced effects.

The contingency measures provided in point 4 above are limited to ensuring that the landholder continues to have a water supply of at least the same standard of quality and quantity as the landowner's bore had prior to the land being affected by the Project.

If, in the event groundwater monitoring and investigation determines that Project-related subsidence effects have resulted in physical damage to the bore (e.g. shearing resulting in the bore casing being affected) or in-hole pump sets, contingency measures and/or compensation for the physical damage would be determined in consultation with the Mine Subsidence Board. Further details in relation to the potential subsidence impacts on infrastructure (including bores) are provided in the Subsidence Assessment (Appendix A of the EA).

9.0 MODEL LIMITATIONS

The numerical groundwater model has been designed to simulate the propagation of both near-field and far-field depressurisation effects throughout the entire aquifer system. It has not been designed to simulate the effects of near-surface tensile cracking due to subsidence of the land surface. The 100 m scale of model cells and the randomness of the cracking process would make such modelling very difficult and largely hypothetical. An assessment of the magnitude of potential water losses through surface cracking has been assessed with a local synthetic model by Gilbert & Associates (Appendix C of the EA).

Although MODFLOW-SURFACT is capable of simulating unsaturated conditions and perched systems, the focus in this study has been on the saturated part of the groundwater system close to land surface. No attempt has been made to replicate the behaviour of near-surface perched water tables.

Groundwater modelling suggests a negligible reduction in baseflow (Section 5.2) derived from the regional water table. Due to the observed isolation between perched and regional water tables, the expectation is that there would be no effect on baseflow derived from a perched aquifer source as a result of mine depressurisation.

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

The model also has assumed a uniformly fractured zone above all historical longwall panels, without recognition of partial protection above the chain pillars, and has maintained historical workings at atmospheric pressure. As a result, the model is being conservative with respect to environmental effects by over-predicting the likely magnitude of depressurisation effects. Chain pillar effects are taken into account to some degree for the Project longwalls and the Metropolitan longwalls, but are constrained by the 100 m adopted cell size. The large size of the model (220 rows, 420 columns, 13 layers) precludes the use of a much finer model grid. The broad extent of the Project precludes any advantage in adoption of a variable grid with refinement only in the area of mining.

The model does not include structural features such as faults and dykes as their hydraulic characteristics, and in some cases their exact location and orientation are not known. Geological structures have the potential to compartmentalise aquifers (i.e. act as a barrier to groundwater flow) or act as a leakage conduit, potentially from surface to depth. The current model has not introduced any candidate geological faults due to the uncertainty in their location, uncertainty over their vertical persistence, and the observation that they are more likely to be resistive barriers than transmissive conduits. ICHPL should develop and implement a geological investigation programme progressively over the Project life to manage the potential for unexpected groundwater related effects as a result of geological structures (Section 6.3). Improved knowledge of geological structures should inform the development of Extraction Plans (Section 8.0), and such features can be added to the model to refine prediction of effects on the groundwater system.

10.0 CONCLUSIONS

The data supports three distinct groundwater systems:

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

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

- no dewatering of swamps from depressurisation at depth (other potential impacts to swamps are assessed in Appendix O of the EA);
- negligible loss of groundwater yield to the Cataract Reservoir and Woronora Reservoir; and
- negligible loss of groundwater yield to surface stream systems.

As would be expected, a lateral hydraulic gradient towards historical/existing mine workings has developed; i.e. a depressurisation effect.

Groundwater modelling has demonstrated that much of the reduction in pressures at depth has been due to past mining in the region (e.g. Appin Mine, West Cliff Colliery, Tower Colliery, Bellambi West [NRE No. 1], Tahmoor Colliery, Darkes Forest and Metropolitan Colliery).

Based on groundwater modelling, there is expected to be:

- extensive depressurisation of aquifers beneath the Bald Hill Claystone;
- negligible reduction in groundwater contribution to total stream flows;
- negligible reduction in cumulative average inflows to the Cataract Reservoir, Broughtons Pass Weir and Woronora Reservoir;
- a final mine inflow in the order of 4 ML/day to the entire Project domain at the completion of mining, averaging about 2 ML/day each year over 30 years; and
- slow but complete recovery of formation groundwater pressures over many decades.

The potential impacts of subsidence on streams and swamps, other than those assessed within this report, are assessed in the Surface Water Assessment (Appendix C of the EA), Upland Swamp Risk Assessment (Appendix O of the EA) and Stream Risk Assessment (Appendix P of the EA).

There would be a reduction in the water level of some private production bores that are pumping from Hawkesbury Sandstone. ICHPL would be required to guarantee continuity of access to a water supply for affected landowners.

11.0 REFERENCES

Agriculture and Resource Management Council of Australia and New Zealand and Australian and New Zealand Environment and Conservation Council (1995) National Water Quality Management Strategy Guidelines for Groundwater Protection in Australia.

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.

BHP Billiton (2006) Georges River Report: Assessment of Georges River Remediation West Cliff Longwalls 5A1-4. Final Report, 23 November 2006.

Booth, C. J. (2002) The Effects of Longwall Coal Mining on Overlying Aquifers. In: Younger P.L. and Robins N.S. (eds.), Mine Water Hydrogeology and Geochemistry, Geological Society, London, Special Publication 198, p. 17-45.

Bureau of Meteorology (2009) Climate Statistics for Australian Locations. Website: http://www.bom.gov.au/climate/averages/. Date accessed: 15 May 2009.

Cardno Forbes Rigby (2008a) West Cliff Area 5 Longwalls 34 to 36 Subsidence Management Plan.

Cardno Forbes Rigby (2008b) Appin Area 7 Longwalls 705 to 710 Subsidence Management Plan Application.

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.

Department of Primary Industries – Agriculture (2008) Agricultural Land Classification for Part of the Wollongong 1:100,000 Map Tile. November 2008.

Earth Tech (2003) Swamps of the Woronora Plateau: Understanding Swamp Conditions. Report prepared for Illawarra Coal Holdings Pty Limited.

Environmental Simulations Inc. (2009) Groundwater Vistas (Version 5.33) software. Developed by J.O. Rumbaugh and D. B. Rumbaugh for Environmental Simulations Inc., Pennsylvania USA.

FloraSearch (2009) Illawarra Coal Bulli Seam Operations Project Flora Survey and Assessment. Report prepared for Illawarra Coal Holdings Pty Limited.

Forster, I. R. (1995) Impact of Underground Mining on the Hydrogeological Regime, Central Coast NSW. In Sloan & Allman (eds.), Conference on Engineering Geology of the Newcastle-Gosford Region, Aust. Geomech. Soc., February 1995, p.156-168.

Forster, I. and Enever, J. (1992) Hydrogeological Response of Overburden Strata to Underground Mining – Central Coast New South Wales. Office of Energy Report OOE 92/105. ISBN 0 7305 6964 0. Volume 1: 78p + 26 figs.

GeoTerra (2006) Douglas Area 7 Longwalls 701 to 704 Groundwater Assessment.

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

Gilbert & Associates (2008) Metropolitan Coal Project Surface Water Assessment. Report prepared for Helensburgh Coal Pty Limited.

Gilbert & Associates (2009) Bulli Seam Operations Project Surface Water Assessment. Report prepared for Illawarra Coal Holdings Pty Limited.

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.

Gujarat NRE Minerals Limited (2009) Water Balance Summary DSC Water Report – June 2009. Email dated 11 August 2009.

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

Heritage Computing (2008) A Hydrogeological Assessment in Support of Metropolitan Colliery Longwalls 20 to 44 Environmental Assessment. Report prepared for Helensburgh Coal Pty Limited.

Heritage Computing (2009) Second Response to Metropolitan Coal Project Planning Assessment Commission. Email dated 29 April 2009.

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.

Illawarra Coal Holdings Pty Ltd (2002) Appin Colliery Stage 2 Aquifer Field Report. February 2002.

Illawarra Coal Holdings Pty Ltd (2005a) West Cliff Area 5 Longwalls 31 to 33 (pt) – Monitoring Programme.

Illawarra Coal Holdings Pty Ltd (2005b) Appin Area 3 Subsidence Monitoring Programme.

Illawarra Coal Holdings Pty Ltd (2005c) Report on Bulgo Sandstone Strata Mine Water Discharge Trial 01 May 2005 – 31 October 2005.

Illawarra Coal Holdings Pty Ltd (2009) Illawarra Coal Holdings Pty Limited Resource and Exploration Department Records.

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.

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.

Mine Subsidence Engineering Consultants (2009) The Prediction of Subsidence Parameters and the Assessment of Mine Subsidence Impacts on Natural Features and Surface Infrastructure Resulting from the Bulli Seam Operations in Support of the Part 3A Application. Report prepared for Illawarra Coal Holdings Pty Limited.

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.

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.

Murray-Darling Basin Commission (1997) Murray-Darling Basin Groundwater Quality Sampling Guidelines. Technical Report No. 3.

Murray-Darling Basin Commission (2001) Groundwater Flow Modelling Guideline. Canberra, August 2001, 125p. ISBN: 1876830166.

National Parks and Wildlife Service (NPWS) (2003) The native vegetation of the Woronora, O'Hares and Metropolitan catchments.

NSW Agriculture (2002) Agfact: Agricultural Land Classification.
Pittock, B. (2003) (ed.) Climate Change - An Australian Guide to the Science and Potential Impacts. Australian Greenhouse Office.

Planning Assessment Commission (2009) The Metropolitan Coal Project Review Report.
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.

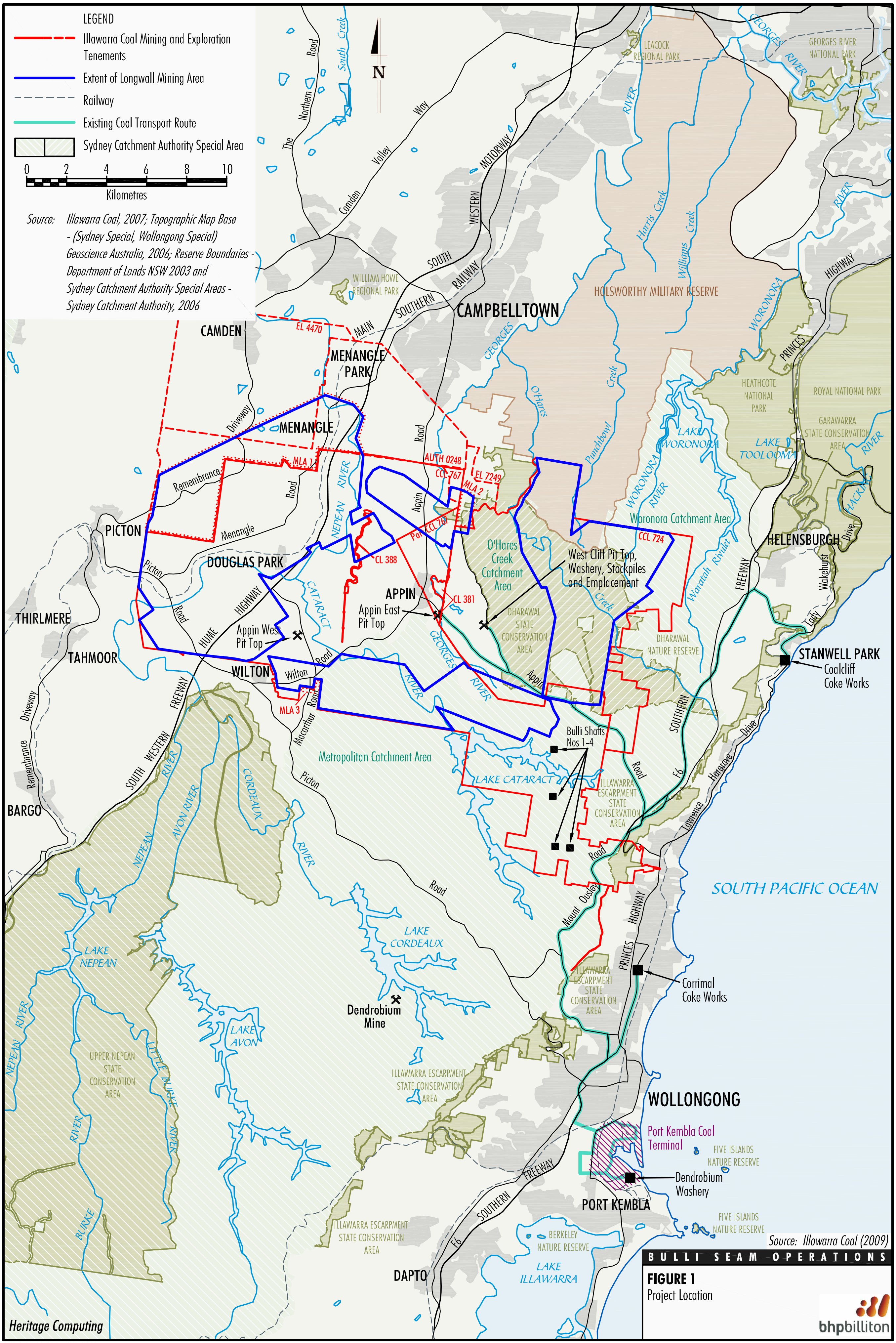
Short, S. A., Golab, A. N., Tippler, C. J. and Walsh, R. V. (2007) Geochemical and Algal Tracing of Potential Flow from a Lake to an Underground Coal Mine. In R. J. Morrison & M. O'Donnell (convenors), Water Quality in the Illawarra – South Coast Region Symposium, University of Wollongong, 7-8 June 2007.

Sydney Catchment Authority (2007) 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.

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.

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

FIGURES

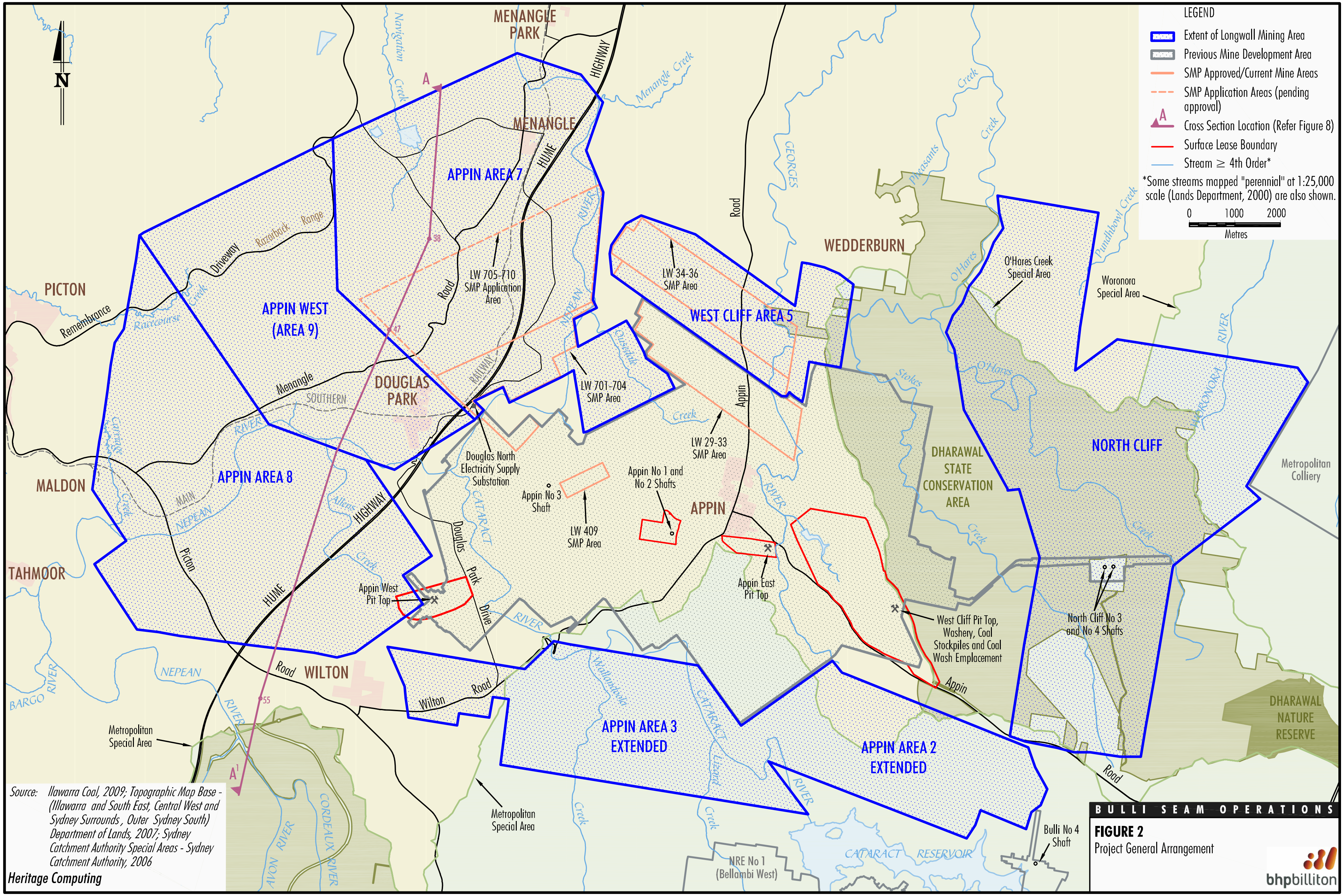


Source: Illawarra Coal (2009)

BULLI SEAM OPERATIONS

FIGURE 1
Project Location

BHPIC-07-01 EA AppGW_106B



Source: Ilawarra Coal, 2009; Topographic Map Base - (Illawarra and South East, Central West and Sydney Surrounds, Outer Sydney South) Department of Lands, 2007; Sydney Catchment Authority Special Areas - Sydney Catchment Authority, 2006

Heritage Computing

BULLI SEAM OPERATIONS

FIGURE 2
Project General Arrangement

bhpbilliton

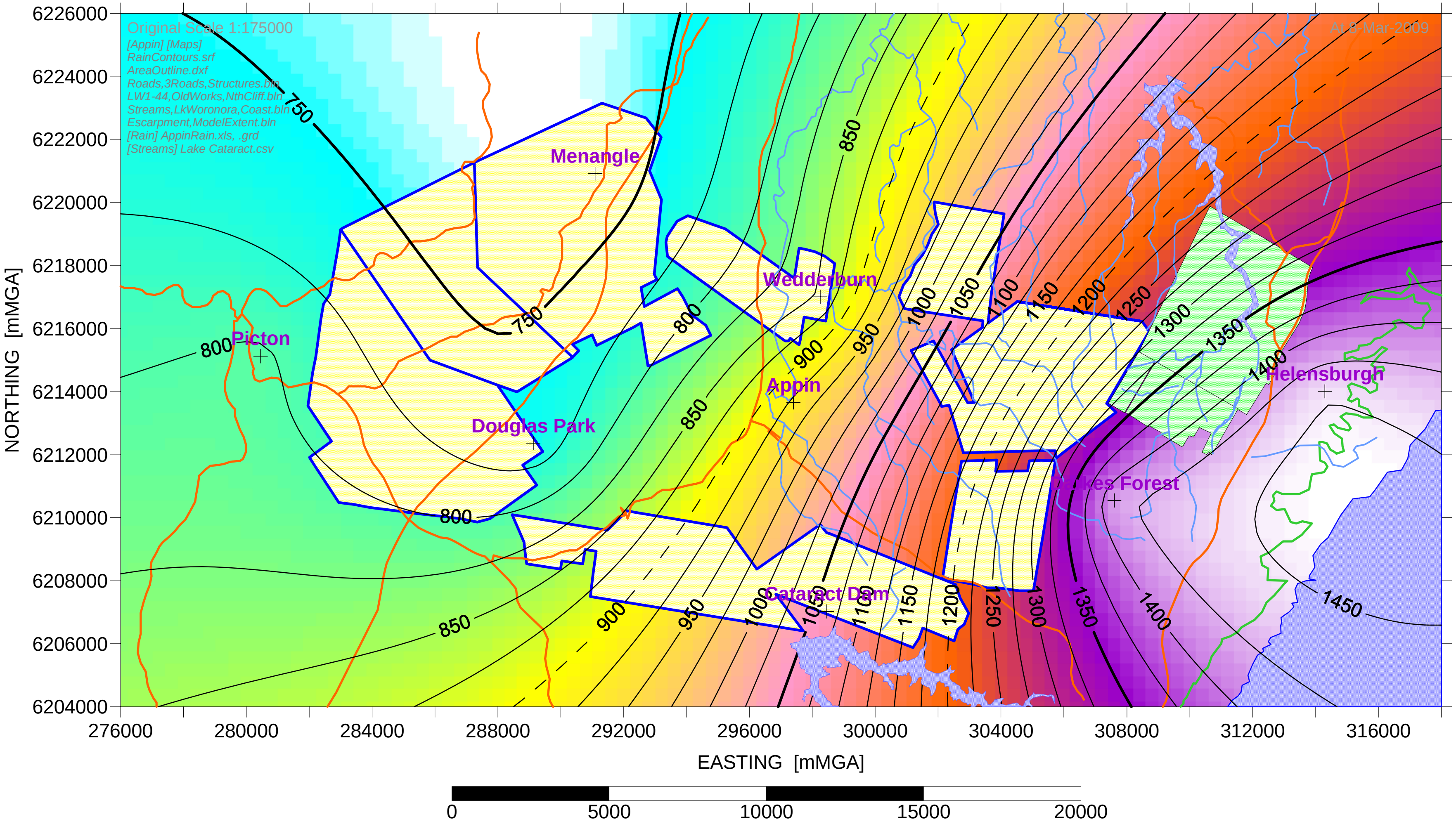


Figure 3. Annual rainfall pattern.

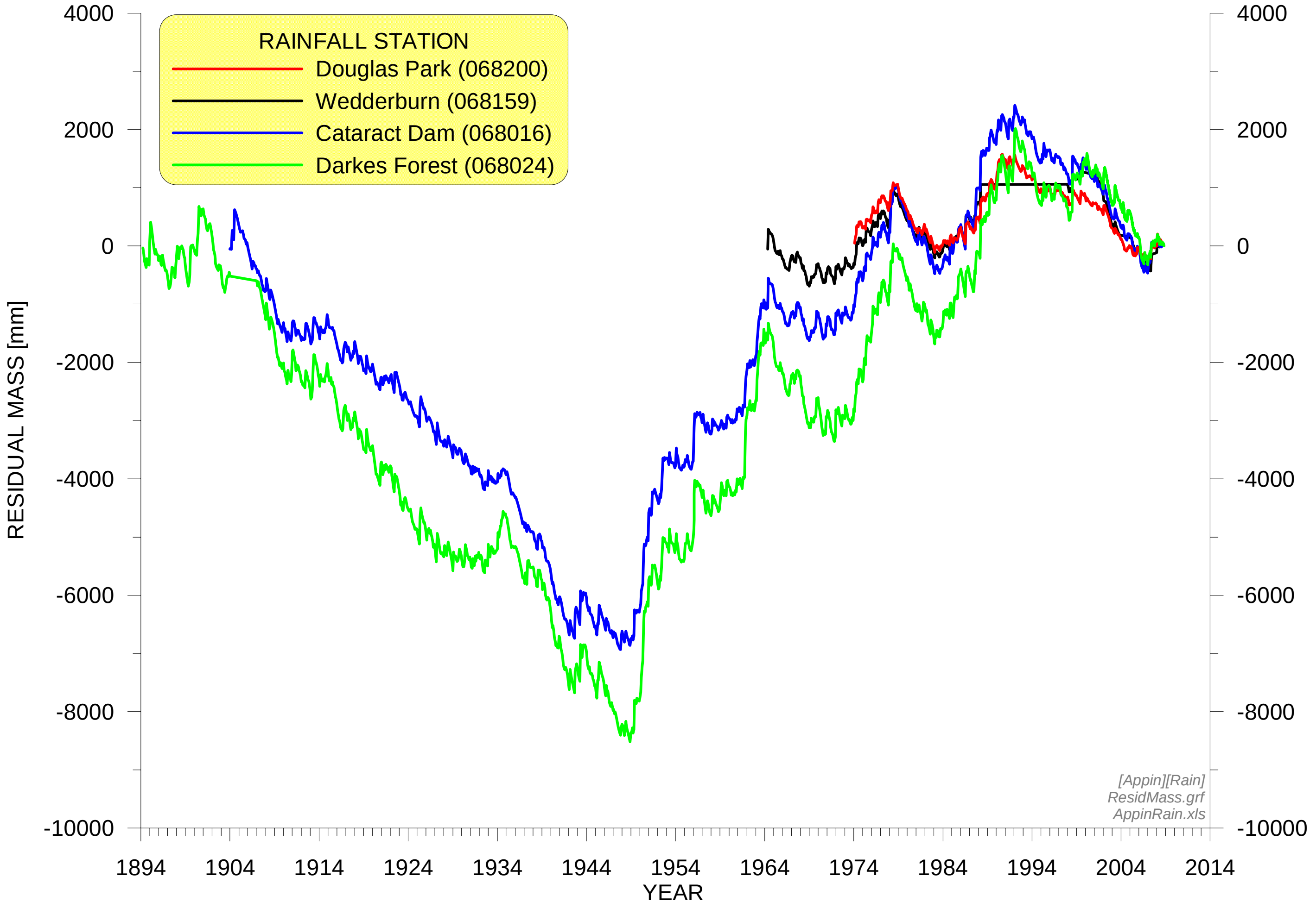


Figure 4. Rainfall – residual mass curve (since 1894).

[Note: Wedderburn station was not established until 1964 and was inoperable from May 1988 to December 1997]

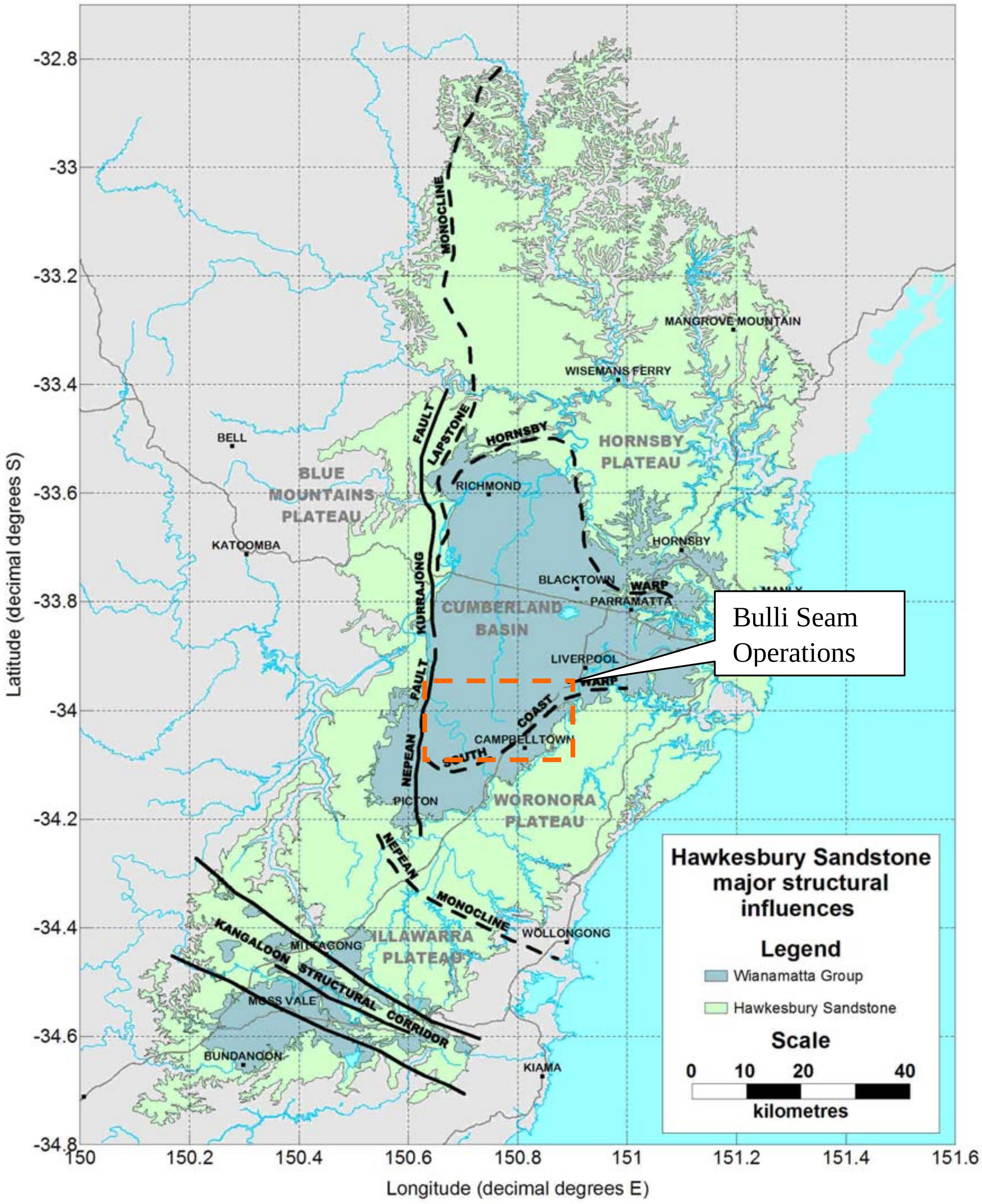


Figure 5. Wianamatta Group and Hawkesbury Sandstone outcrop extent [from Russell, 2007].

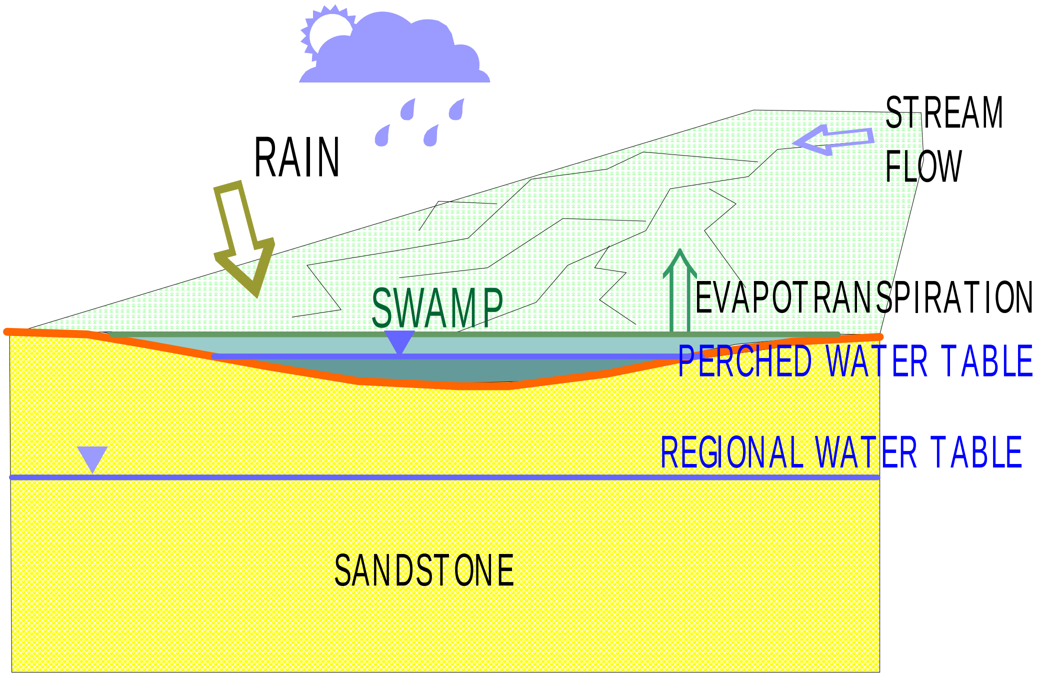


Figure 6a. Conceptual model of headwater upland swamp.

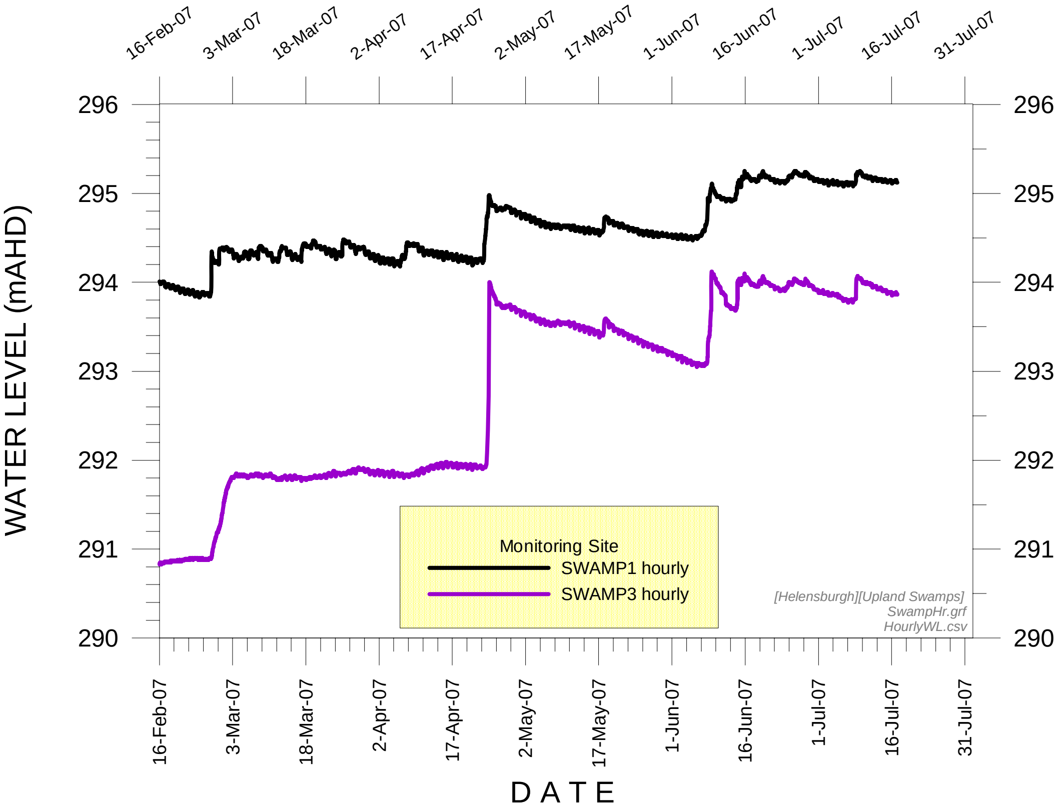


Figure 6b. Water level response to rainfall and evapotranspiration at a headwater upland swamp near Metropolitan Colliery.

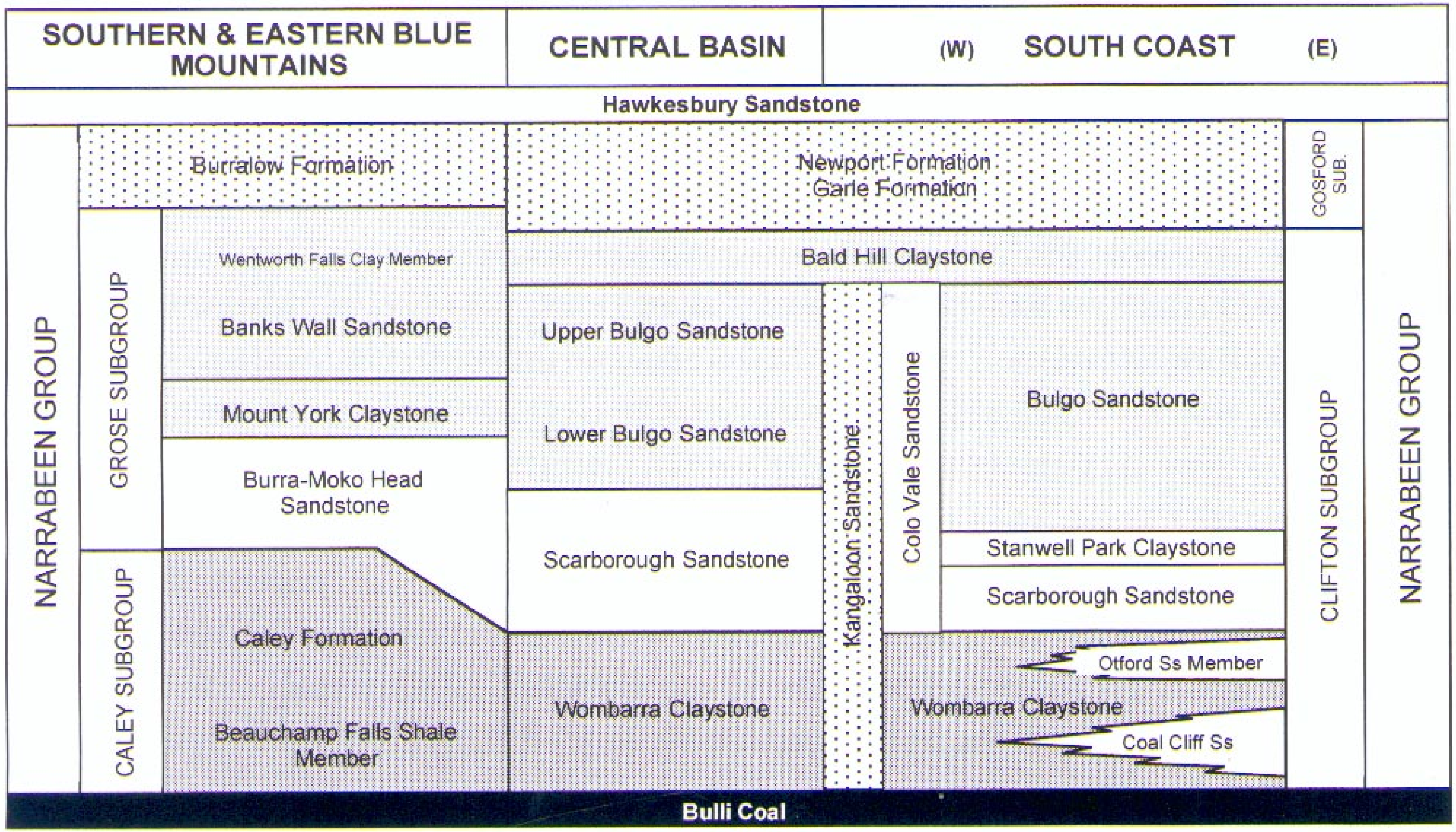
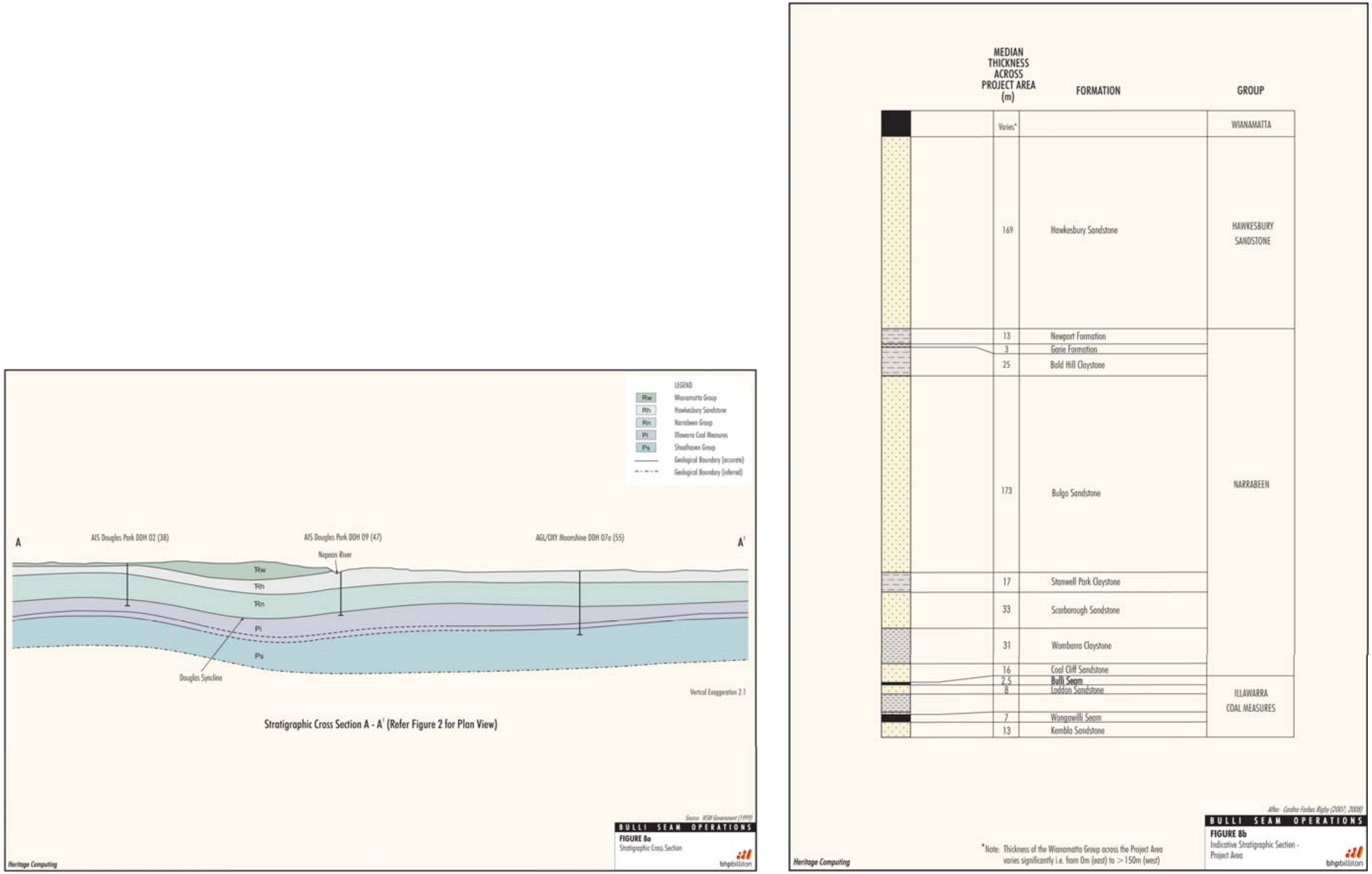


Figure 7. General stratigraphy and facies changes across the Narrabeen Group from the Southern Coalfield (right) to the Western Coalfield (left) [from Moffitt, 2000].

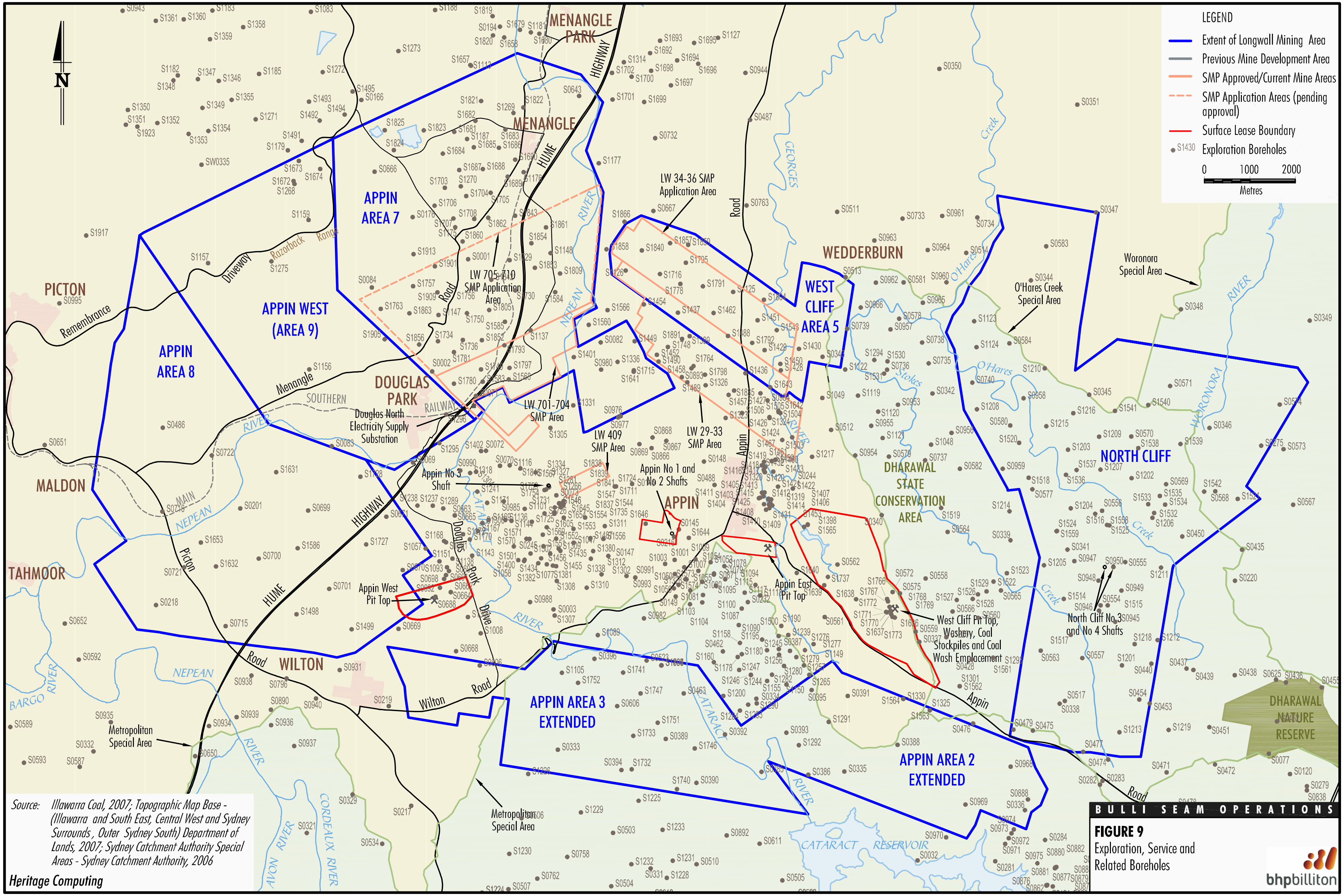


MEDIAN THICKNESS ACROSS PROJECT AREA (m)	FORMATION	GROUP
Varies*		WIANAMATTA
169	Hawkesbury Sandstone	HAWKESBURY SANDSTONE
13	Newport Formation	NARRABEEN
3	Garie Formation	
25	Bald Hill Claystone	
173	Bulgo Sandstone	
17	Stanwell Park Claystone	
33	Scarborough Sandstone	
31	Wombarra Claystone	
16	Coal Cliff Sandstone	
2.5	Bulli Seam	ILLAWARRA COAL MEASURES
8	Loddon Sandstone	
7	Wongawilli Seam	
13	Kembla Sandstone	

*Note: Thickness of the Wianamatta Group across the Project Area varies significantly i.e. from 0m (east) to >150m (west)

After: Cardno Forbes Rigby (2007, 2008)

Figure 8. Geological cross sections.



Source: *Illawarra Coal, 2007; Topographic Map Base - (Illawarra and South East, Central West and Sydney Surrounds, Outer Sydney South) Department of Lands, 2007; Sydney Catchment Authority Special Areas - Sydney Catchment Authority, 2006*

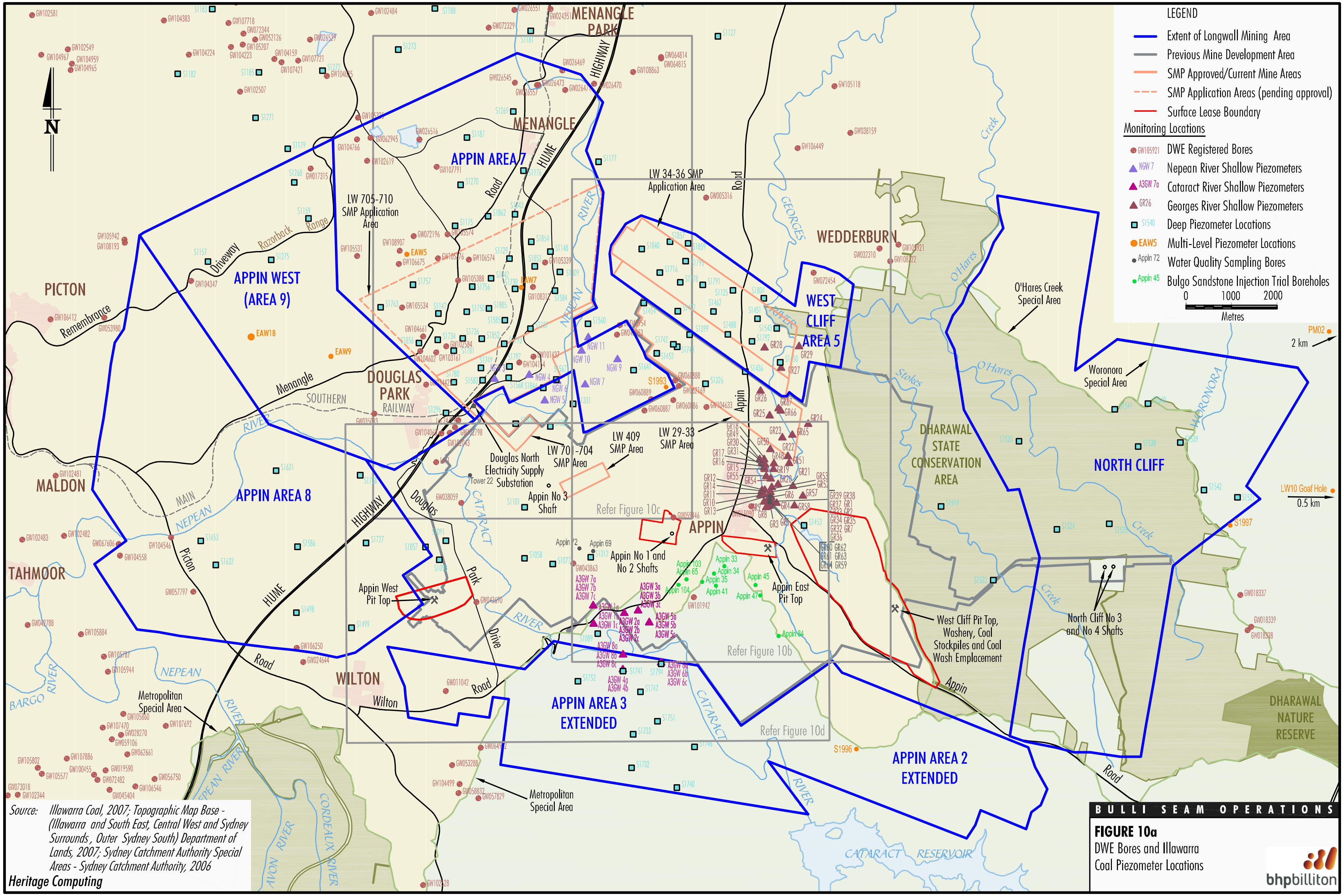
Heritage Computing

BULLI SEAM OPERATIONS

FIGURE 9
Exploration, Service and Related Boreholes

bhpbilliton

BHPIC-07-01 EA AppGW_1011



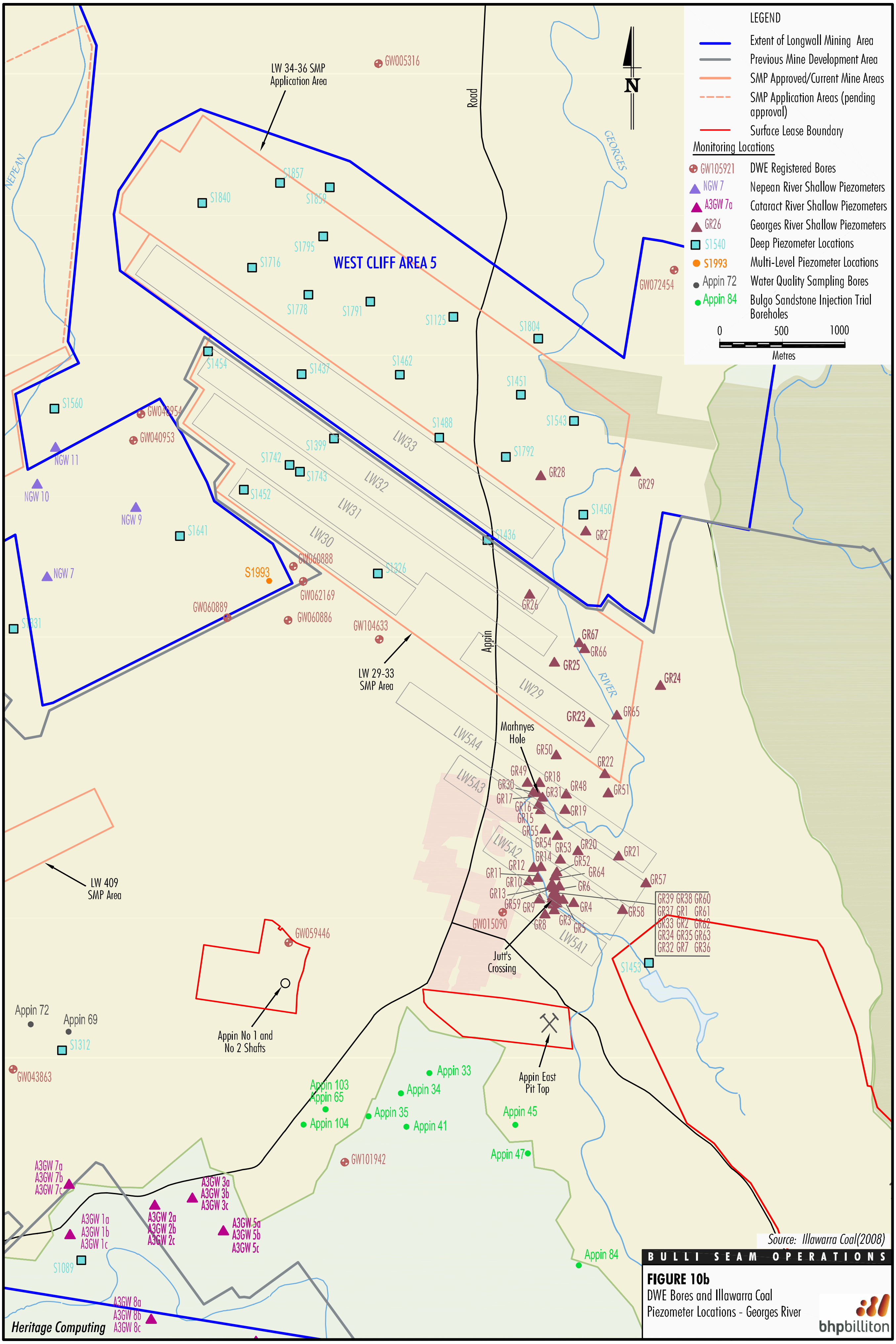
Source: Illawarra Coal, 2007; Topographic Map Base - (Illawarra and South East, Central West and Sydney Surrounds, Outer Sydney South) Department of Lands, 2007; Sydney Catchment Authority Special Areas - Sydney Catchment Authority, 2006

Heritage Computing

BULLI SEAM OPERATIONS

FIGURE 10a

DWE Bores and Illawarra Coal Piezometer Locations

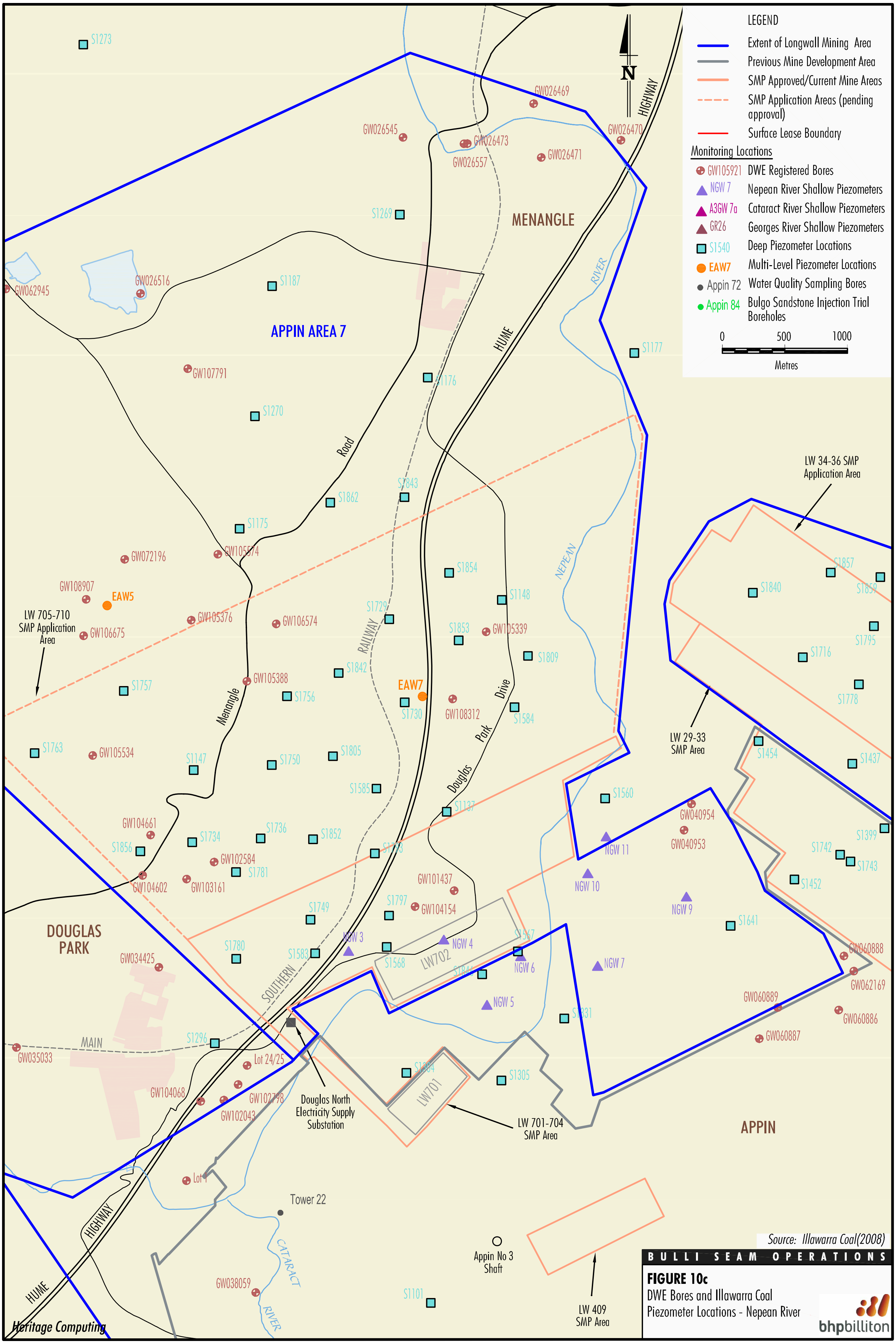


Source: *Illawarra Coal(2008)*

BULLI SEAM OPERATIONS

FIGURE 10b
DWE Bores and Illawarra Coal Piezometer Locations - Georges River

BHPIC-07-01 EA AppGW_104E



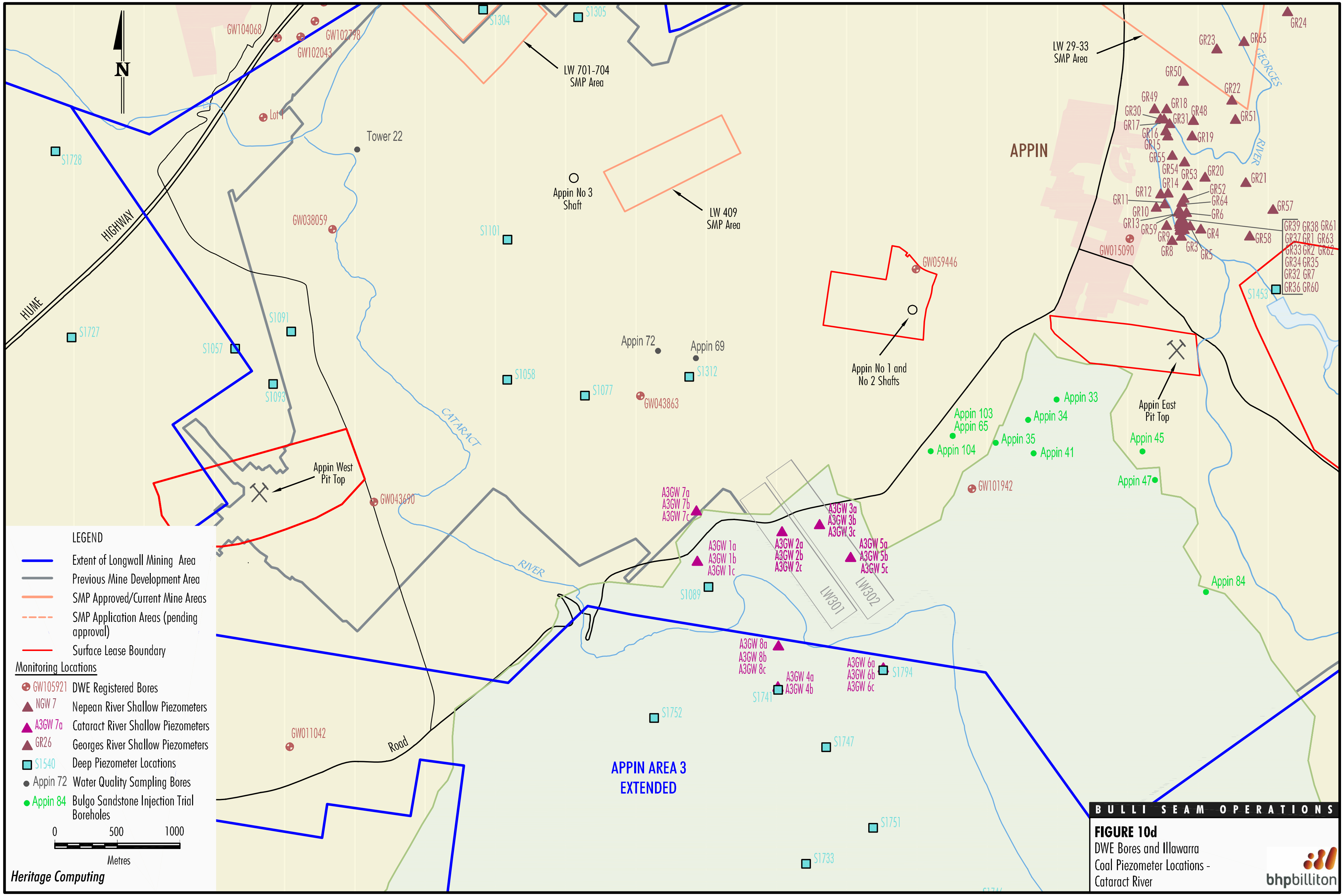
Source: Illawarra Coal(2008)

BULLI SEAM OPERATIONS

FIGURE 10c
DWE Bores and Illawarra Coal
Piezometer Locations - Nepean River

bhpbilliton

BHPIC-07-01 EA GW_103E



BULLI SEAM OPERATIONS

FIGURE 10d
DWE Bores and Illawarra Coal Piezometer Locations - Cataract River

BHPIC-07-01 EA AppGW_105E

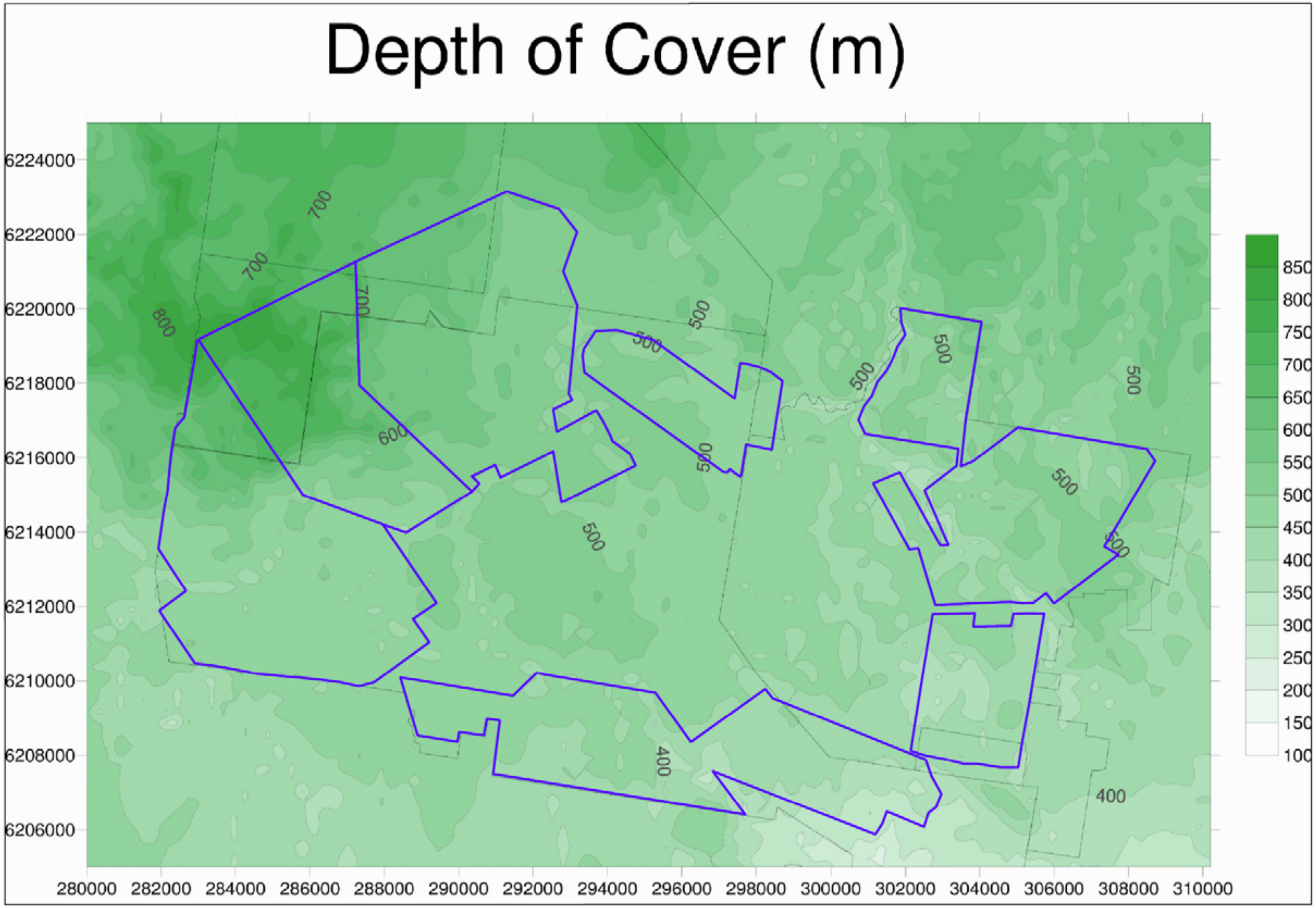


Figure 11. Depth of cover contours [m].

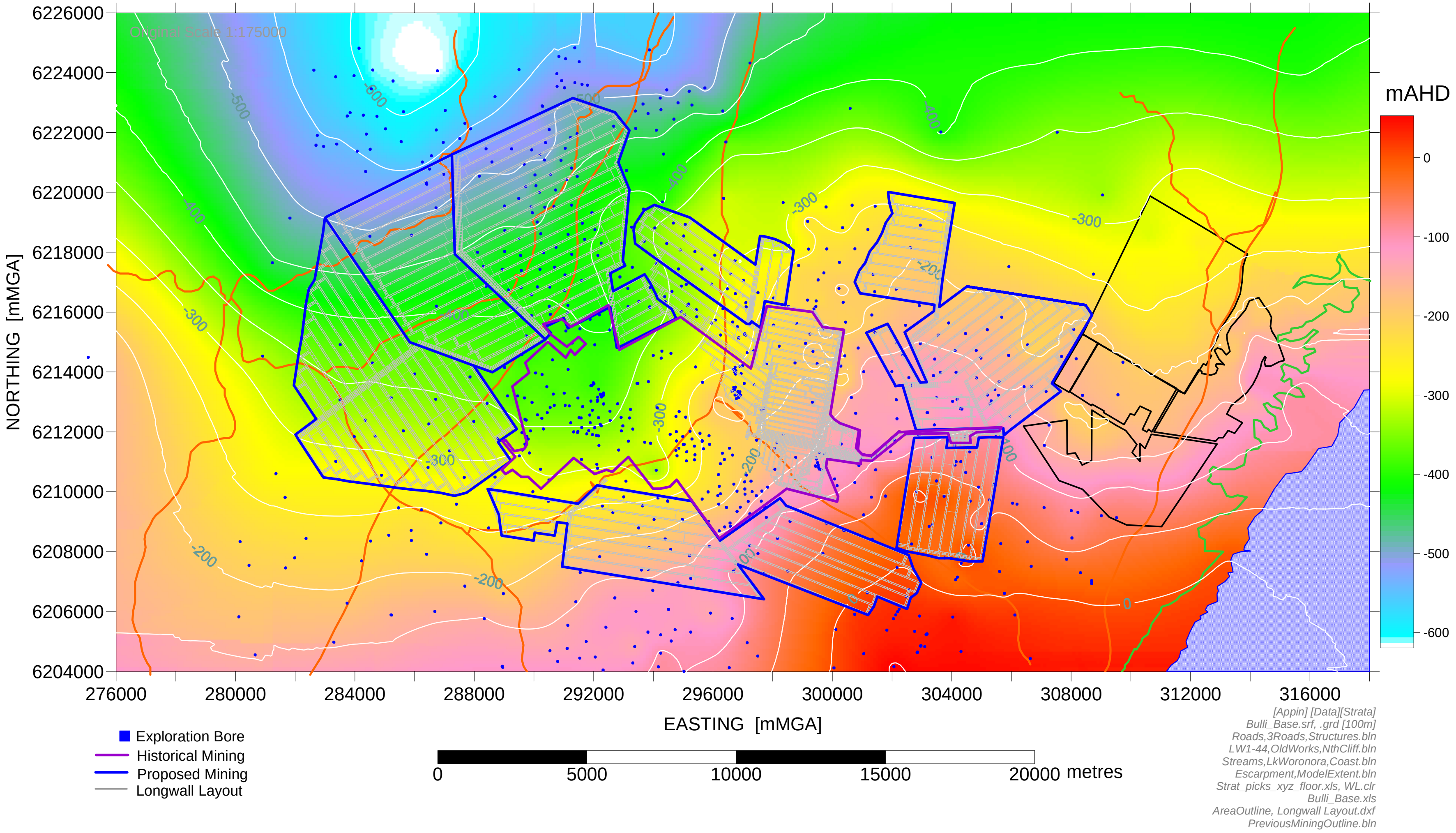


Figure 12. Structural contours for the base of the Bulli Seam [mAHD]

*Note: Longwall 901 at Appin West (Area 9) has been removed from the EA Base Plan Longwalls since the groundwater modelling was undertaken.

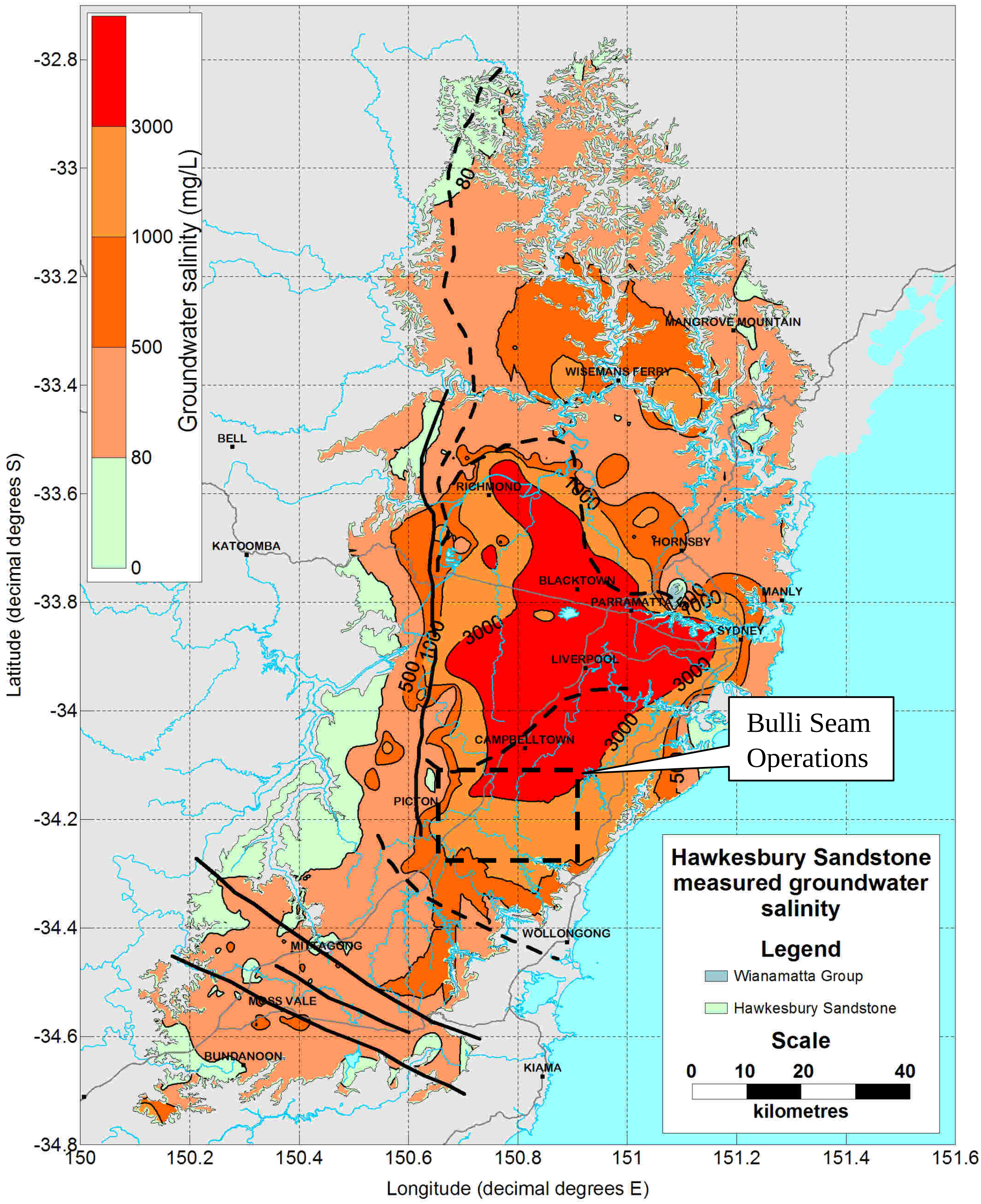


Figure 13. Groundwater salinity pattern in the Hawkesbury Sandstone [from Russell, 2007].

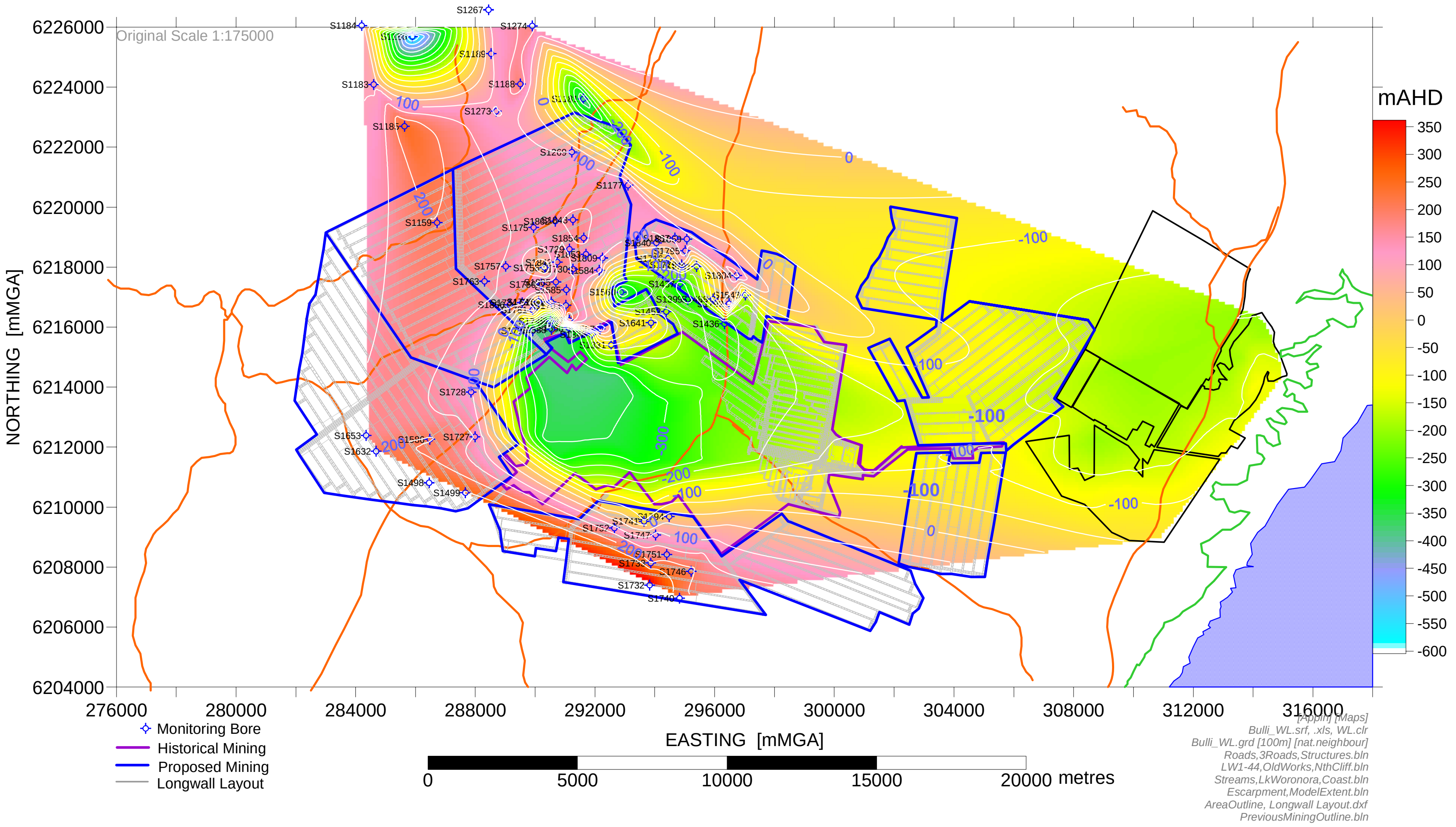


Figure 14. Inferred groundwater heads in the Bulli Seam [mAHD]. [Groundwater levels are assumed the same as seam floor levels in no-data areas previously mined. Only the most recent head measurement in the period 2006-2008 has been used.]

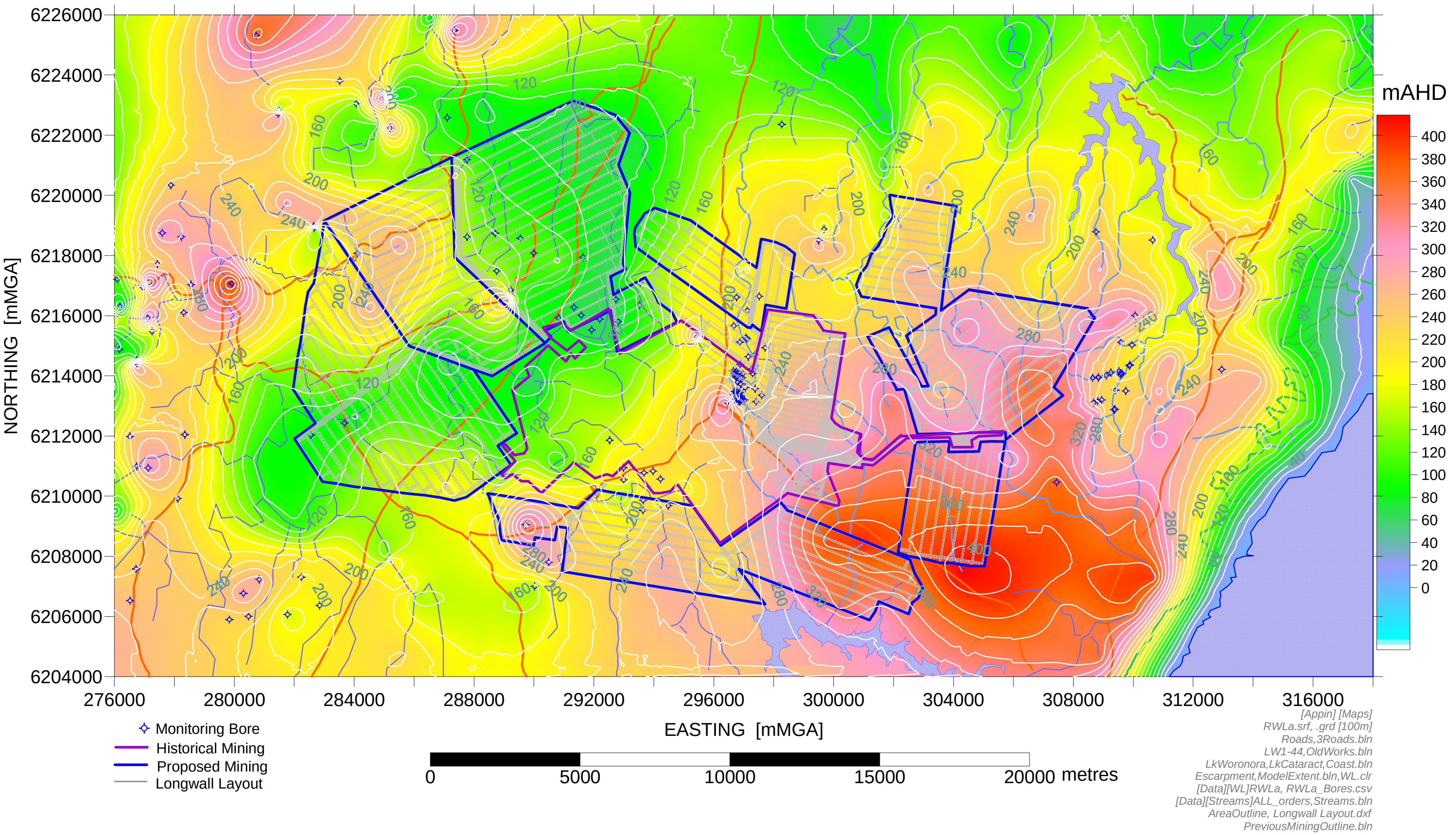


Figure 15. Inferred regional water table contours [mAHD]. [Groundwater levels are assumed the same as streambed elevations in no-data areas.]

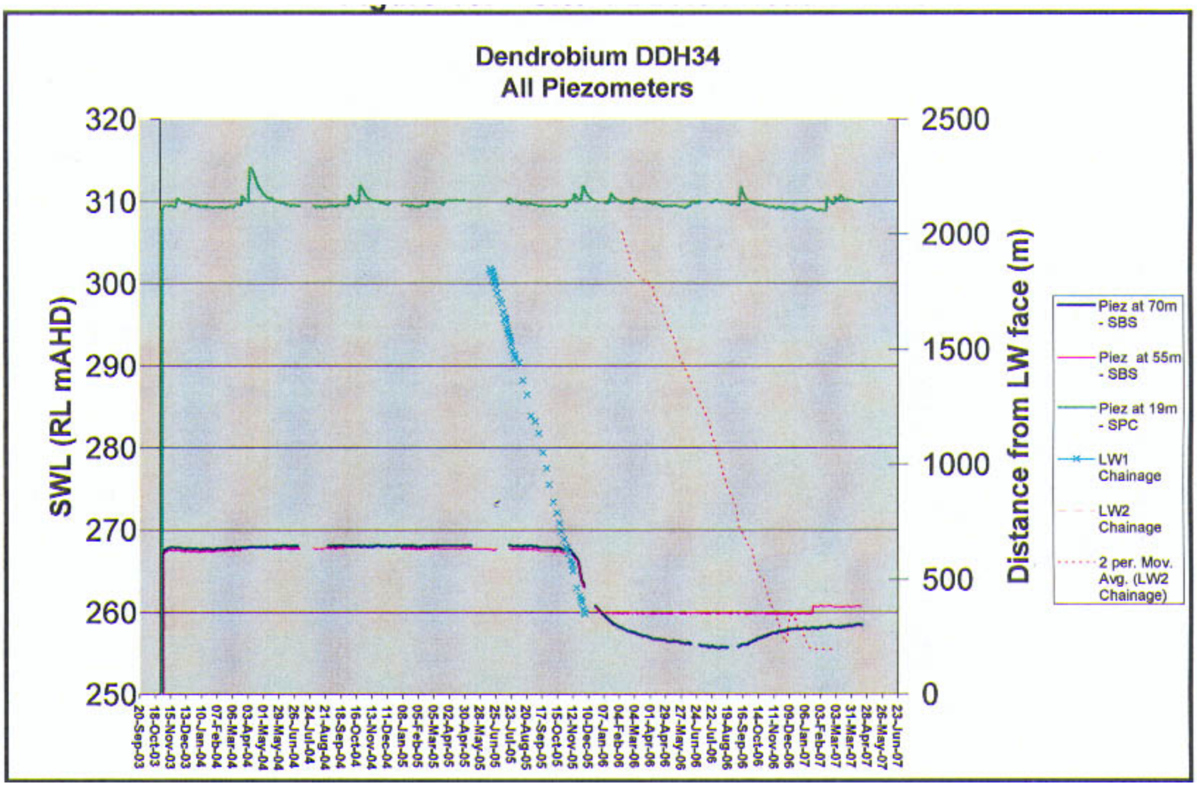


Figure 16. Time variations in total head at Dendrobium Area 1 Site 4: Bore DDH34A.

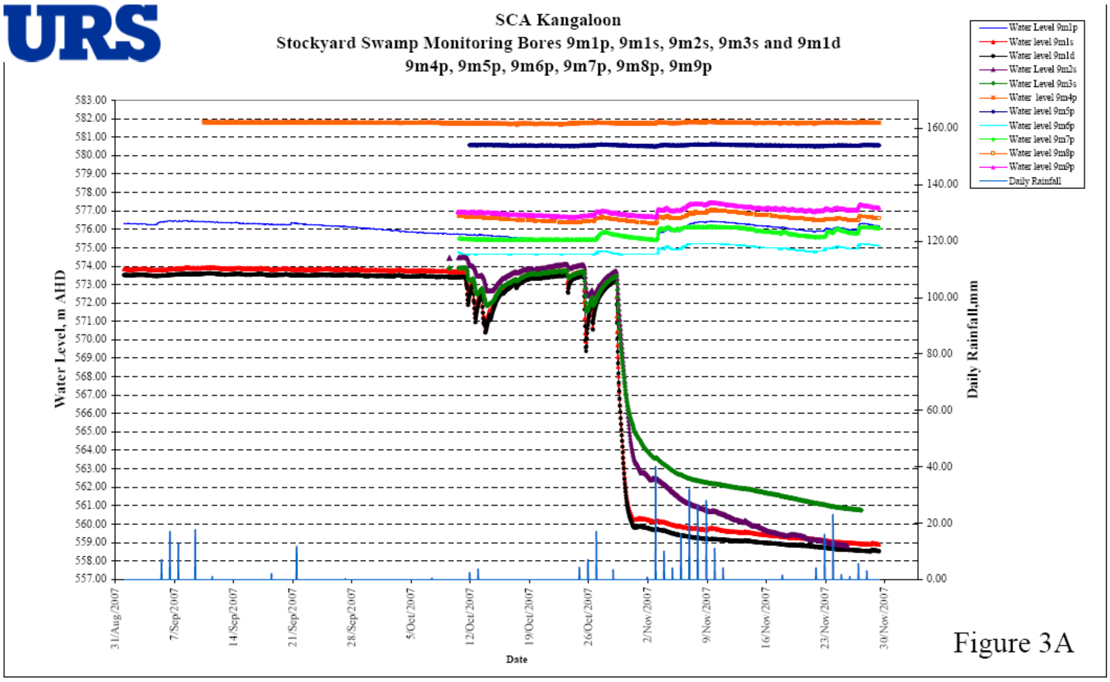


Figure 17. Kangaloon swamp monitoring for a pumping trial beneath Stockyard Swamp [from KBR (2008) – Upper Nepean (Kangaloon) Borefield Project].

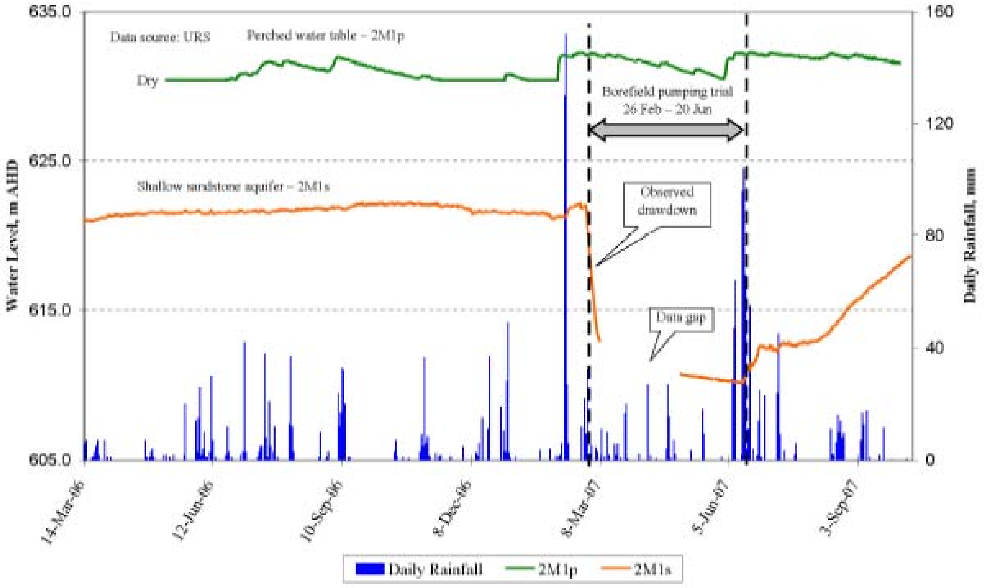


Figure 18. Kangaloon swamp monitoring for a pumping trial beneath Butlers Swamp [from KBR (2008) – Upper Nepean (Kangaloon) Borefield Project].

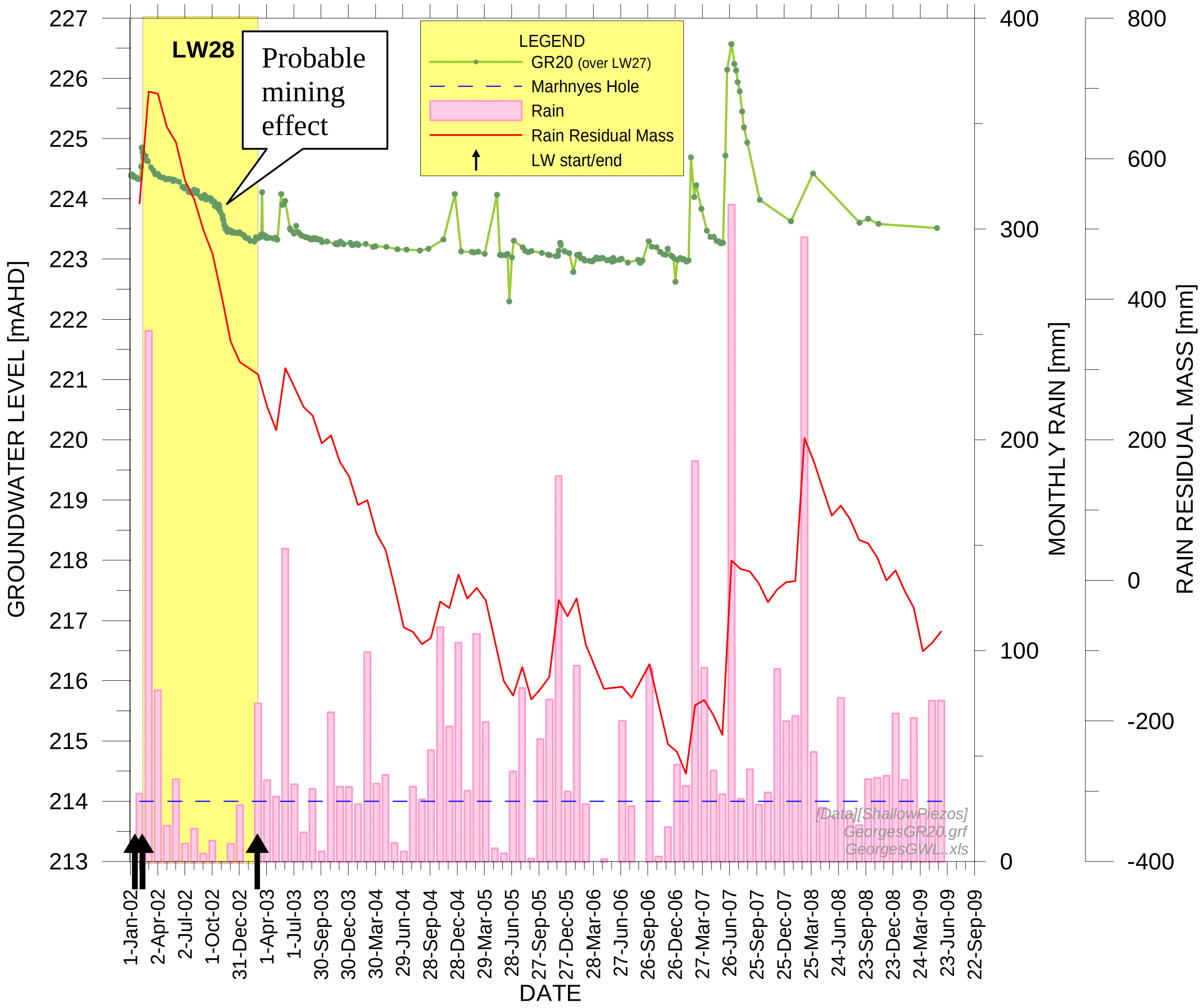


Figure 19a. Shallow groundwater hydrograph at Georges River site GR20, compared with longwall duration, rain and river levels. [Rain is for Douglas Park station – See Figure 4]

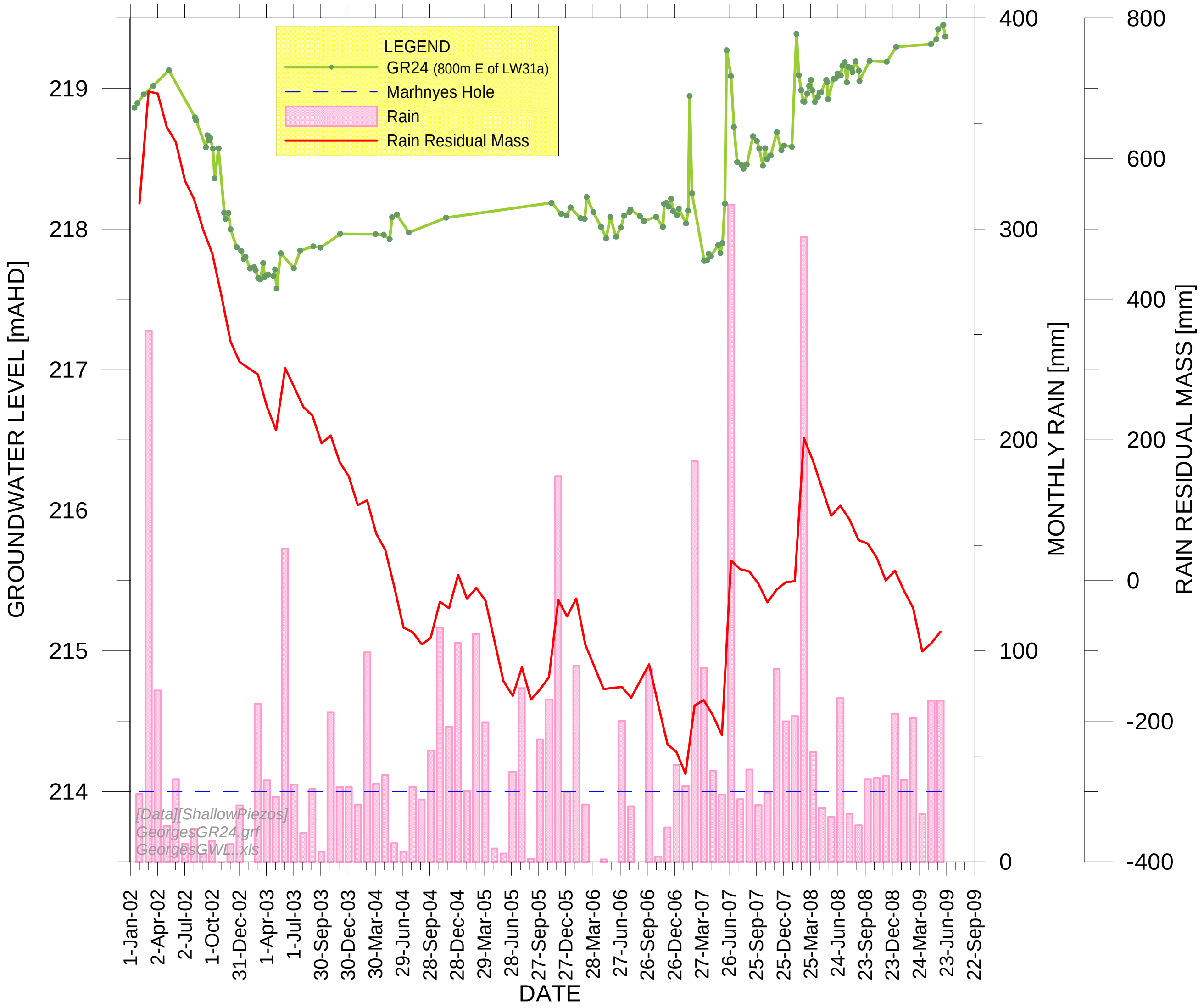


Figure 19b. Shallow groundwater hydrograph at Georges River site GR24, compared with rain and river levels. [Rain is for Douglas Park station – See Figure 4]

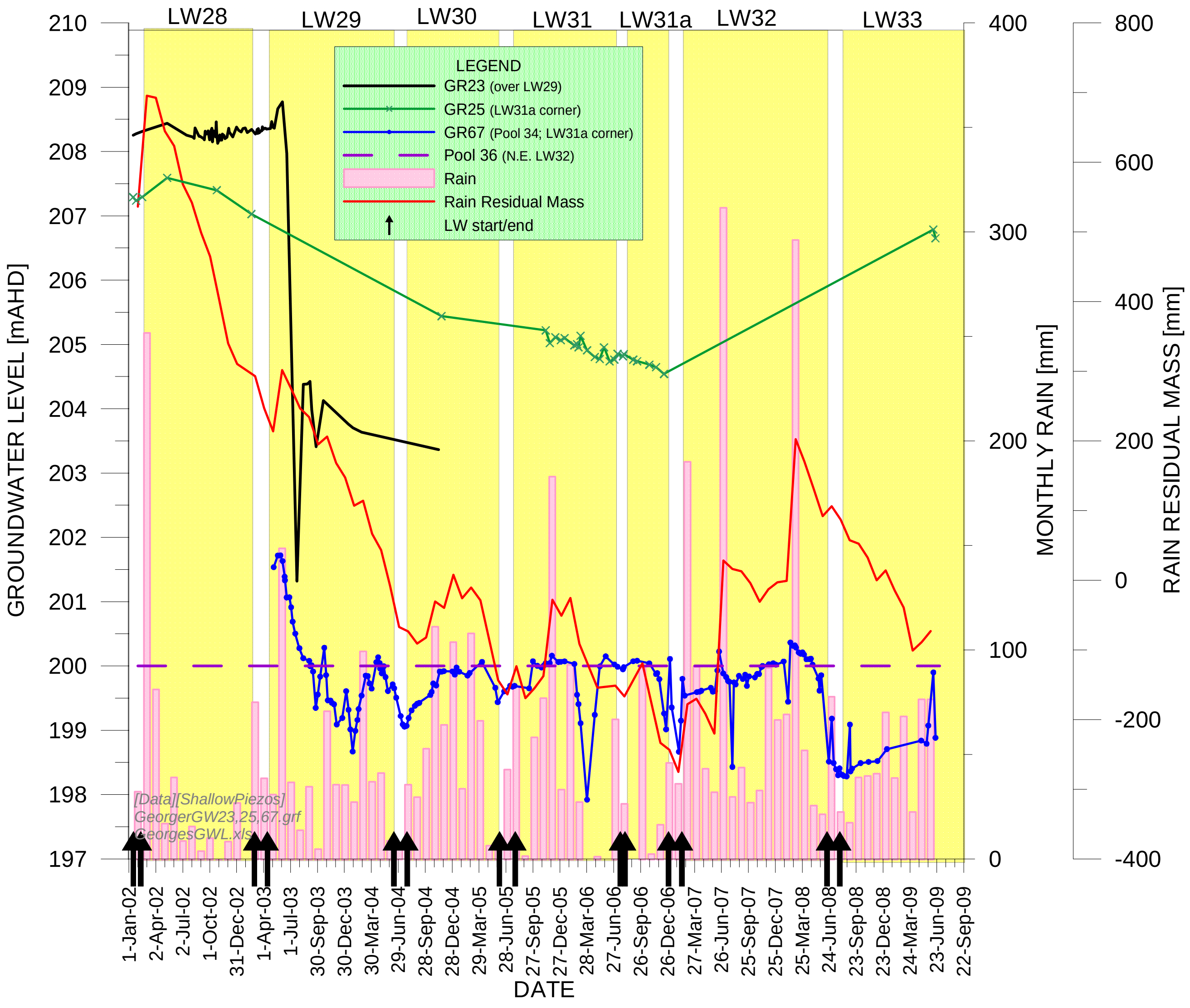


Figure 19c. Shallow groundwater hydrographs at Georges River sites GR23, GR25 and GR67, compared with longwall duration, rain and river levels. [Rain is for Douglas Park station – See Figure 4]

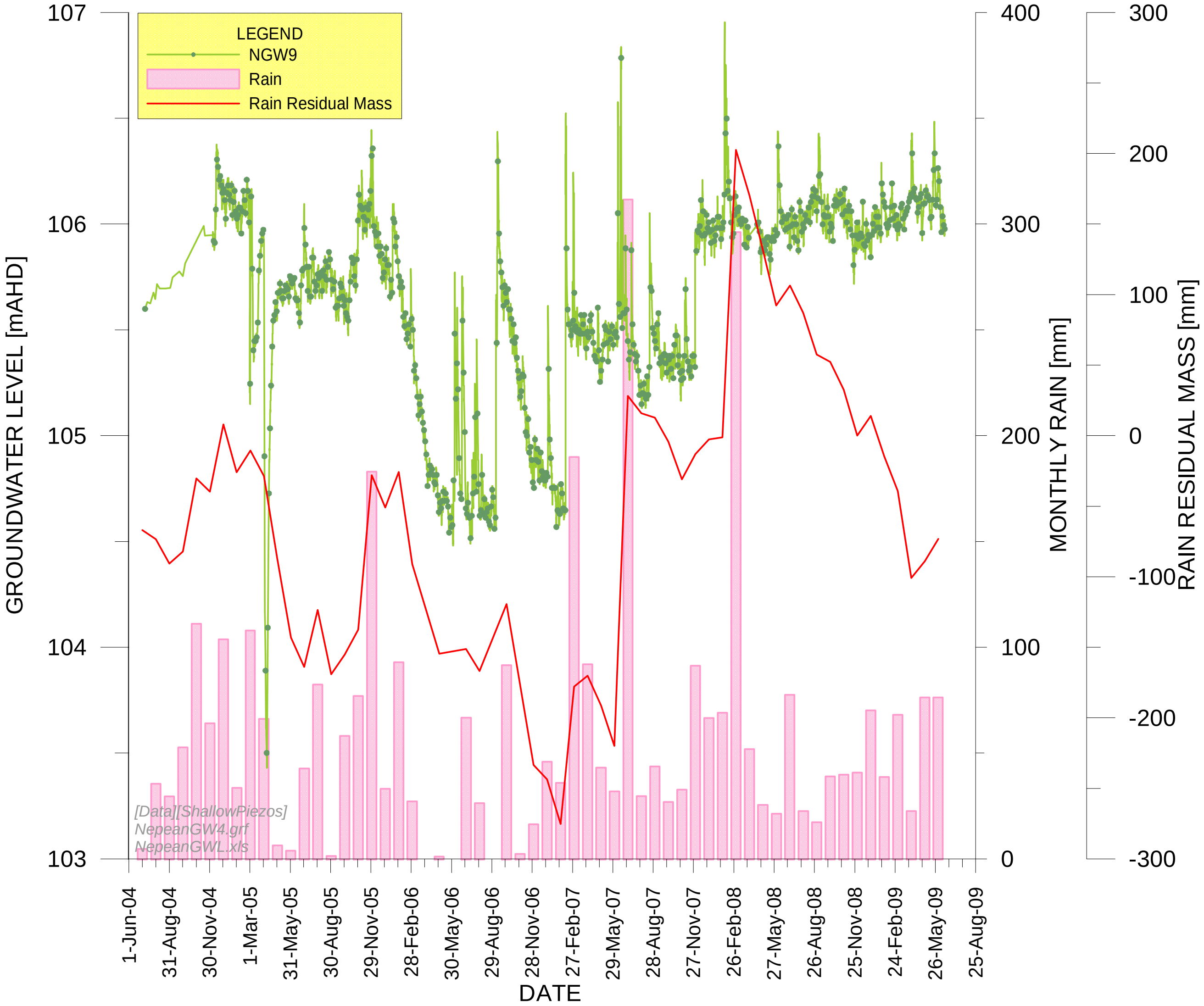


Figure 20a. Shallow groundwater hydrograph at Nepean River site NGW9, compared with rain dynamics and trend. [Rain is for Douglas Park station – See Figure 4]

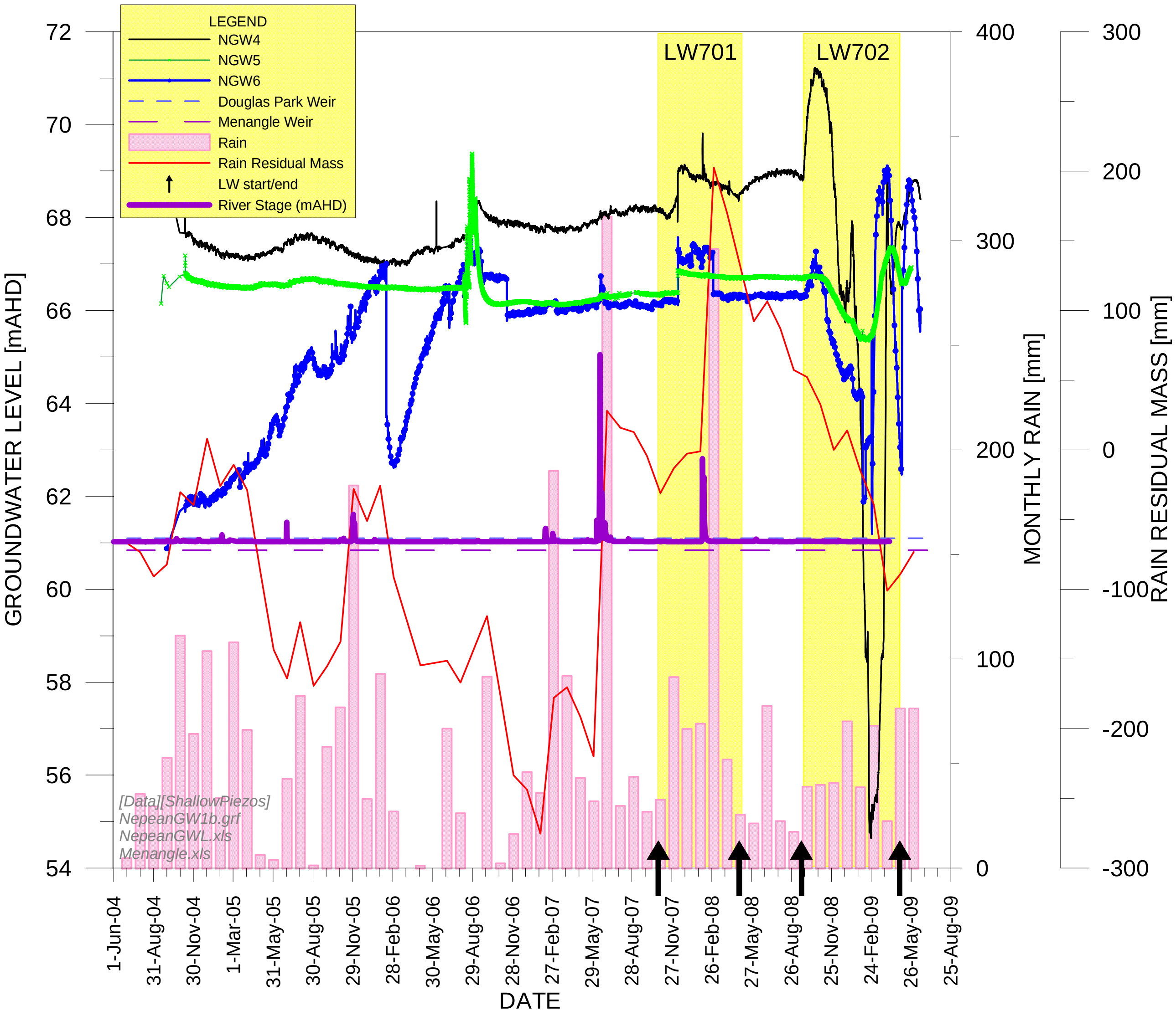


Figure 20b. Shallow groundwater hydrographs at Nepean River sites NGW4, NGW5 and NGW6, compared with rain and river levels. [Rain is for Douglas Park station – See Figure 4]

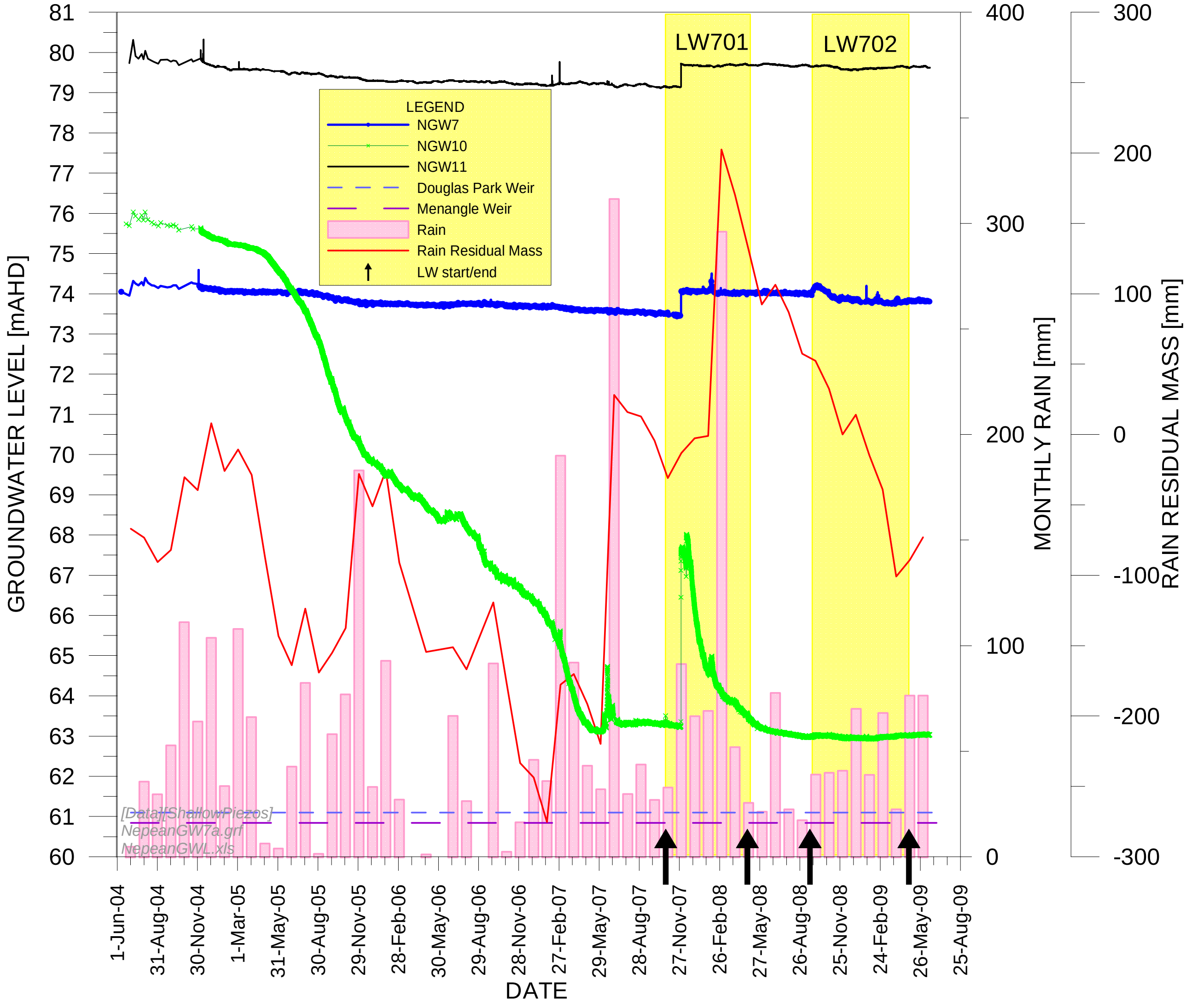


Figure 20c. Shallow groundwater hydrographs at Nepean River sites NGW7, NGW10 and NGW11, compared with rain and river levels. [Rain is for Douglas Park station – See Figure 4]

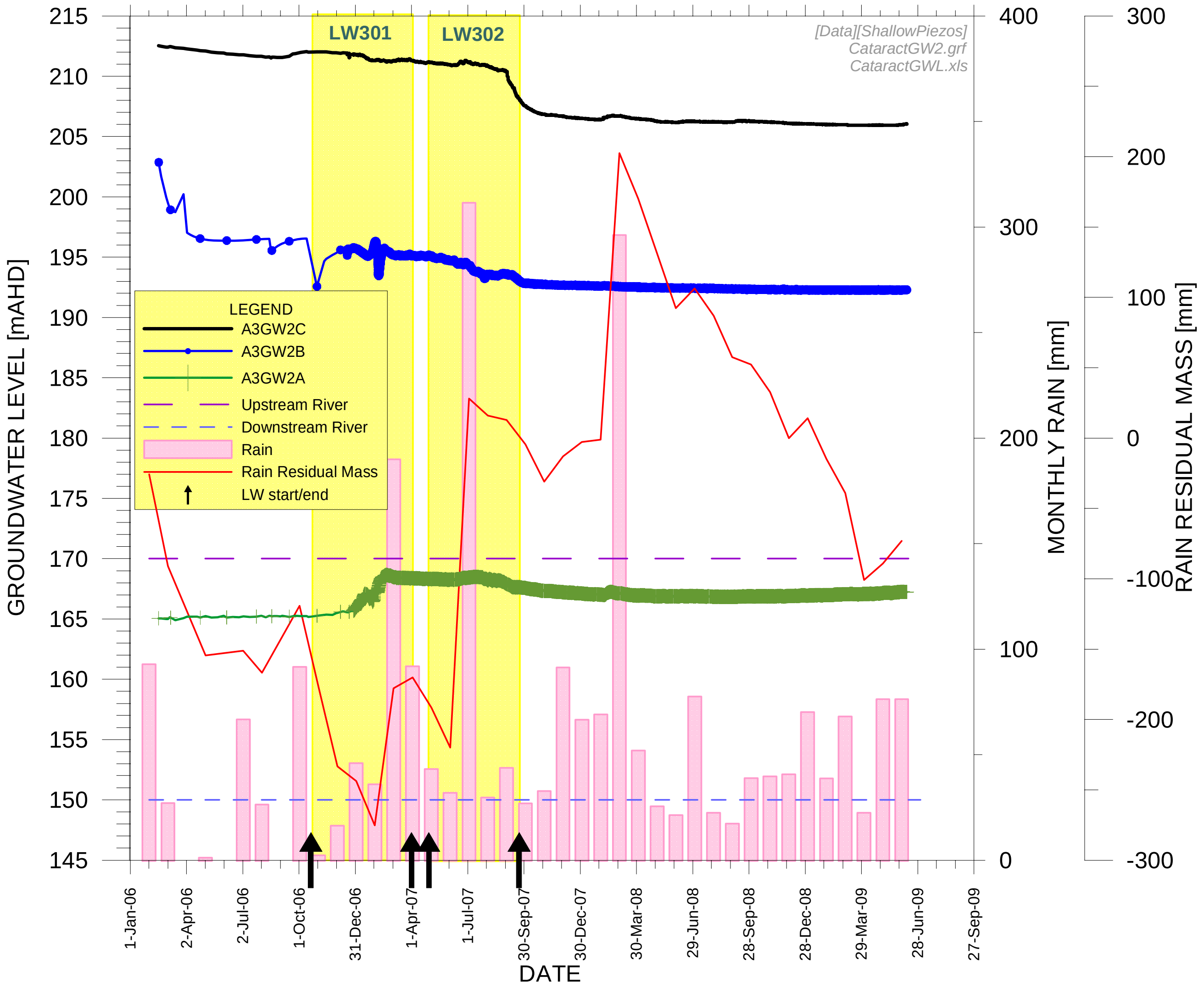


Figure 21a. Shallow groundwater hydrographs at Cataract River site A3GW2, compared with longwall duration, rain and river levels. [Rain is for Douglas Park station – See Figure 4]

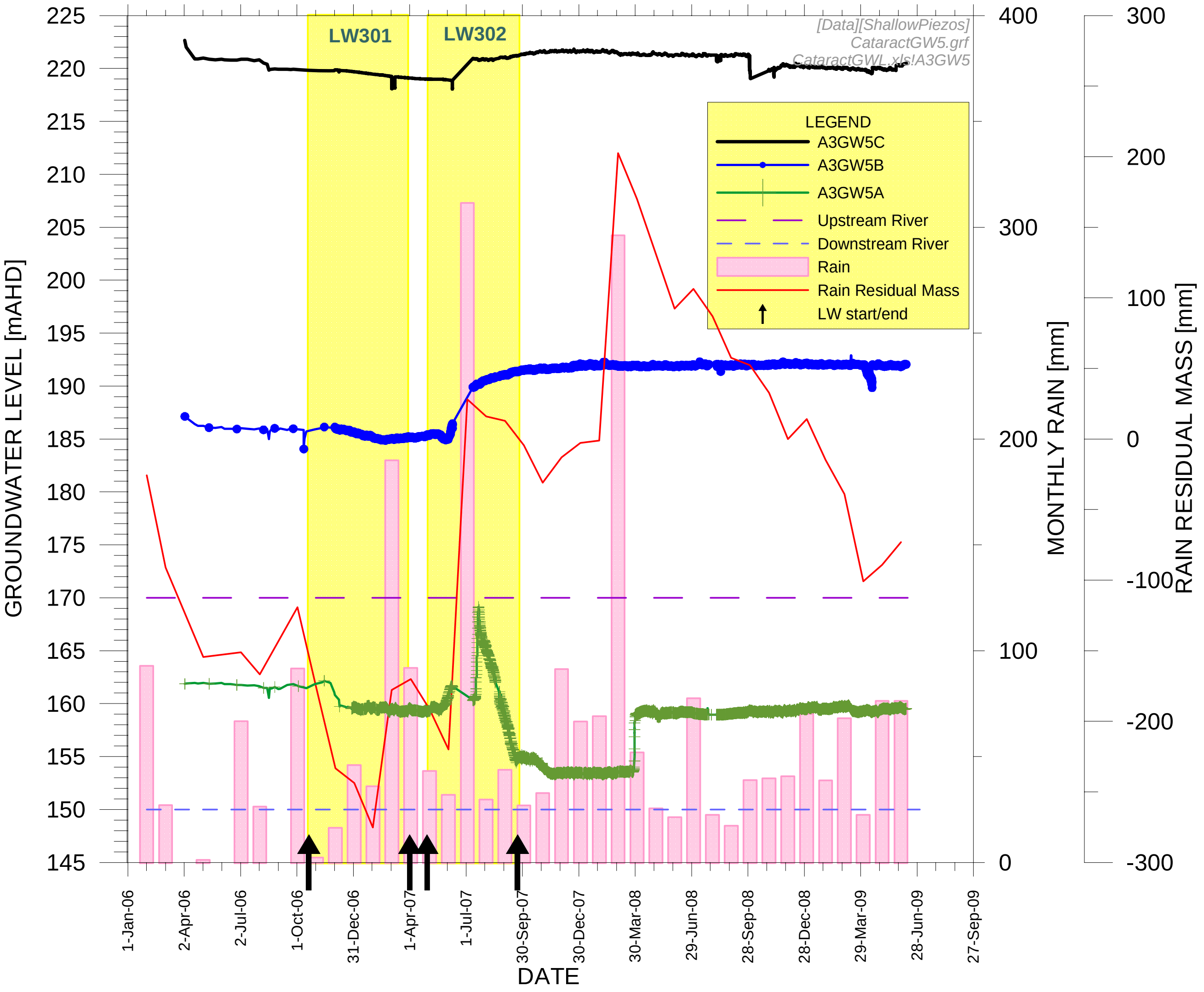


Figure 21b. Shallow groundwater hydrographs at Cataract River site A3GW5, compared with longwall duration, rain and river levels. [Rain is for Douglas Park station – See Figure 4]

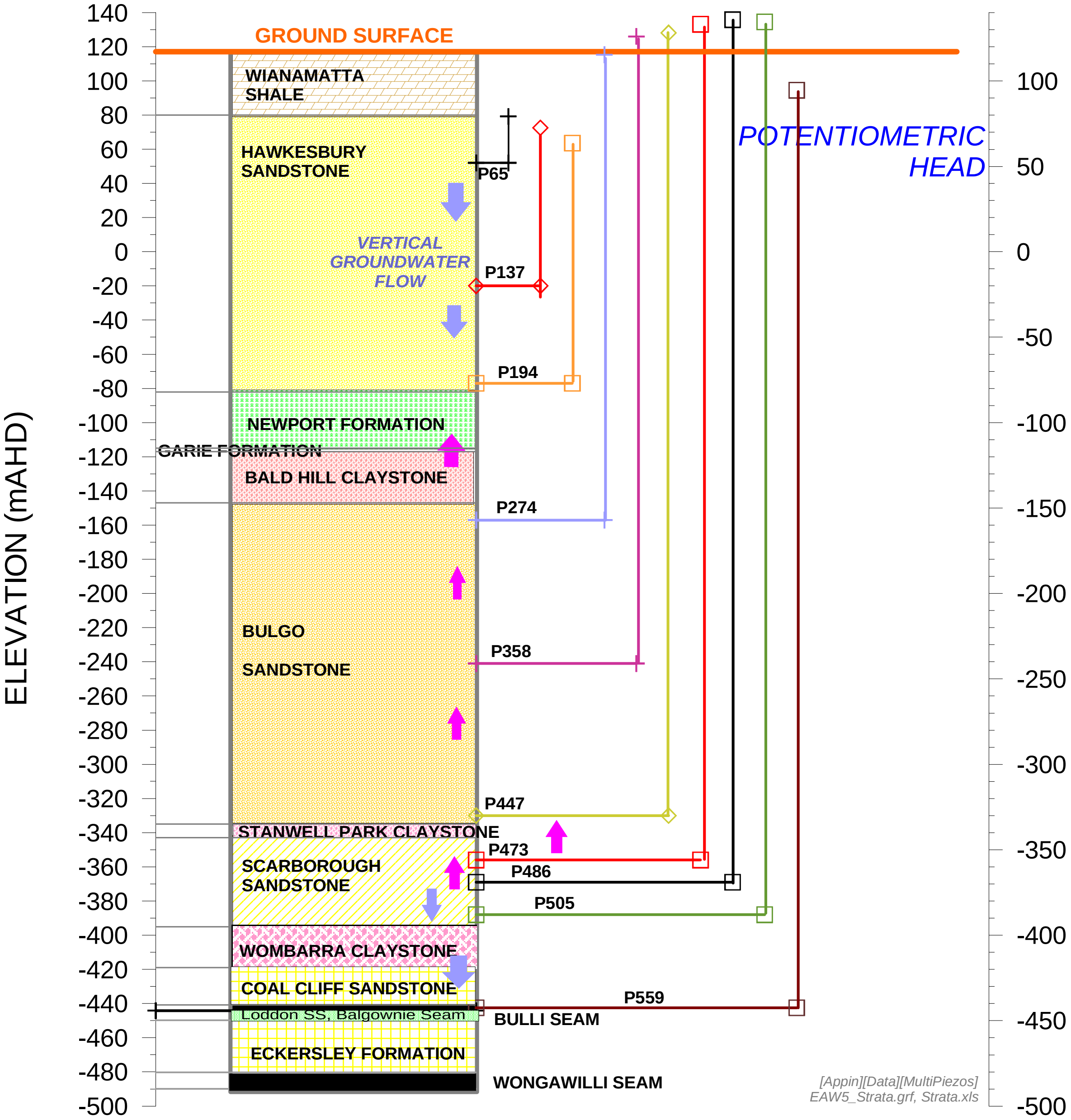


Figure 22. Vertical groundwater flow directions, relative piezometer elevations and averaged total potentiometric heads at the EAW5 hole. *[Averaging period 1 July 2008 to 25 February 2009]*

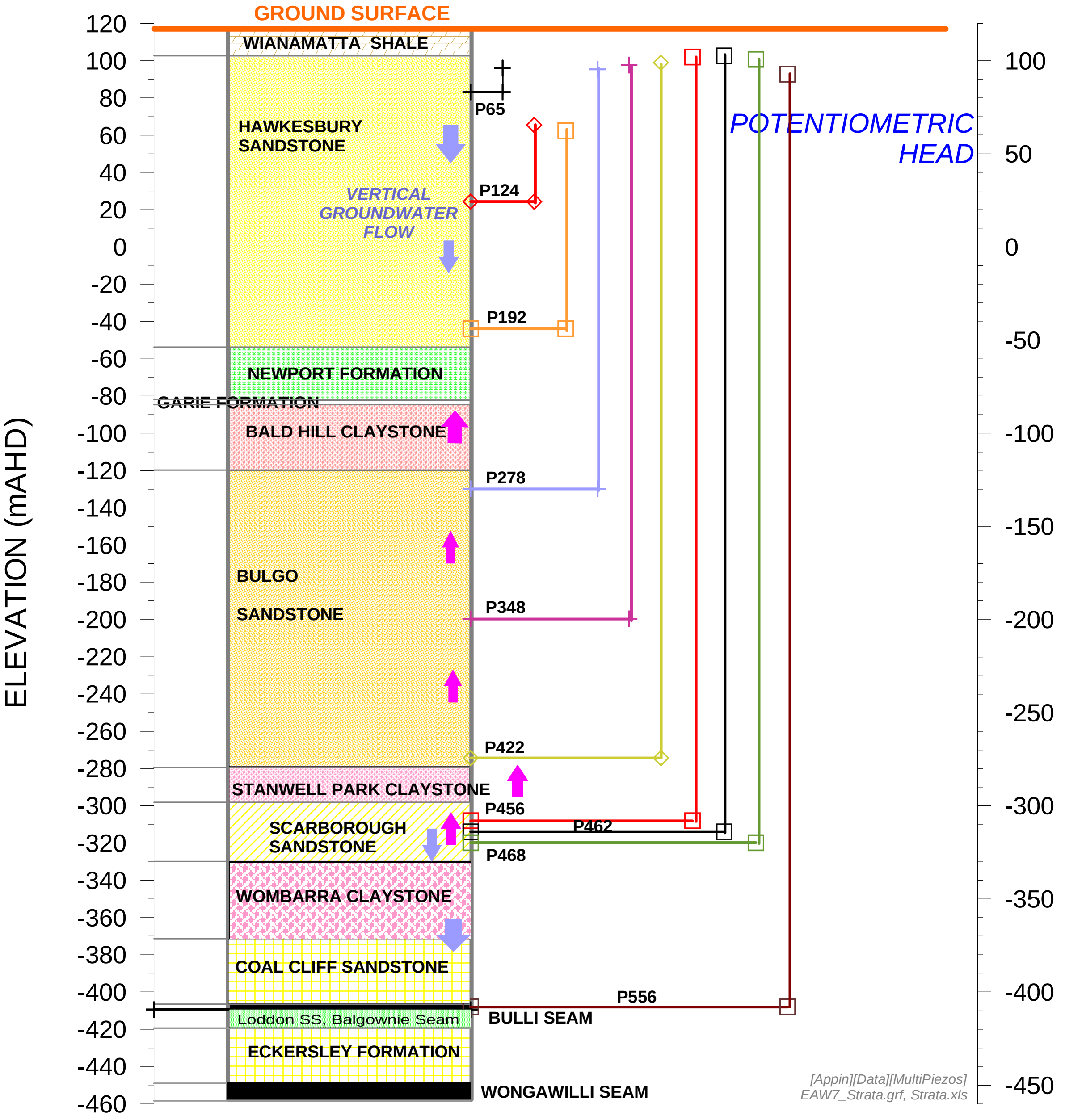
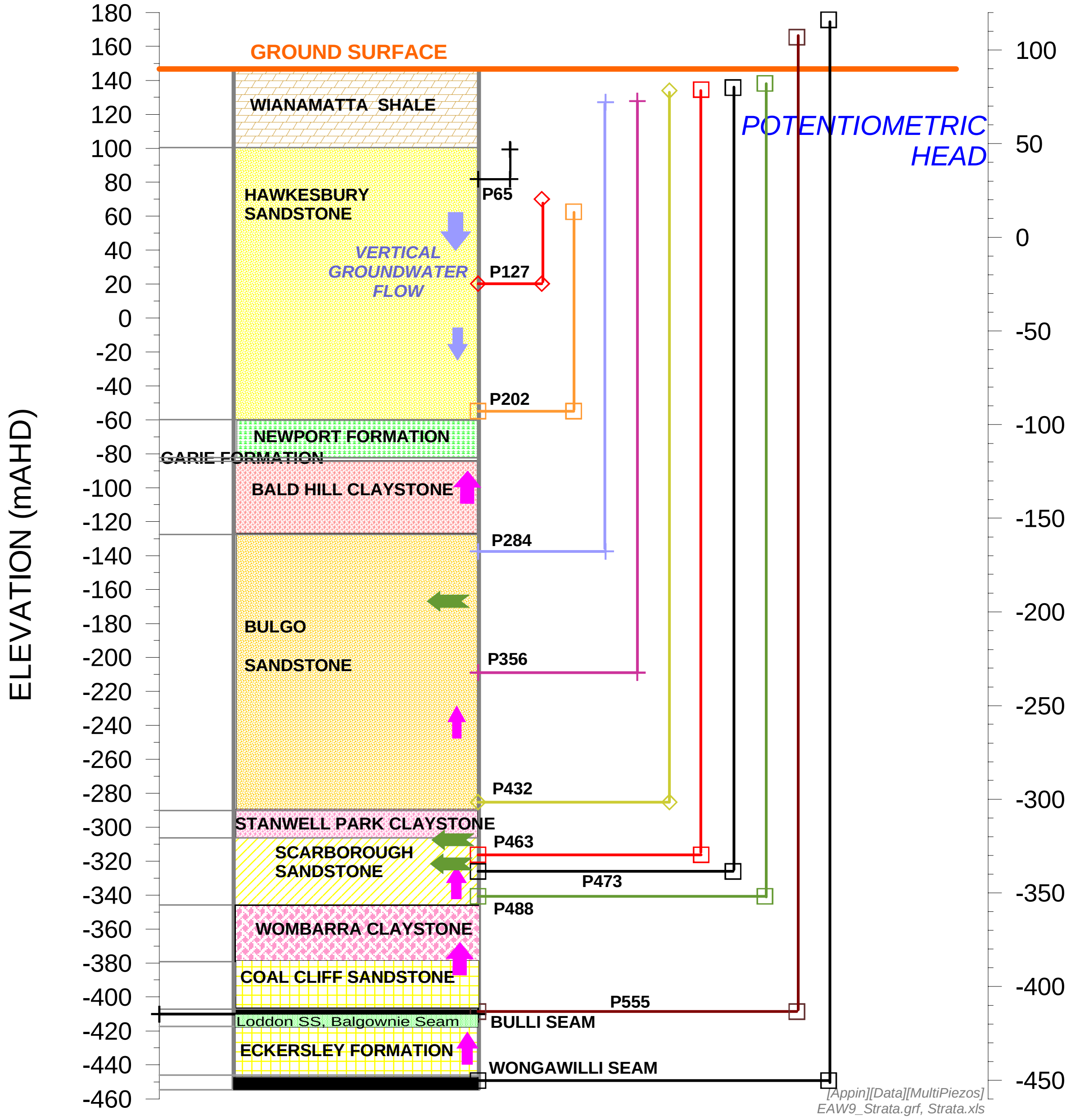
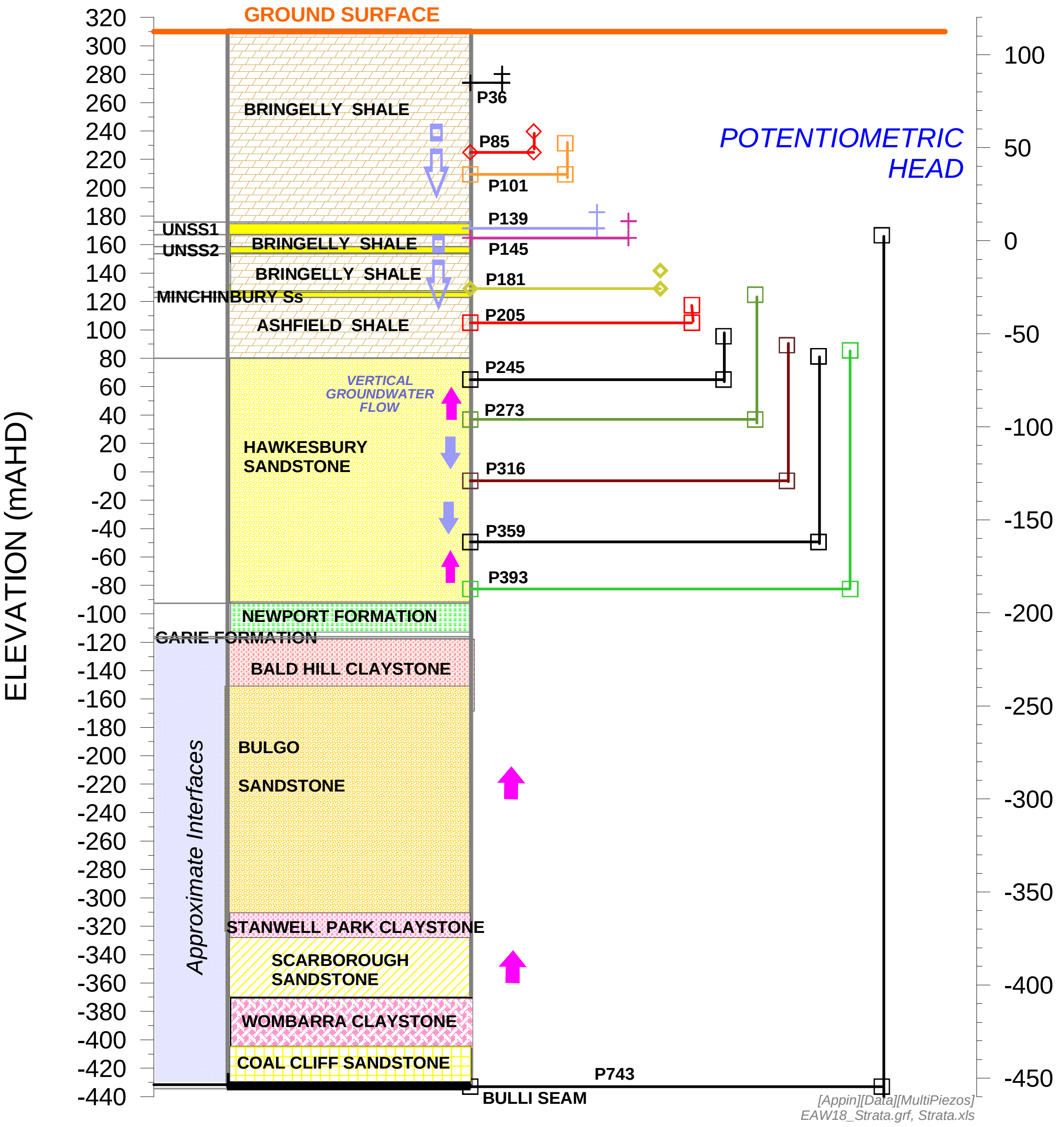


Figure 23. Vertical groundwater flow directions, relative piezometer elevations and averaged total potentiometric heads at the EAW7 hole. *[Averaging period 1 October 2008 to 25 February 2009]*



[Appin][Data][MultiPiezos]
EAW9_Strata.grf, Strata.xls

Figure 24. Vertical groundwater flow directions, relative piezometer elevations and averaged total potentiometric heads at the EAW9 hole. *[Averaging period 1 November 2008 to 25 February 2009]*



[Appin][Data][MultiPiezos] EAW18_Strata.grf, Strata.xls

Figure 25. Vertical groundwater flow directions, relative piezometer elevations and averaged total potentiometric heads at the EAW18 hole. *[Averaging period 12 January 2009 to 24 March 2009]*

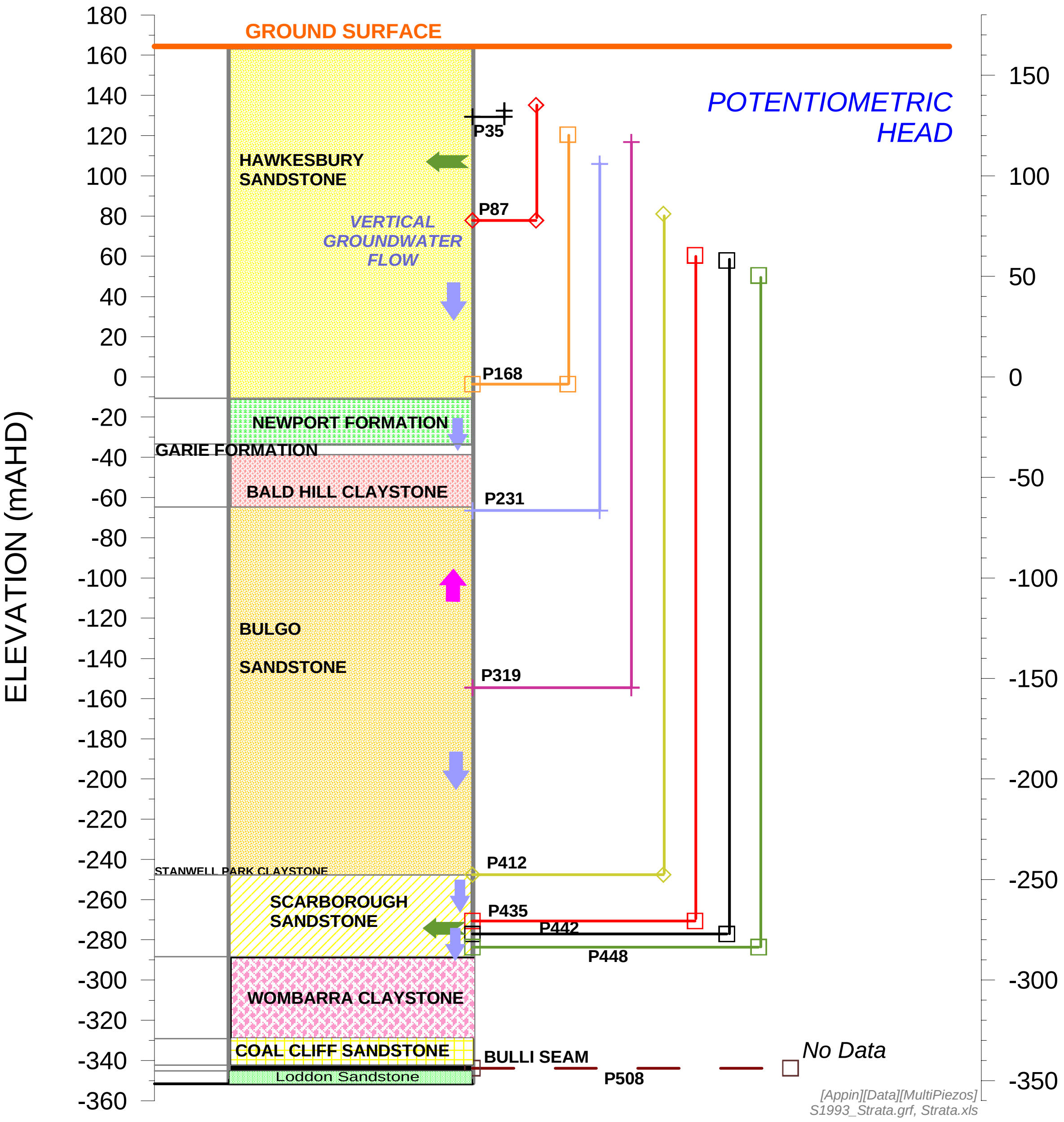


Figure 26. Vertical groundwater flow directions, relative piezometer elevations and initial potentiometric heads at the S1993 hole. *[Sampled 23 June 2009]*

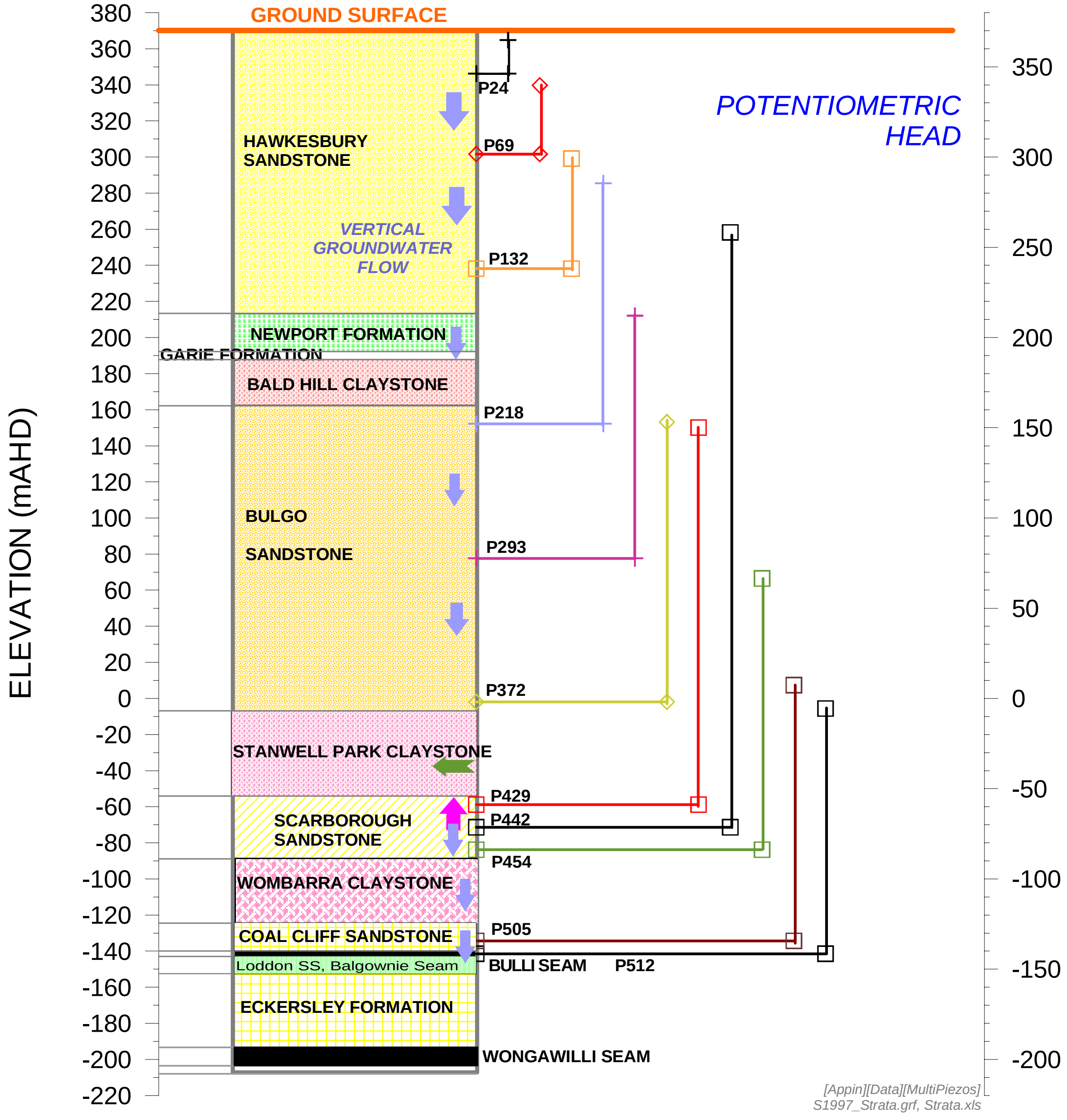


Figure 27. Vertical groundwater flow directions, relative piezometer elevations and initial potentiometric heads at the S1997 hole. *[Sampled 15 June 2009]*

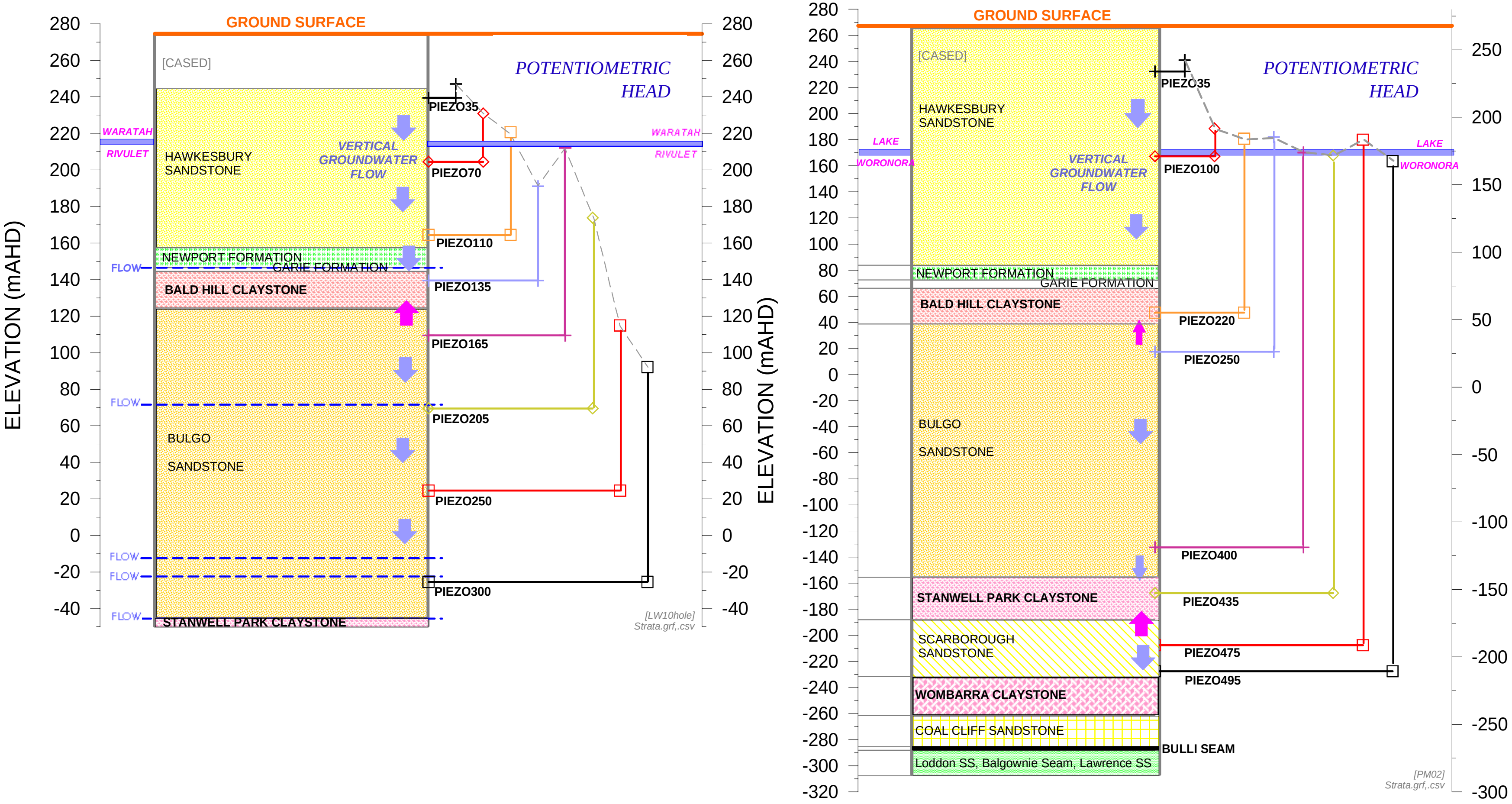


Figure 28. Vertical groundwater flow directions and relative elevations of piezometers, averaged total potentiometric heads and Lake Woronora level in the context of the stratigraphic section at the Metropolitan LW10 goaf hole (left) and PM02 (right)

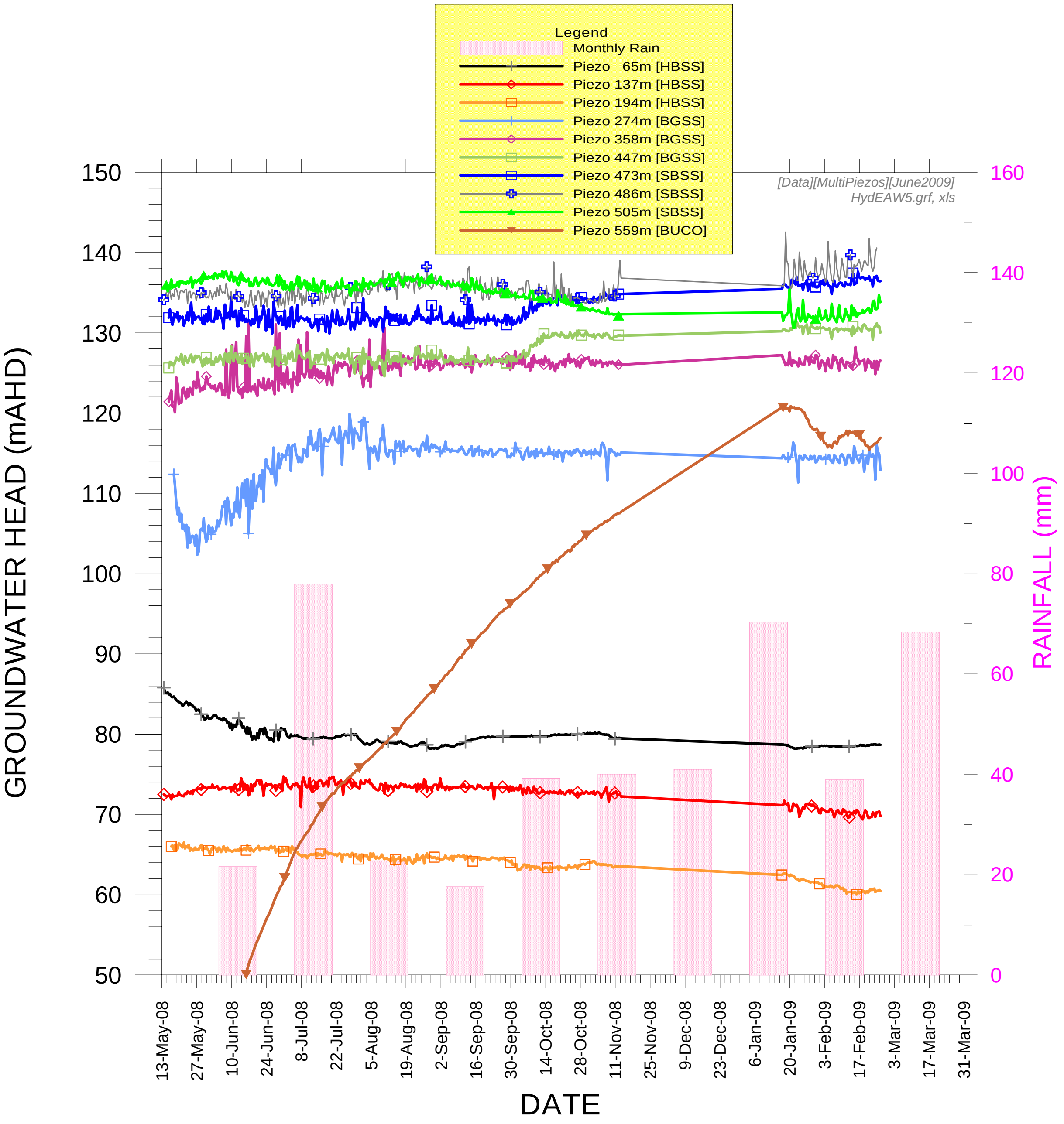


Figure 29. Time variations in total groundwater head at all piezometers in the EAW5 hole.

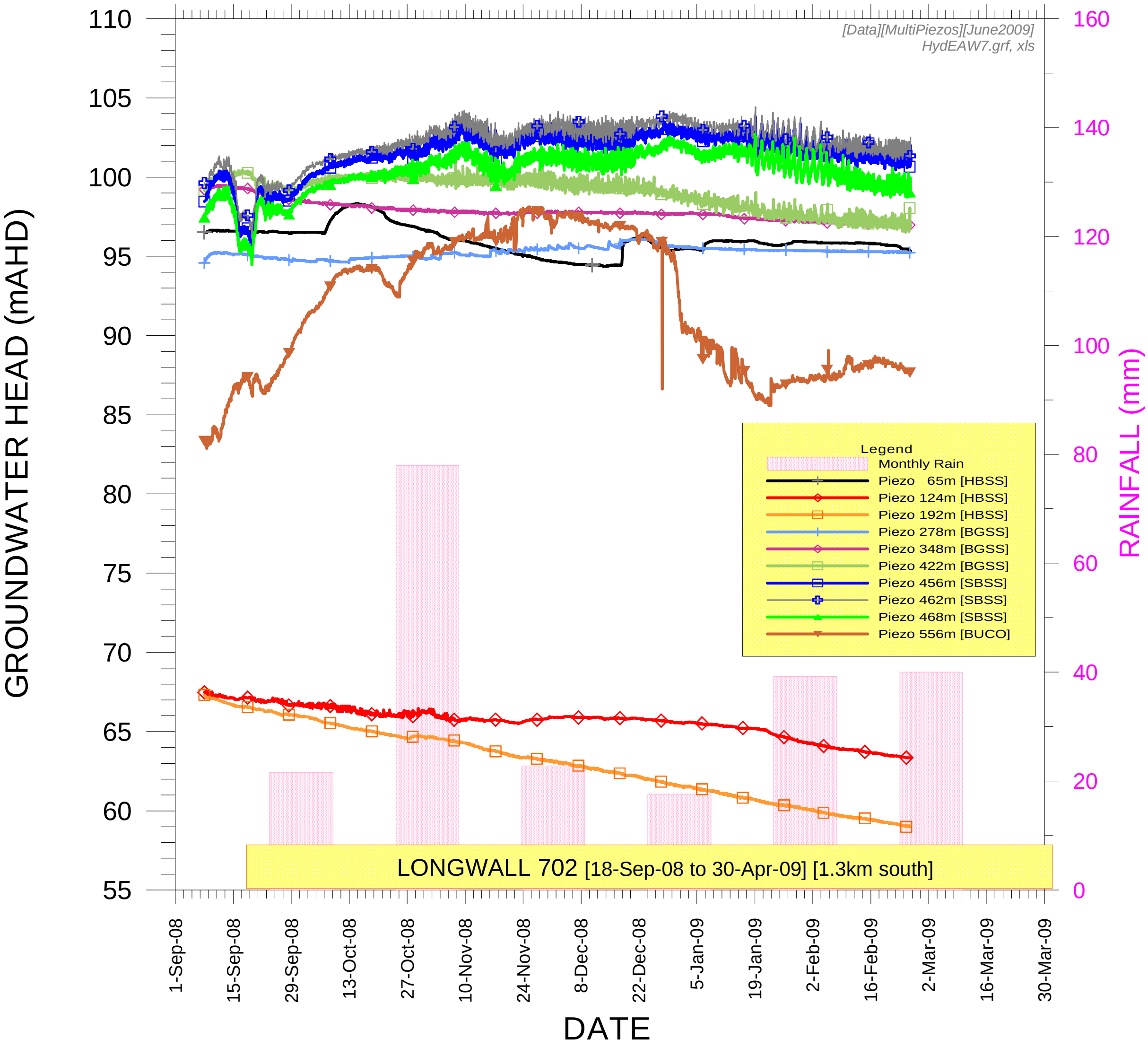


Figure 30. Time variations in total groundwater head at all piezometers in the EAW7 hole.

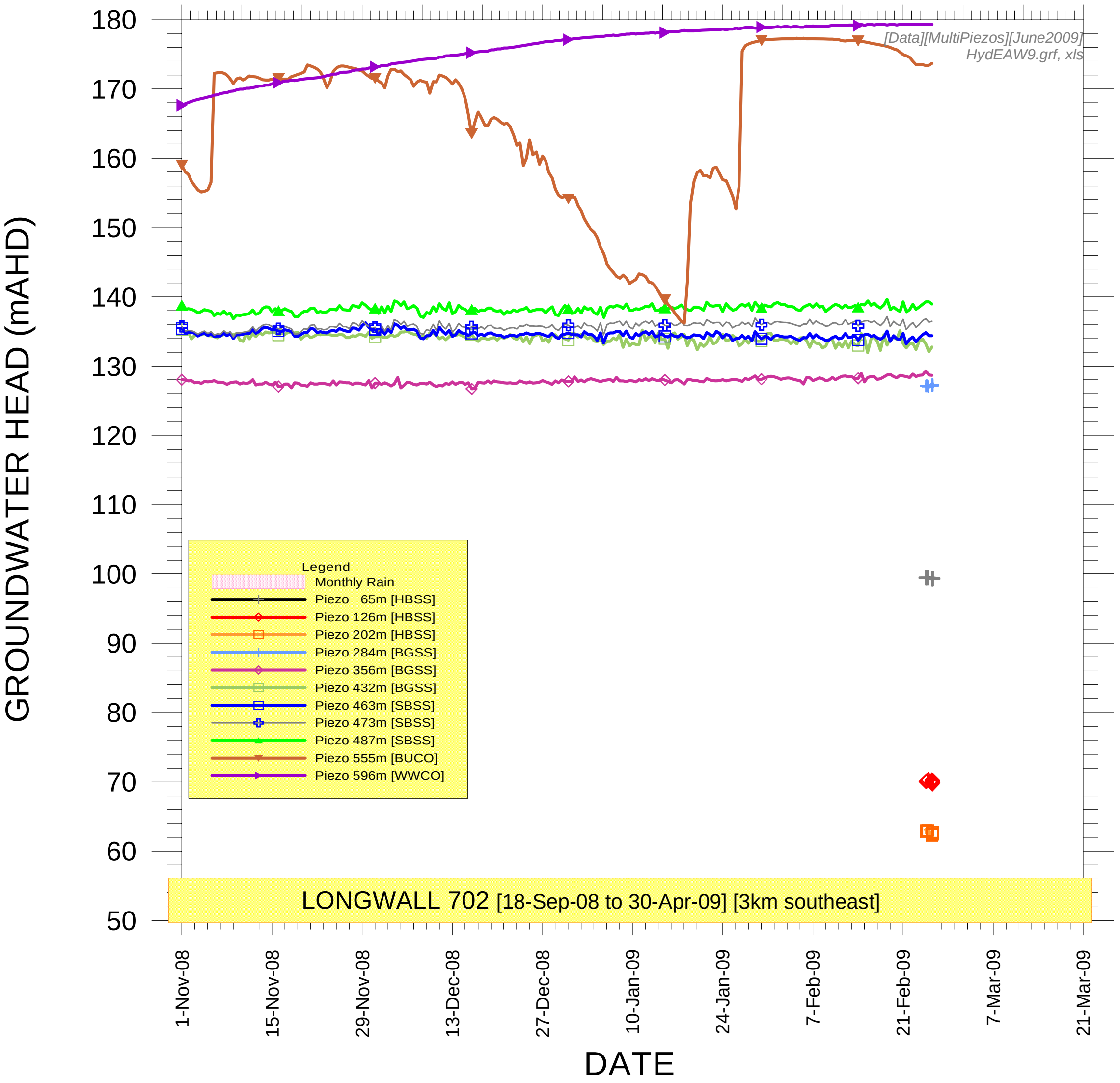


Figure 31. Time variations in total groundwater head at all piezometers in the EAW9 hole.

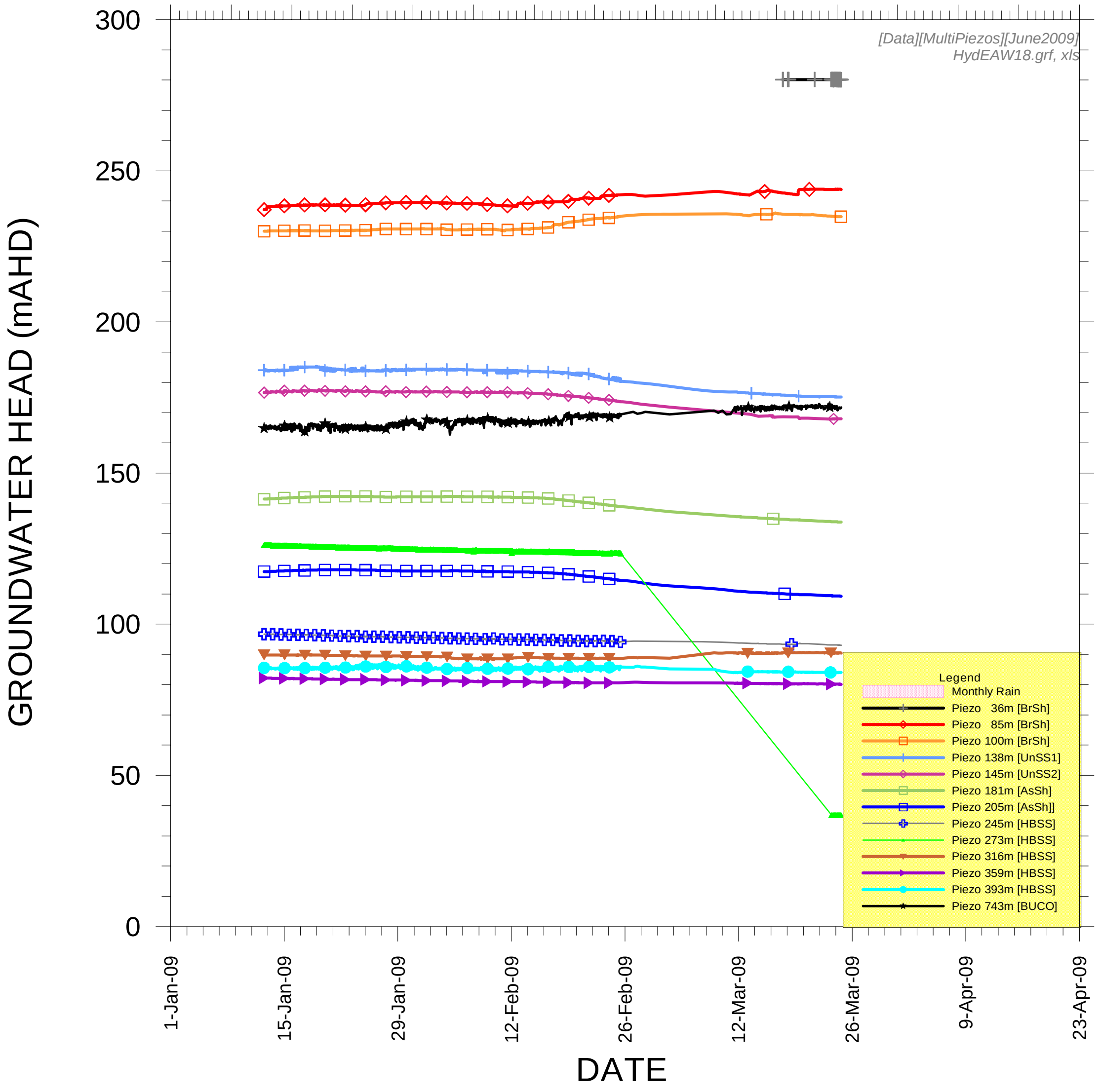


Figure 32. Time variations in total groundwater head at all piezometers in the EAW18 hole.

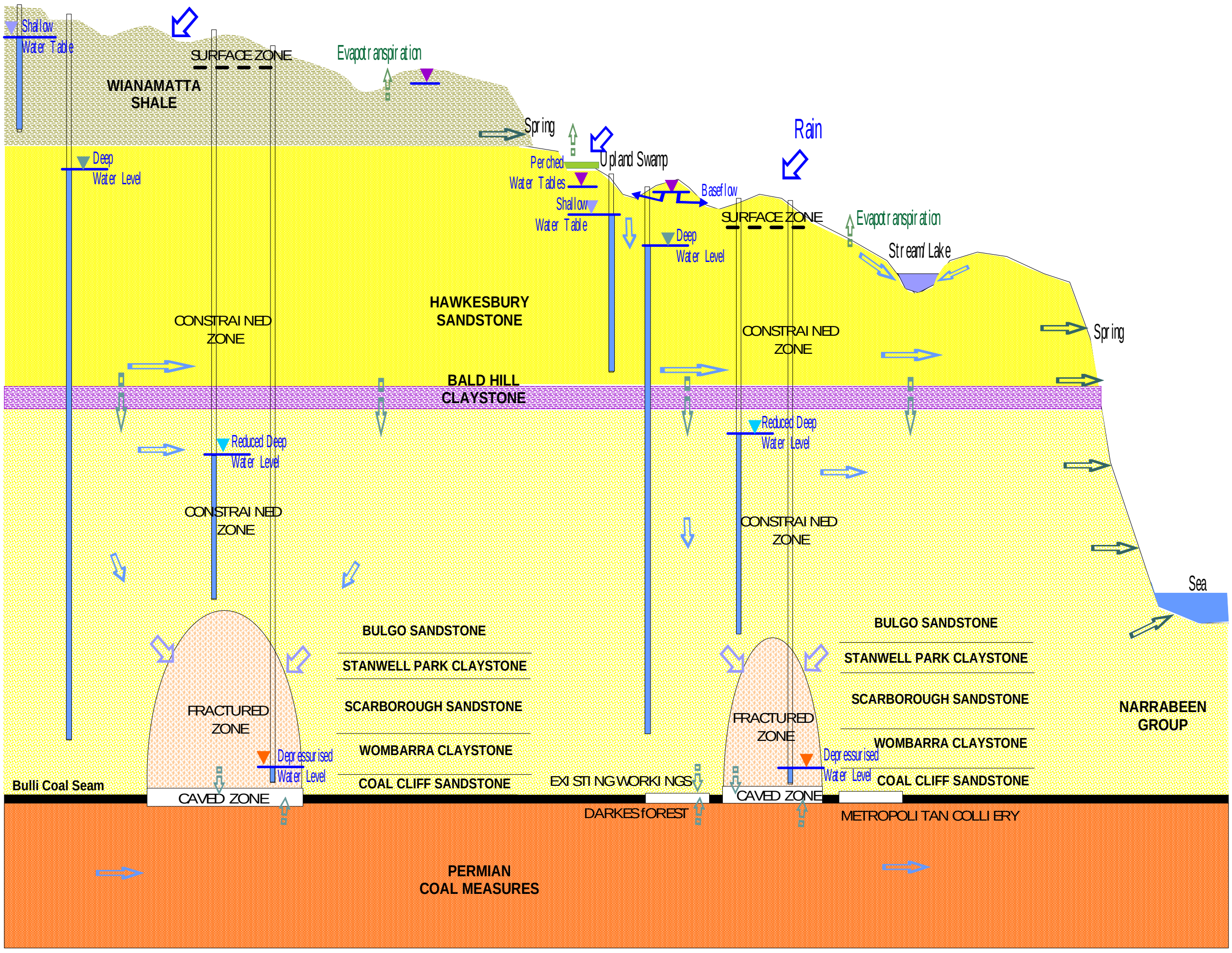
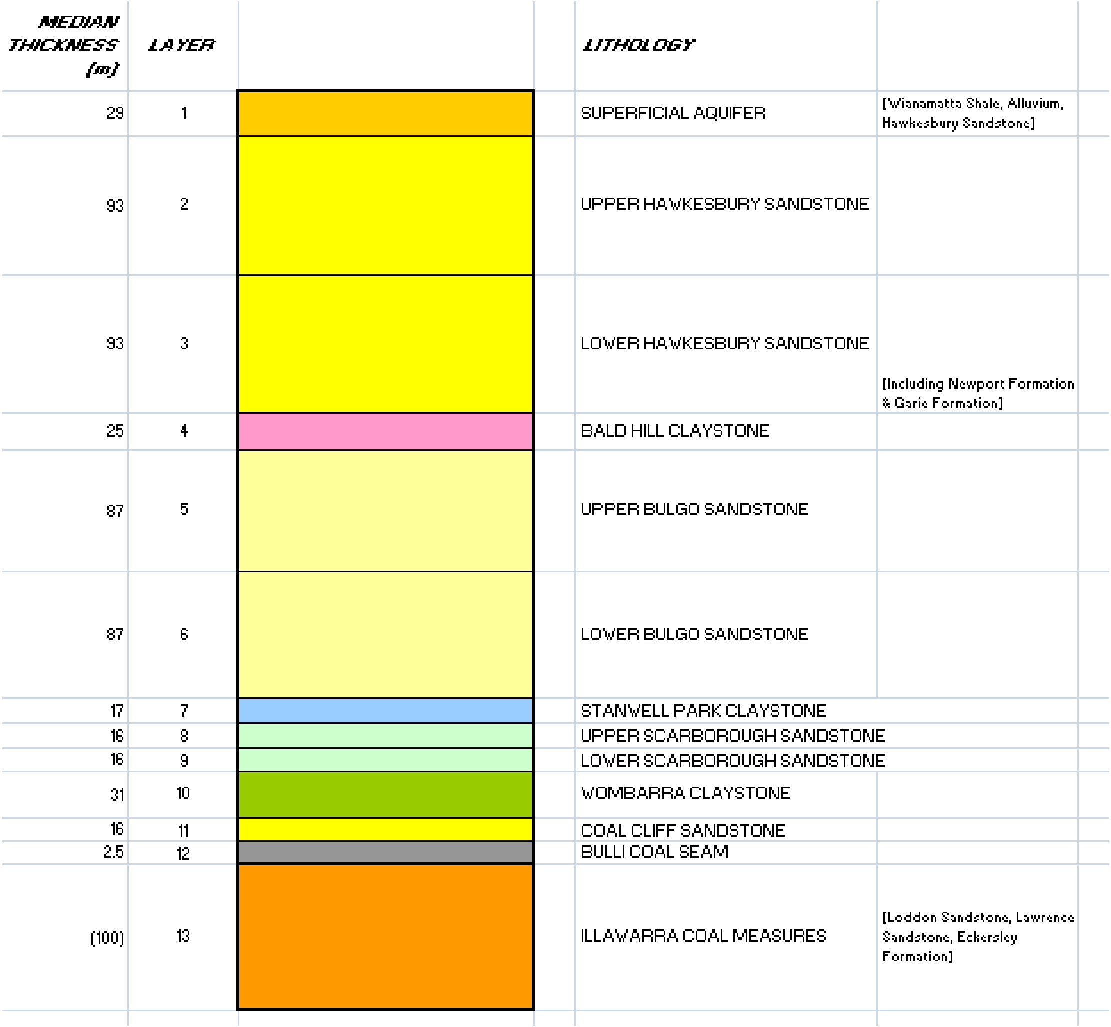


Figure 33. Conceptual hydrogeological model. *[Not to scale]*



MEDIAN THICKNESS (m)	LAYER	LITHOLOGY	
29	1	SUPERFICIAL AQUIFER	[Wianamatta Shale, Alluvium, Hawkesbury Sandstone]
93	2	UPPER HAWKESBURY SANDSTONE	
93	3	LOWER HAWKESBURY SANDSTONE	[Including Newport Formation & Garie Formation]
25	4	BALD HILL CLAYSTONE	
87	5	UPPER BULGO SANDSTONE	
87	6	LOWER BULGO SANDSTONE	
17	7	STANWELL PARK CLAYSTONE	
16	8	UPPER SCARBOROUGH SANDSTONE	
16	9	LOWER SCARBOROUGH SANDSTONE	
31	10	WOMBARRA CLAYSTONE	
16	11	COAL CLIFF SANDSTONE	
2.5	12	BULLI COAL SEAM	
(100)	13	ILLAWARRA COAL MEASURES	[Loddon Sandstone, Lawrence Sandstone, Eckersley Formation]

Figure 34. Numerical model layers.

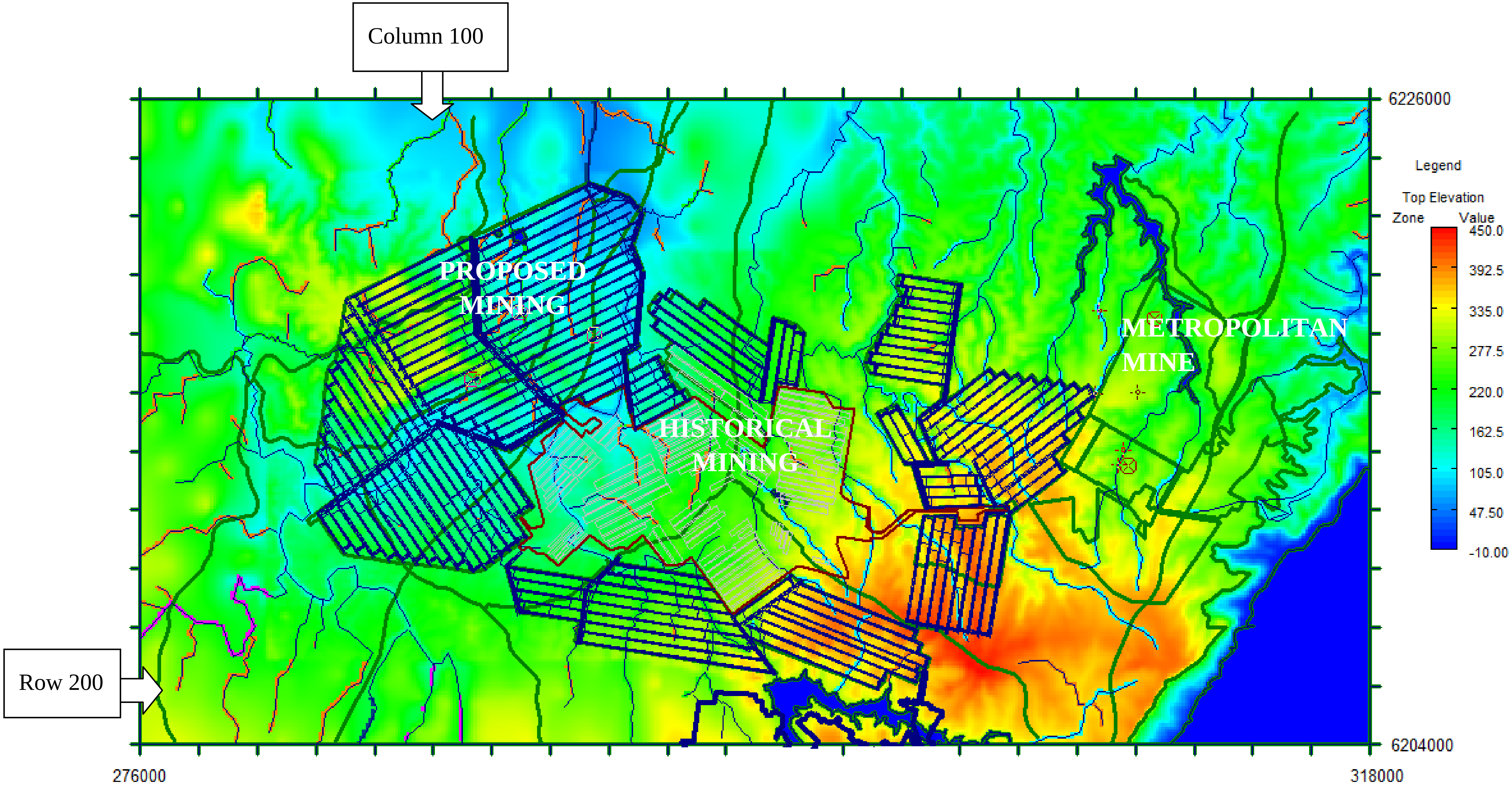


Figure 35. Model extent, surface topography, drainage network and mine outlines.

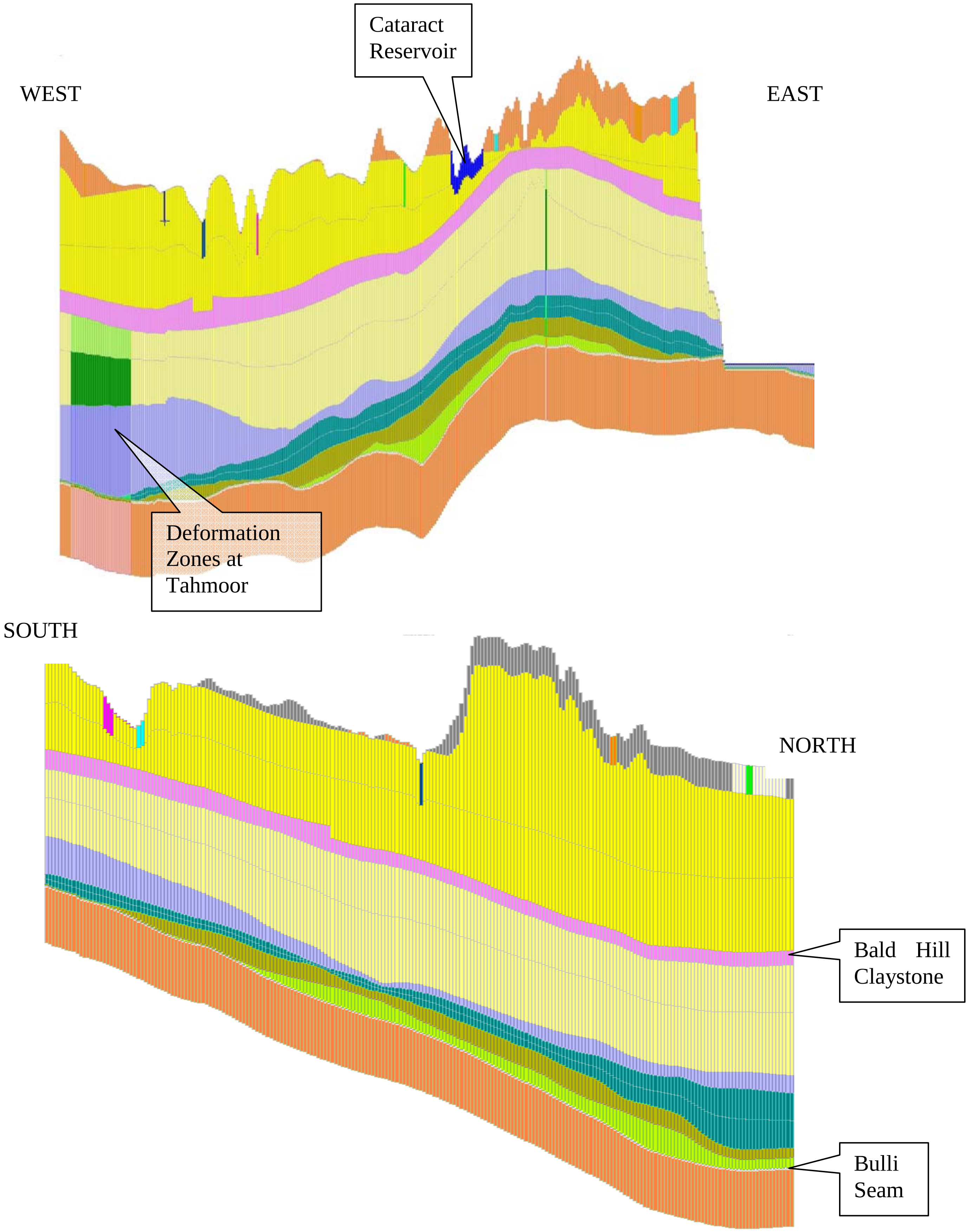
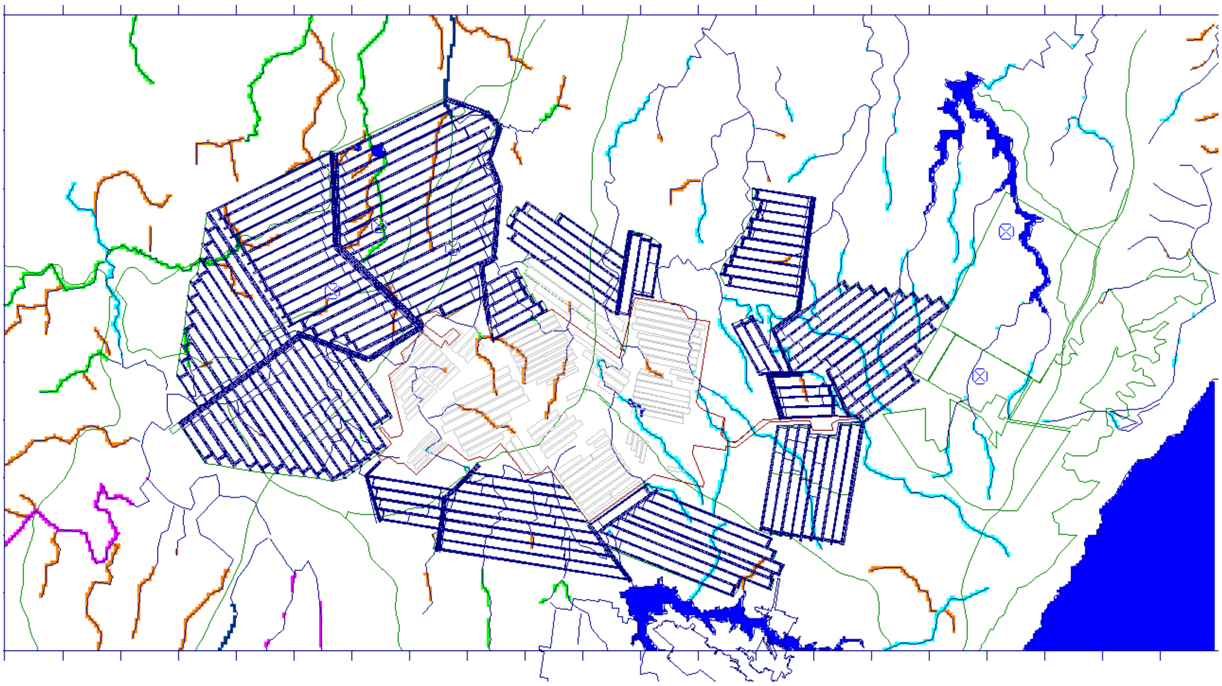


Figure 36. Representative model cross-sections along Row 200 (West-East) and Column 100 (South-North)

[a]



[b]

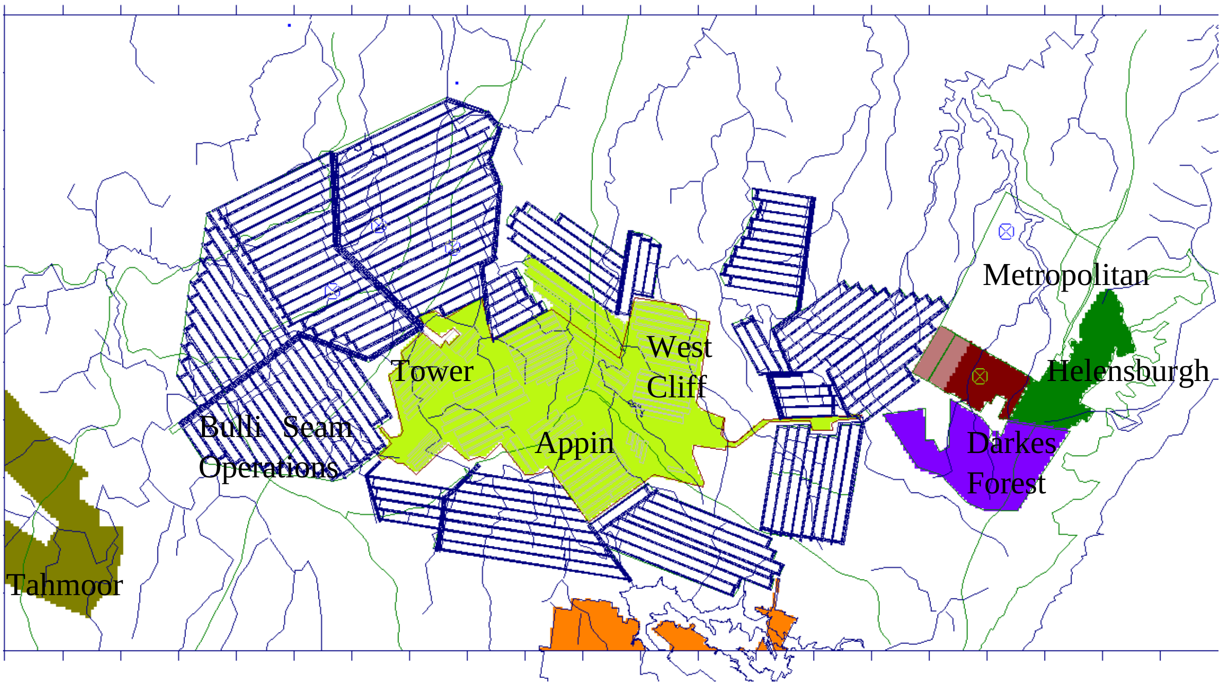


Figure 37. Boundary conditions applied to [a] model layer 1 (water bodies) and [b] model layer 12 (mine workings)

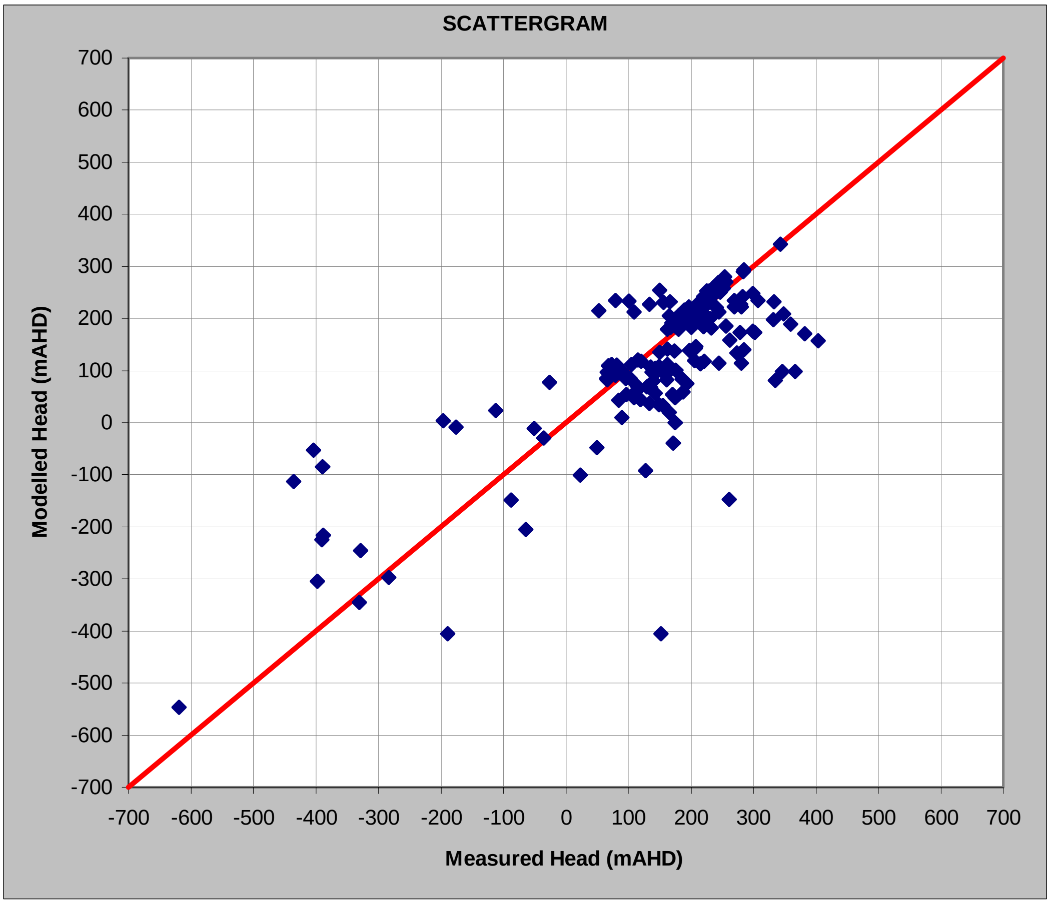


Figure 38. Scatter plot for steady state calibration.

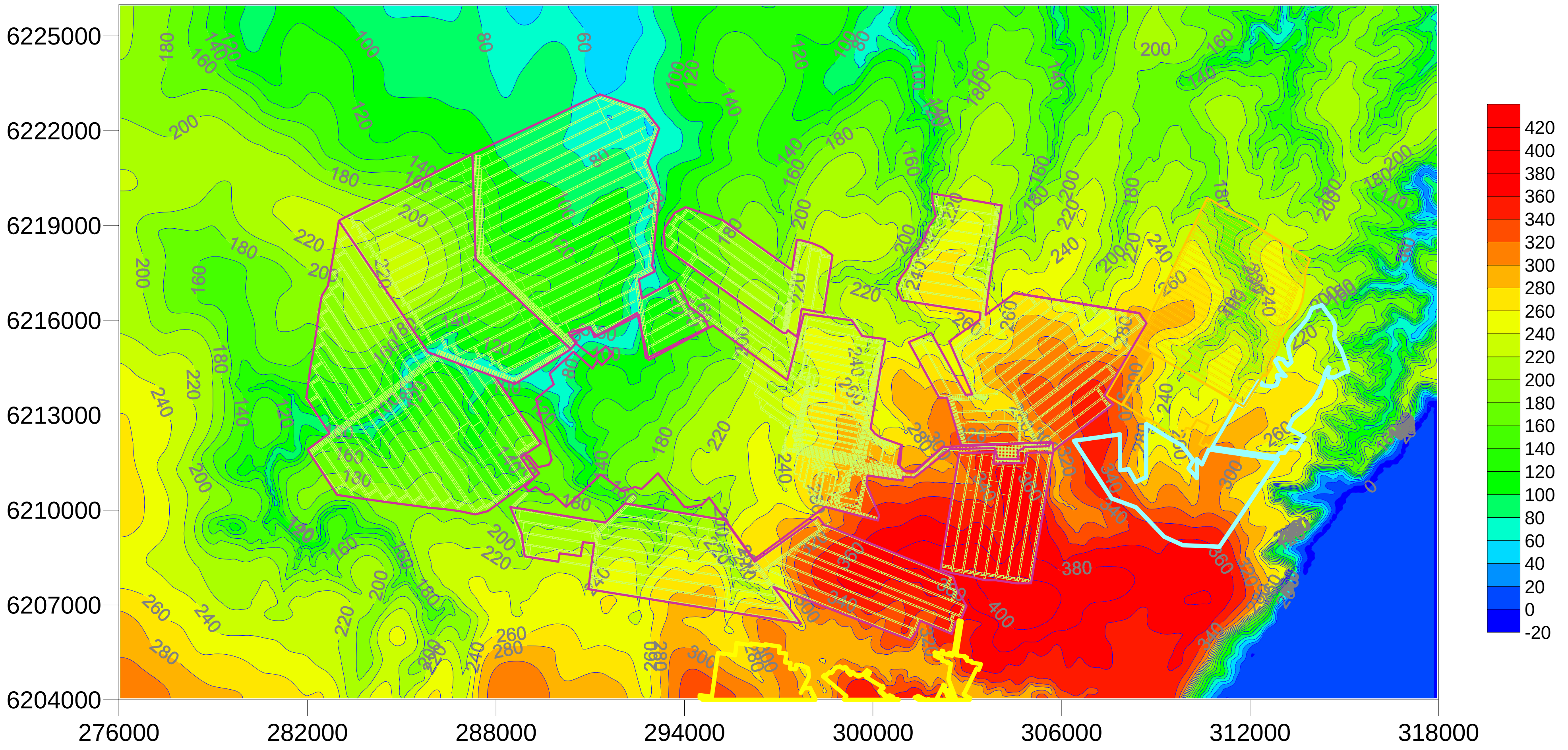


Figure 39. Simulated steady state Hawkesbury Sandstone groundwater levels (layer 2)

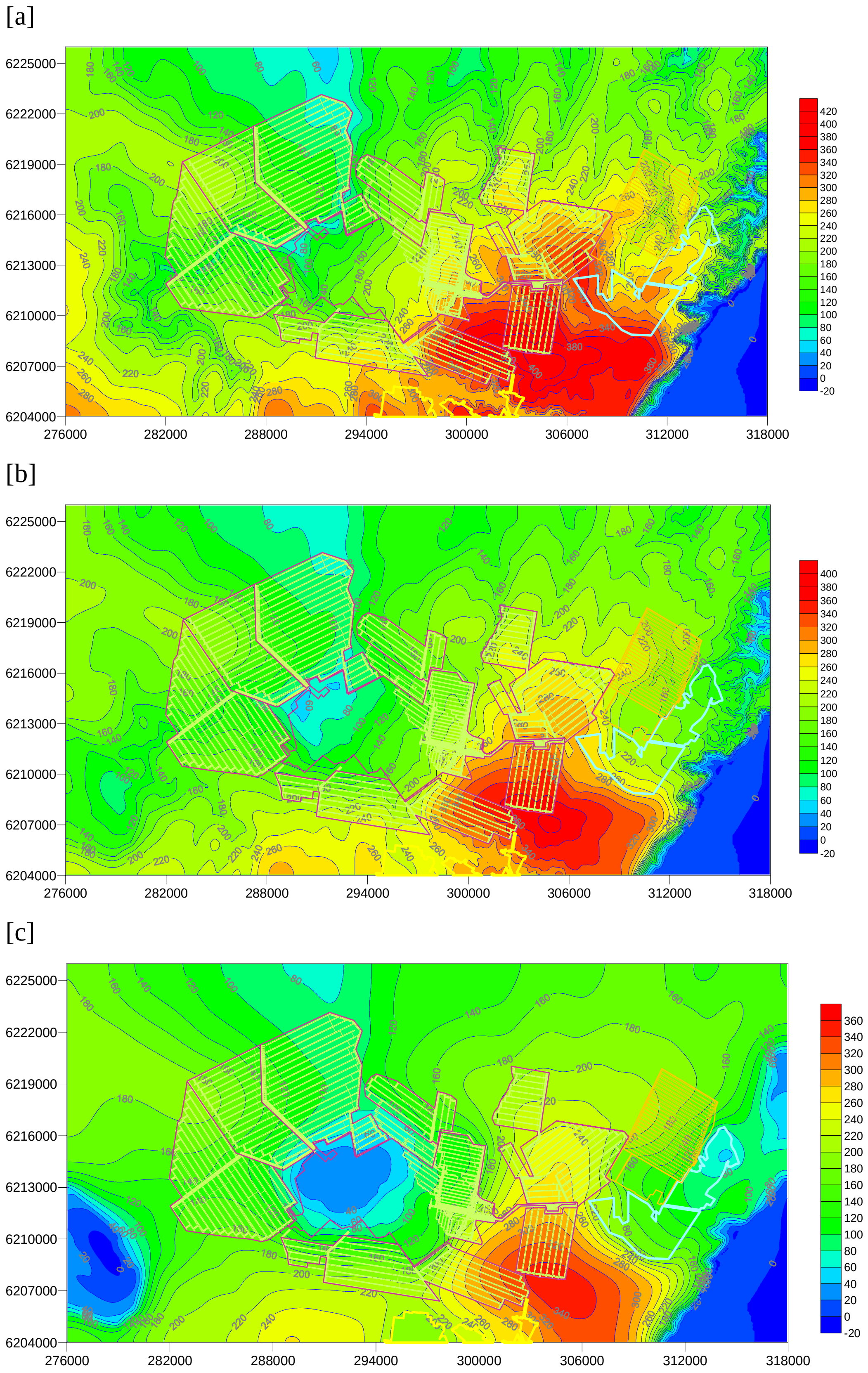


Figure 40. Simulated groundwater levels at mine year 0: [a] Layer 3 (Lower Hawkesbury Sandstone); [b] Layer 4 (Bald Hill Claystone); [c] Layer 5 (Upper Bulgo Sandstone).

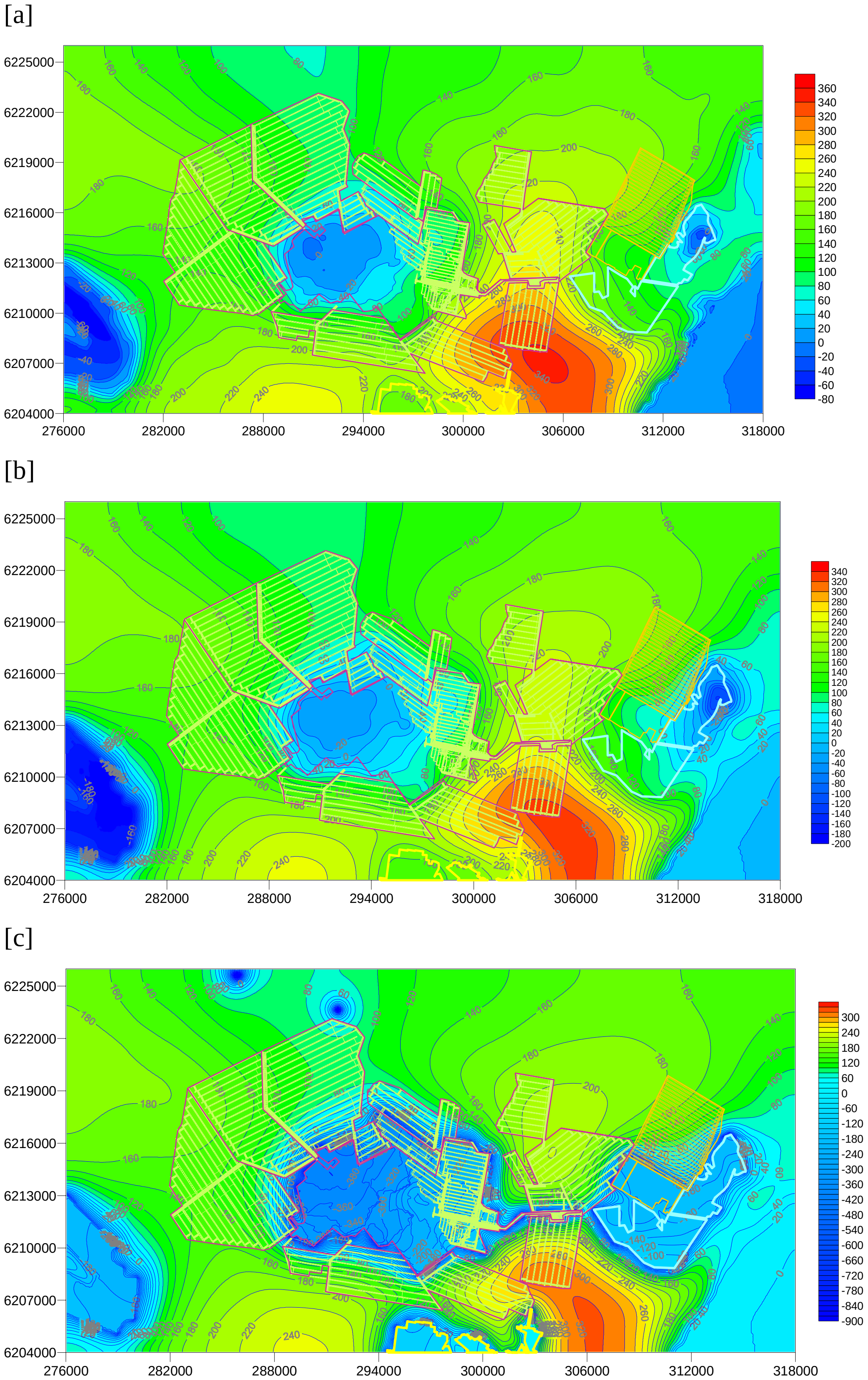
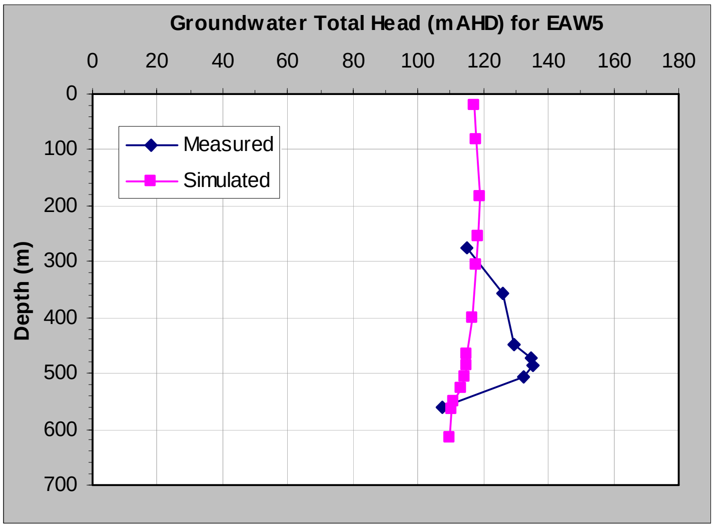
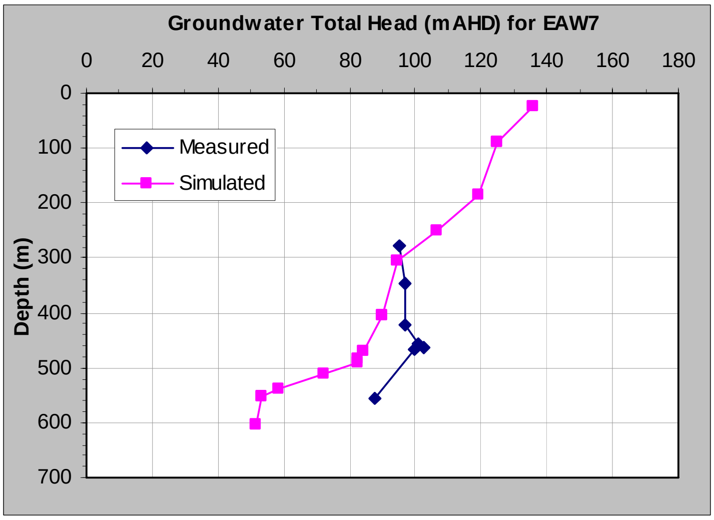


Figure 41. Simulated groundwater levels at mine year 0: [a] Layer 6 (Lower Bulgo Sandstone); [b] Layer 9 (Lower Scarborough Sandstone); [c] Layer 12 (Bulli Coal Seam).

[a]



[b]



[c]

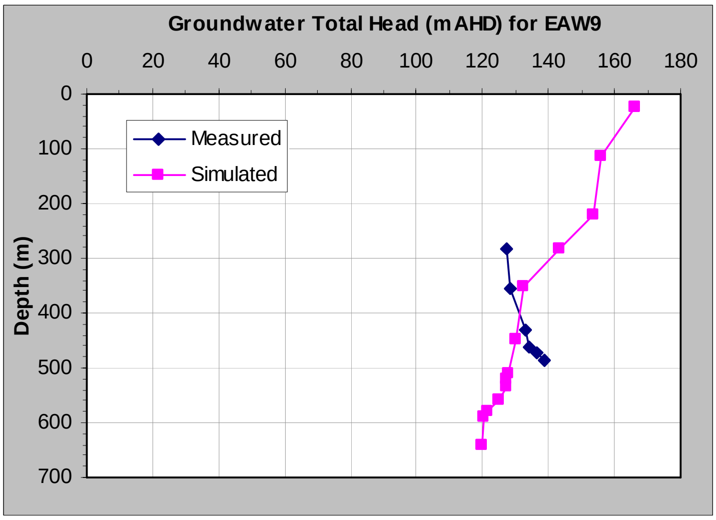
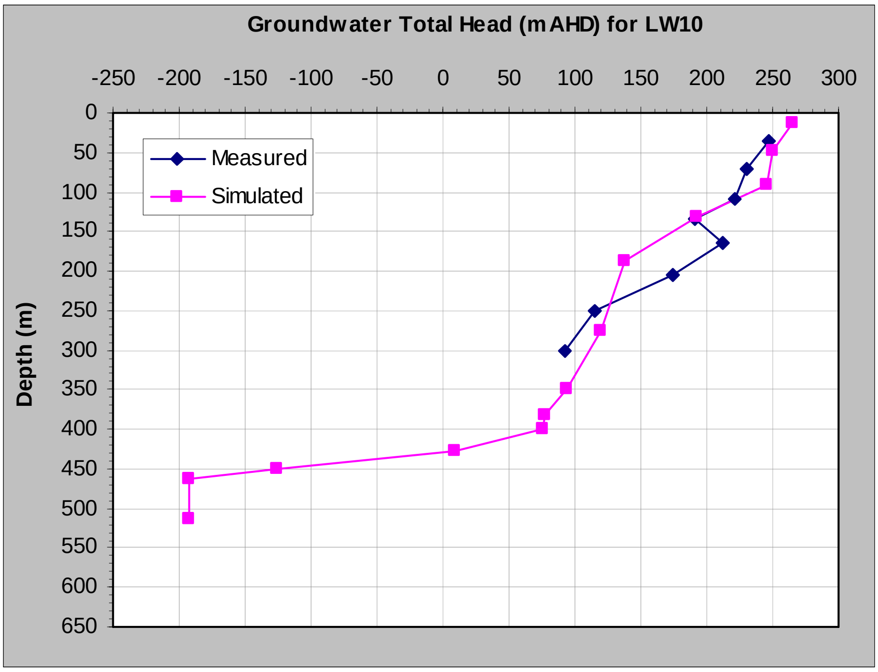


Figure 42. Vertical head profiles for [a] EAW5; [b] EAW7 and [c] EAW9.

[a]



[b]

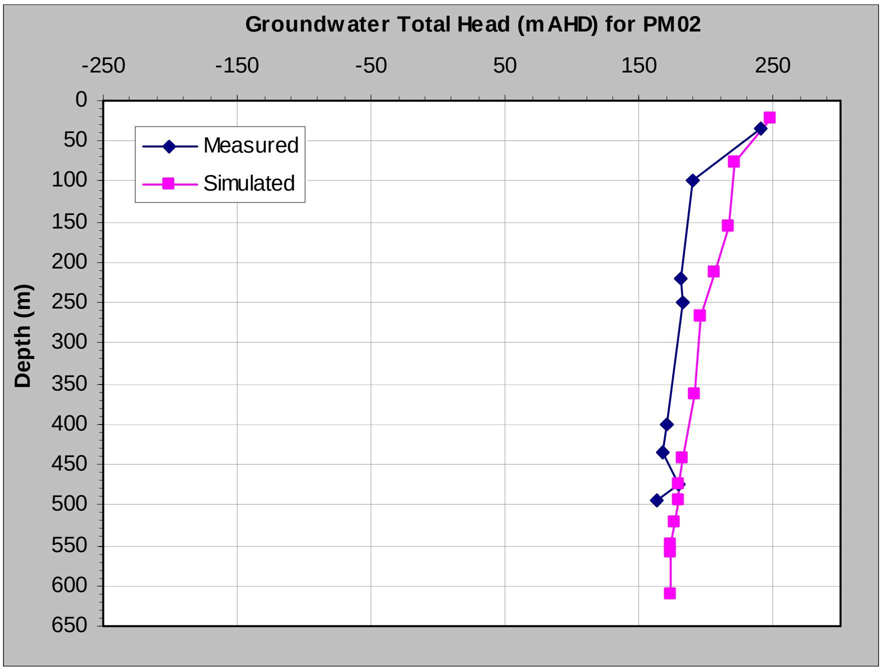


Figure 43. Vertical head profiles for [a] LW10 goaf hole and [b] hole PM02.

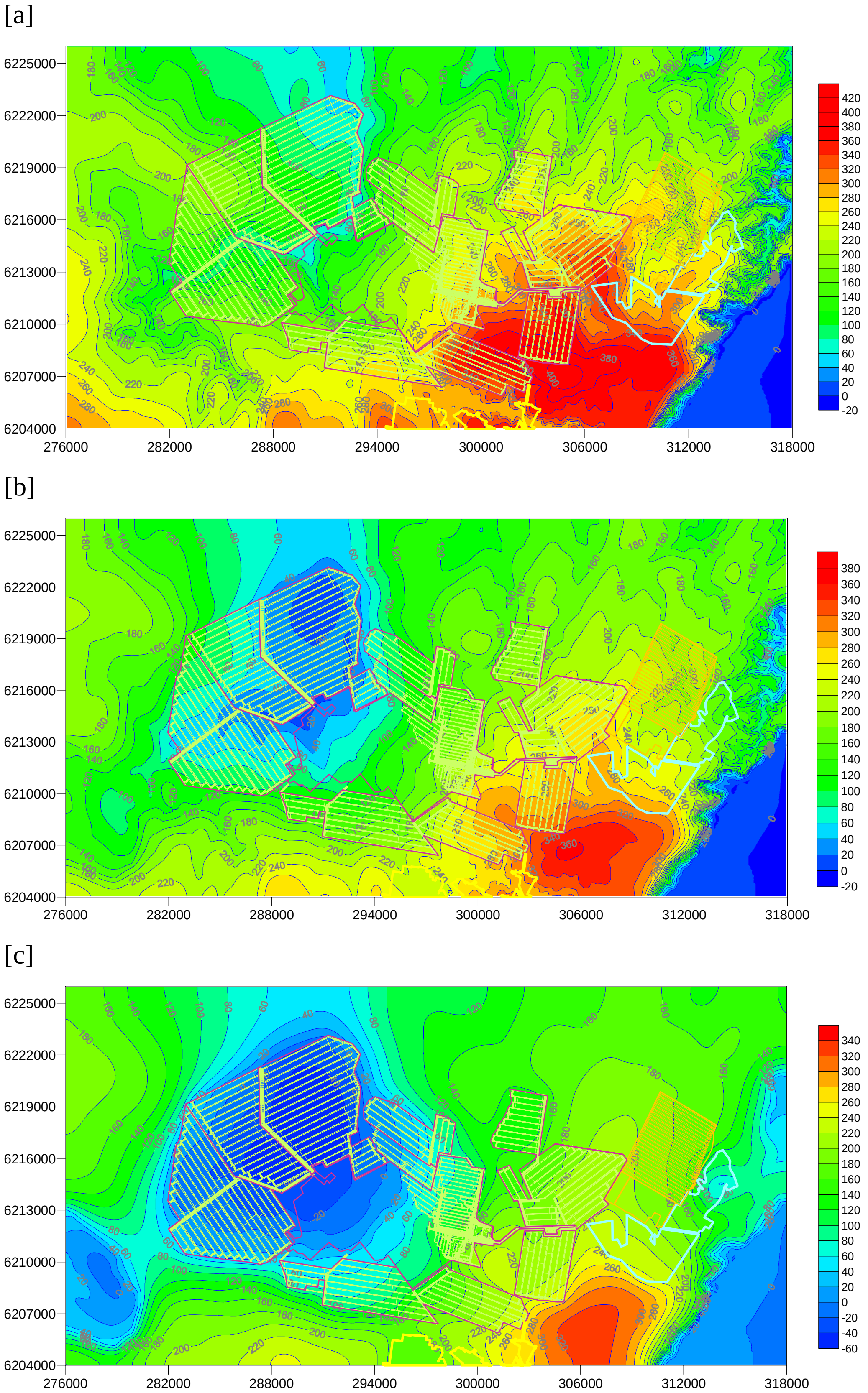


Figure 44. Simulated groundwater levels at the end of mine year 30:

[a] Layer 3 (Lower Hawkesbury Sandstone); [b] Layer 4 (Bald Hill Claystone); [c] Layer 5 (Upper Bulgo Sandstone).

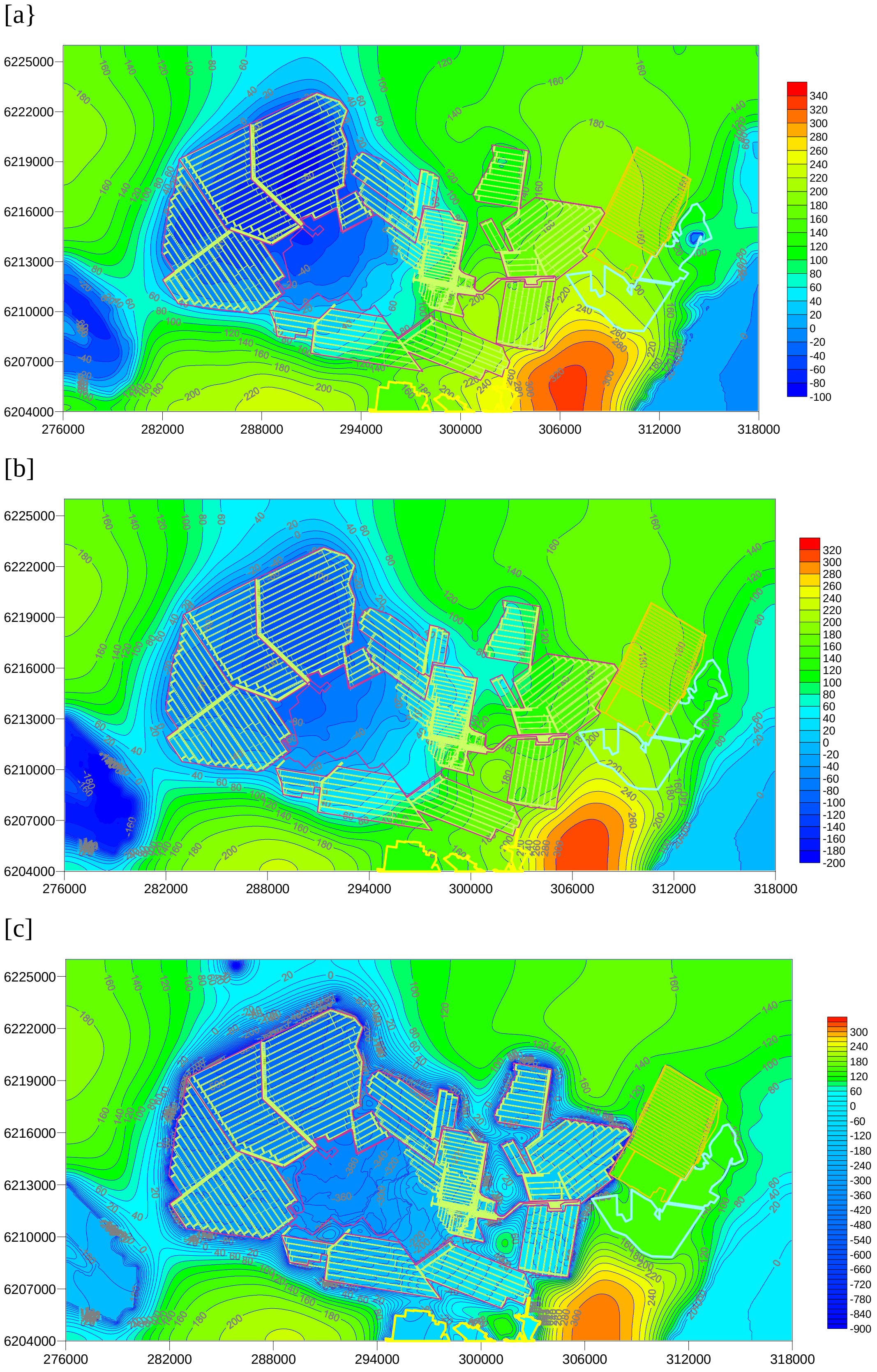


Figure 45. Simulated groundwater levels at the end of year 30:

[a] Layer 6 (Lower Bulgo Sandstone); [b] Layer 9 (Lower Scarborough Sandstone); [c] Layer 12 (Bulli Coal Seam).

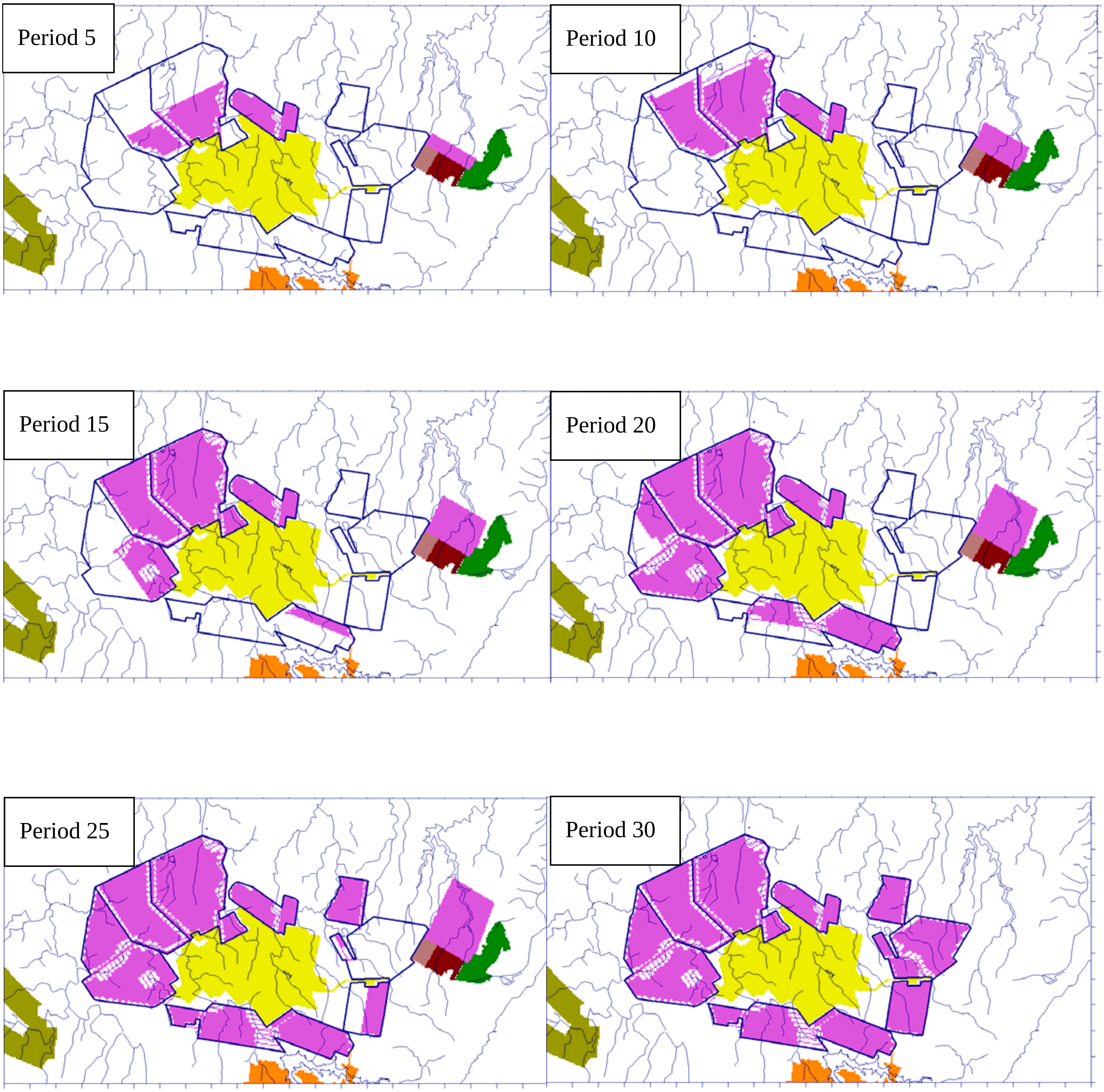


Figure 46. Indicative snapshots of progressive mine development.*

*Note: Longwall 901 at Appin West (Area 9) has been removed from the EA Base Plan Longwalls since the groundwater modelling was undertaken.

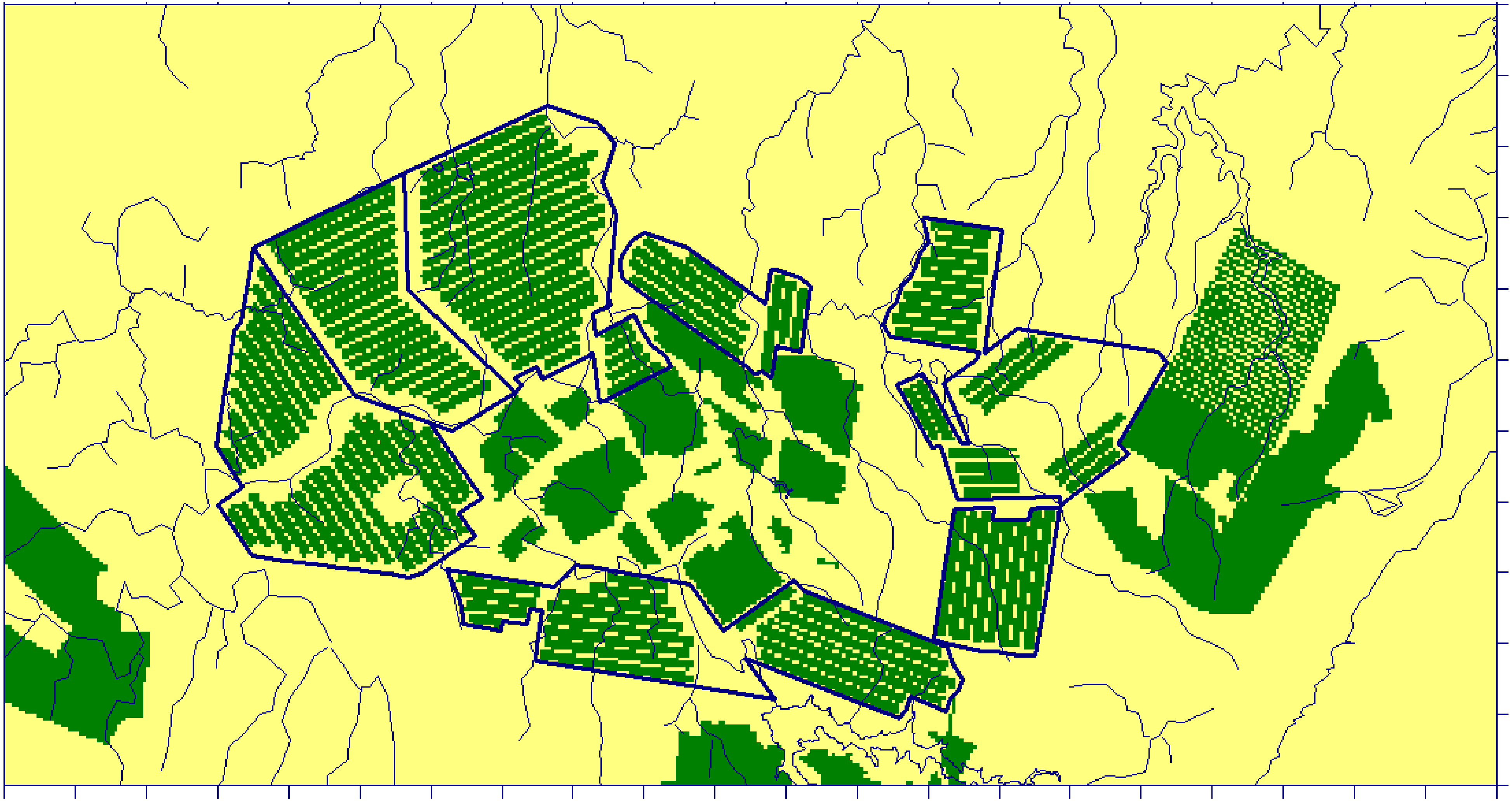


Figure 47. Activated fractured zone cells at the end of mining simulation.*

*Note: Longwall 901 at Appin West (Area 9) has been removed from the EA Base Plan Longwalls since the groundwater modelling was undertaken.

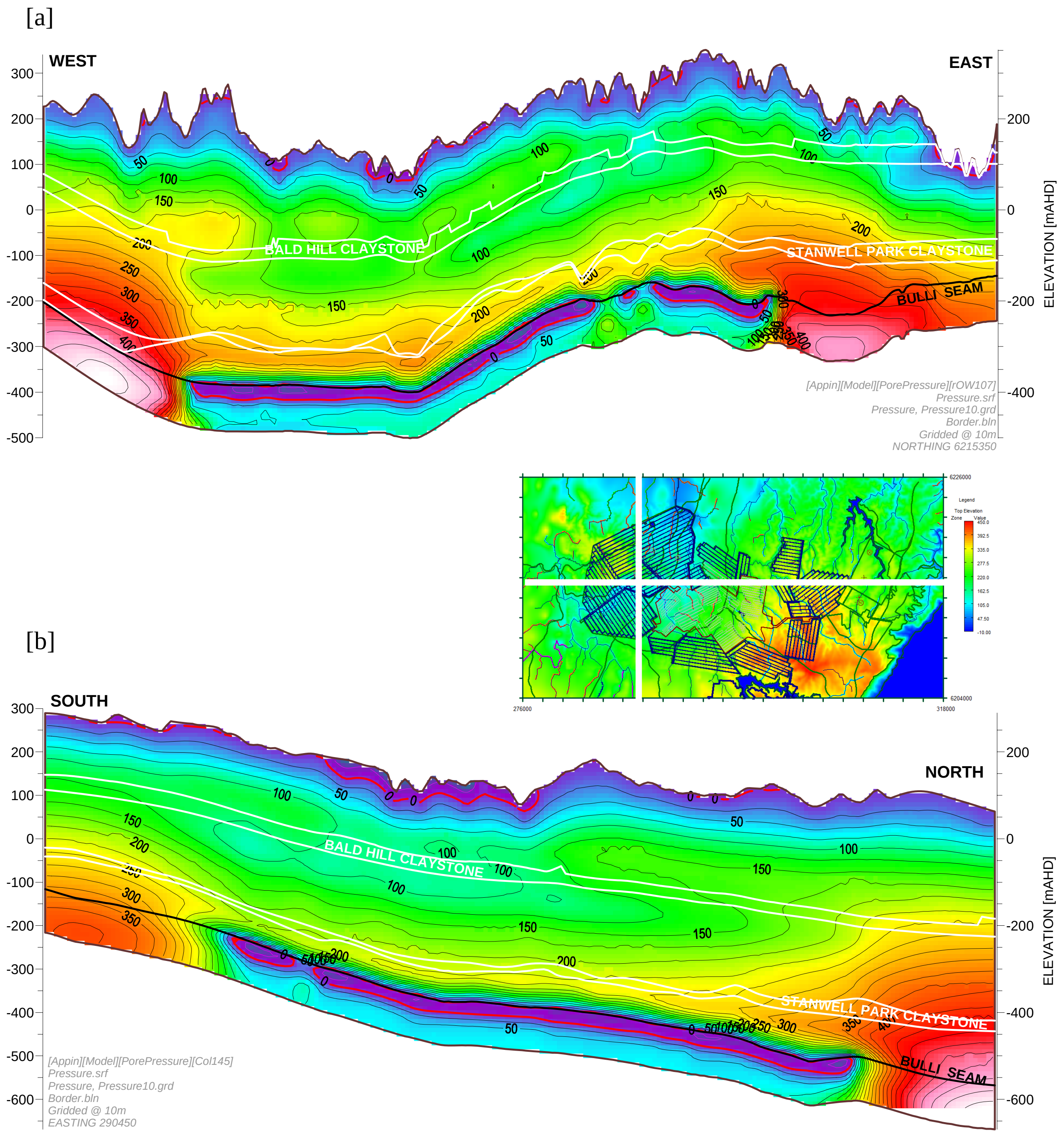
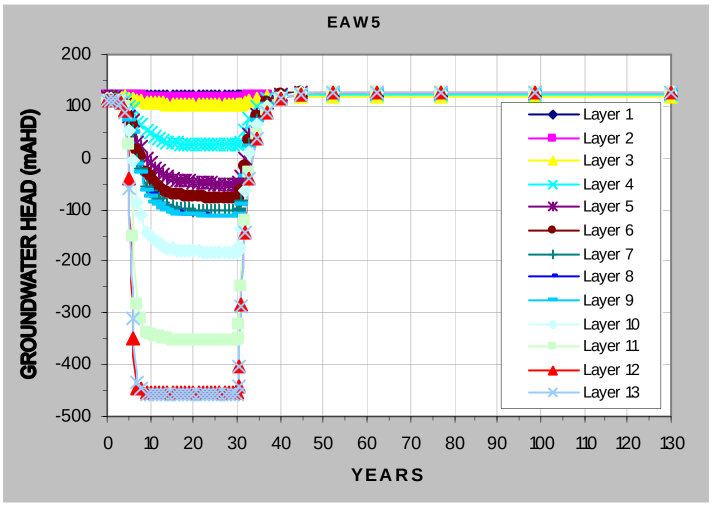
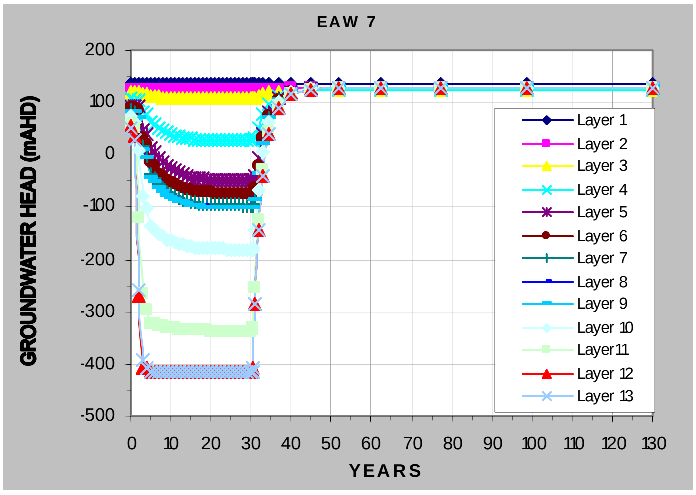


Figure 48. Simulated pressure head (m) cross-sections at the end of Project mining along [a] Northing 6215350, and [b] Easting 290450. *[Section locations are shown on the inset]*

[a]



[b]



[c]

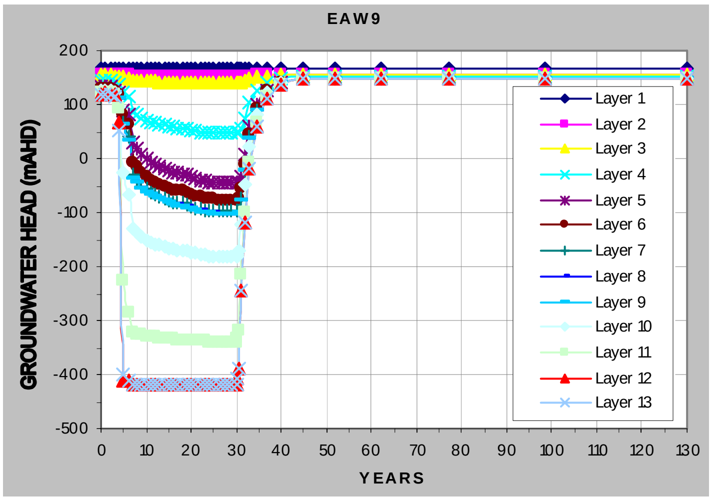
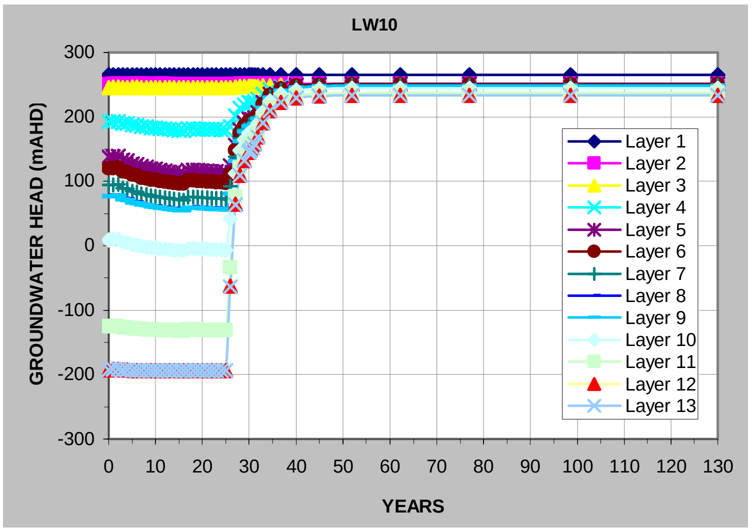


Figure 49. Recovery hydrographs after cessation of mining (low storage coefficient) for [a] EAW5 hole; [b] EAW7 hole and [c] hole EAW9

[a]



[b]

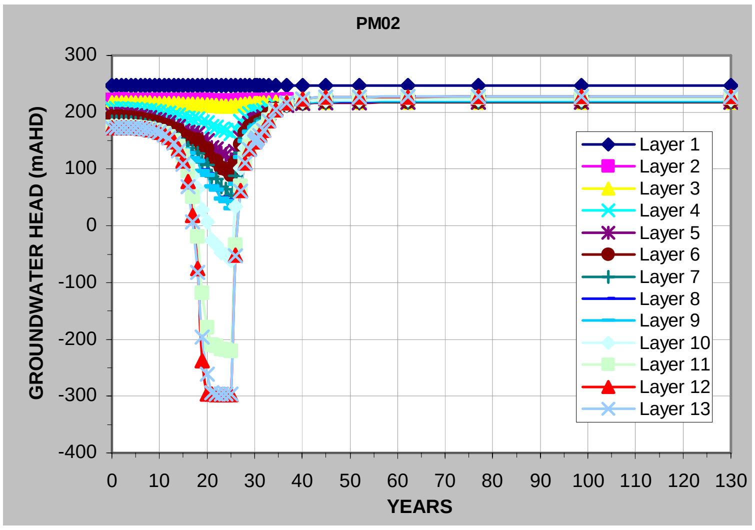


Figure 50. Recovery hydrographs after cessation of mining (low storage coefficient) for [a] LW10 goaf hole and [b] hole PM02

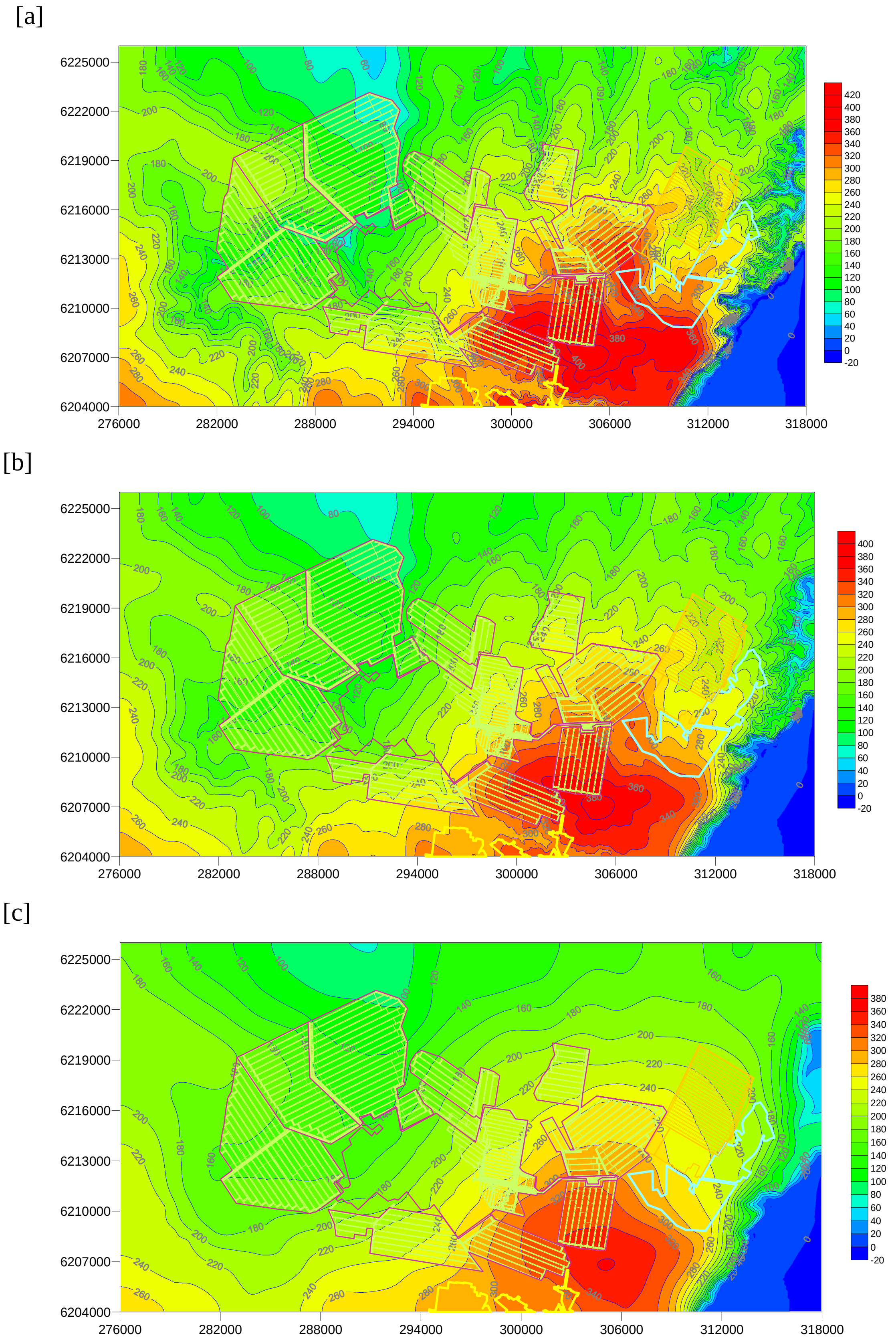


Figure 51. Simulated groundwater levels at the end of the recovery period year 130 (low storage coefficient): [a] Layer 3 (Lower Hawkesbury Sandstone); [b] Layer 4 (Bald Hill Claystone); [c] Layer 5 (Upper Bulgo Sandstone).

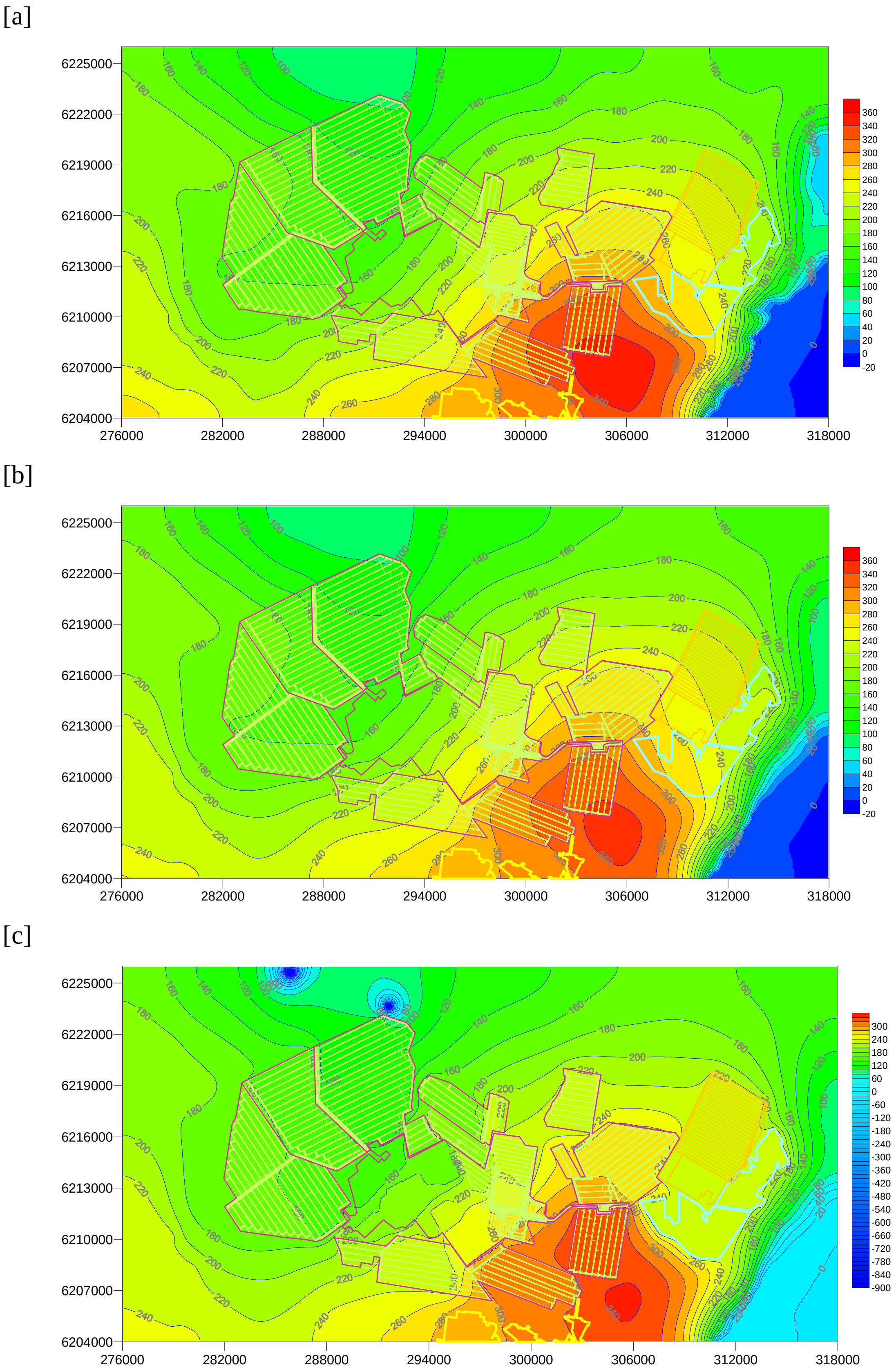


Figure 52. Simulated groundwater levels at the end of the recovery period year 130 (low storage coefficient): [a] Layer 6 (Lower Bulgo Sandstone); [b] Layer 9 (Lower Scarborough Sandstone); [c] Layer 12 (Bulli Coal Seam).

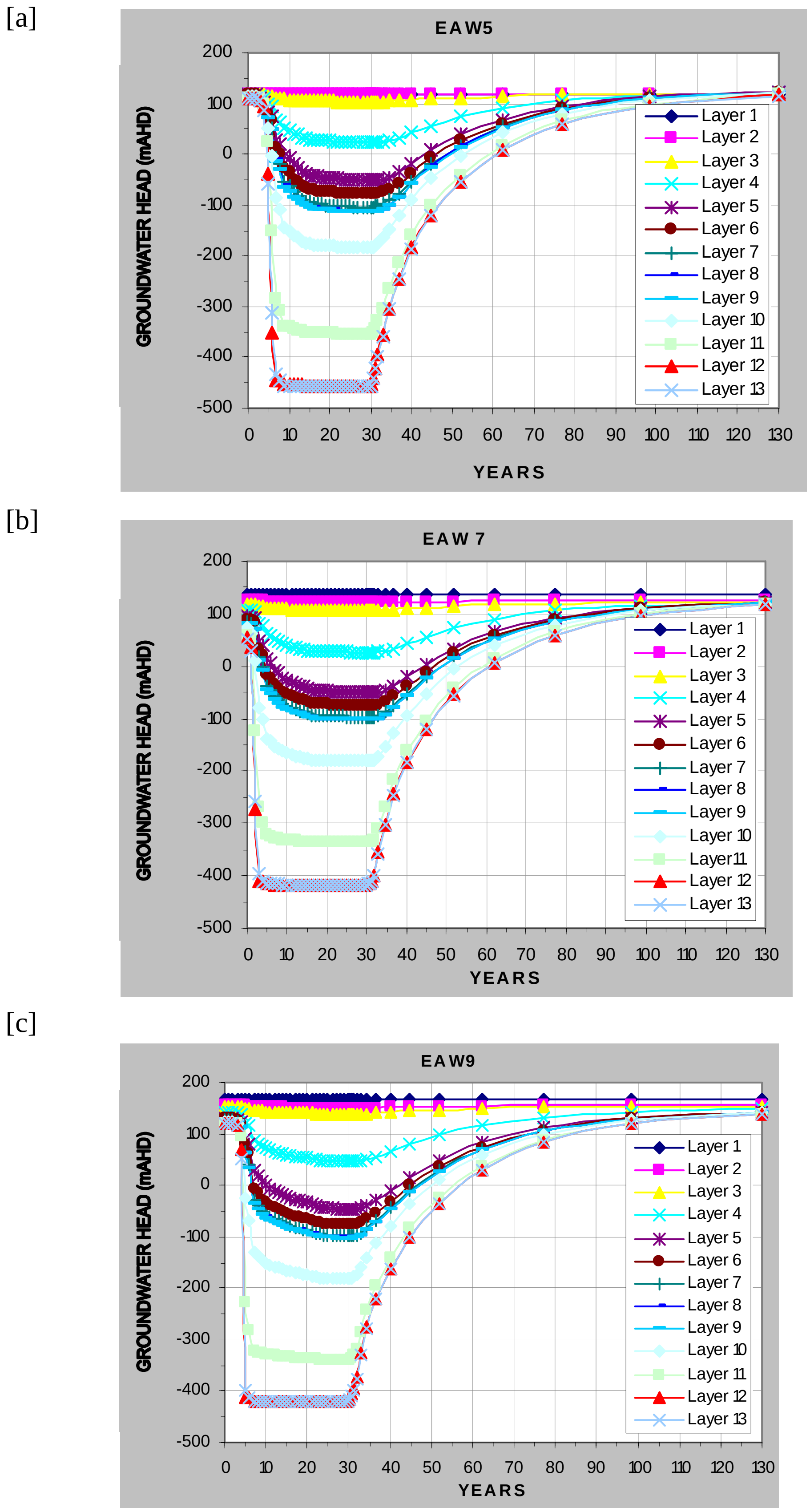


Figure 53. Recovery hydrographs after cessation of mining (higher storage coefficient) for [a] EAW5 hole; [b] EAW7 hole and [c] hole EAW9.

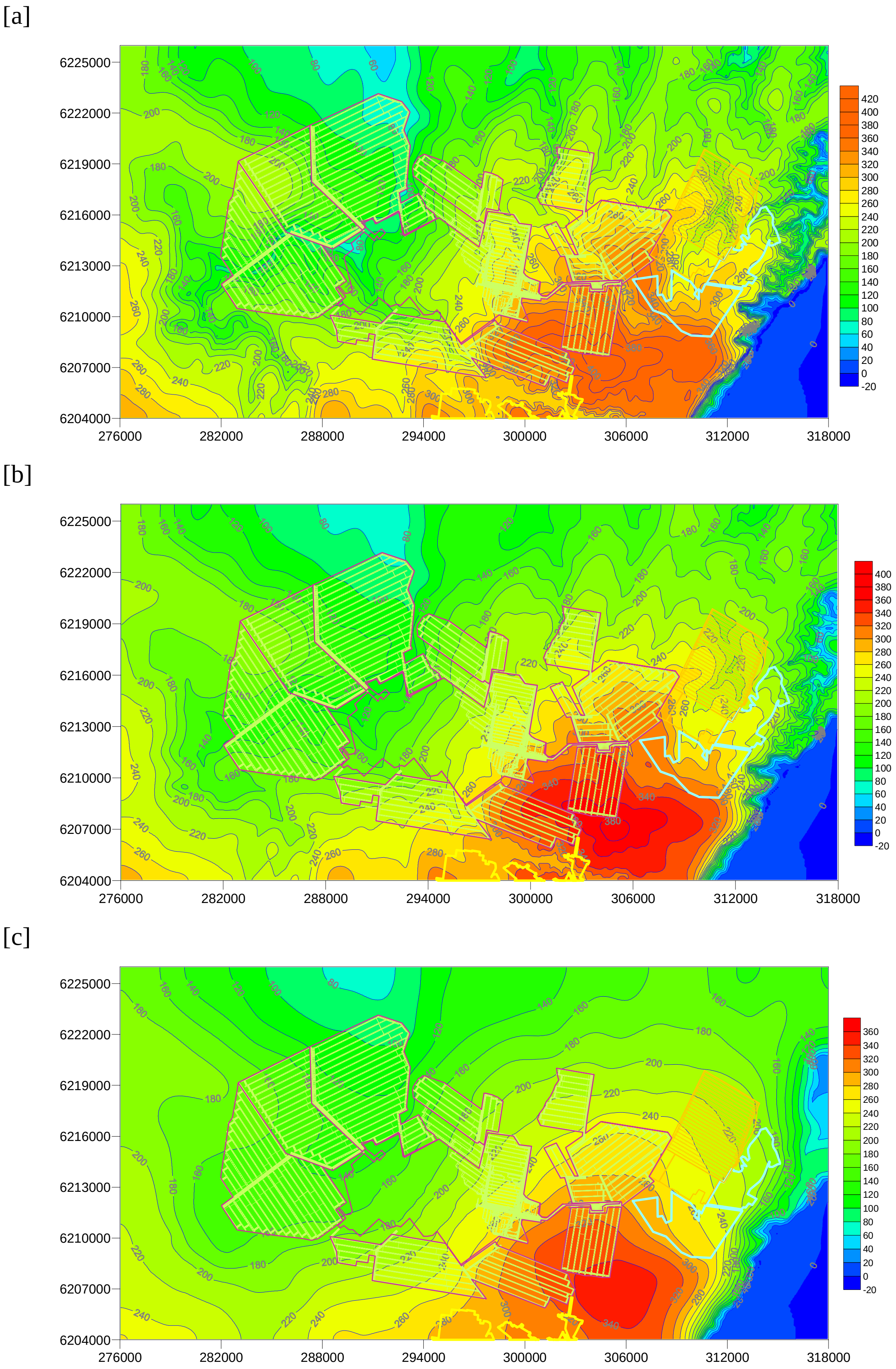


Figure 54. Simulated groundwater levels at the end of the recovery period year 130 (higher storage coefficient): [a] Layer 3 (Lower Hawkesbury Sandstone); [b] Layer 4 (Bald Hill Claystone); [c] Layer 5 (Upper Bulgo Sandstone).

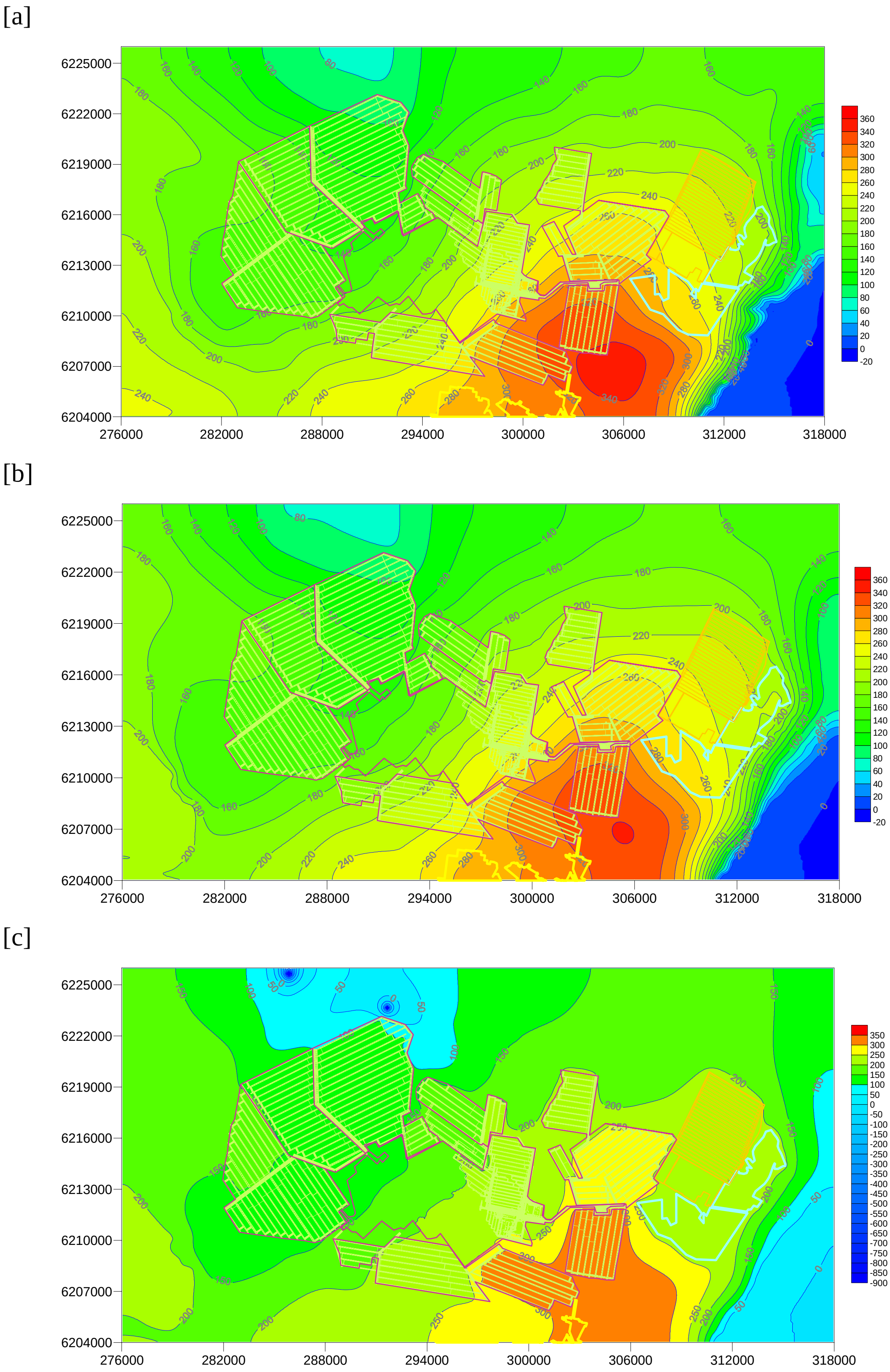
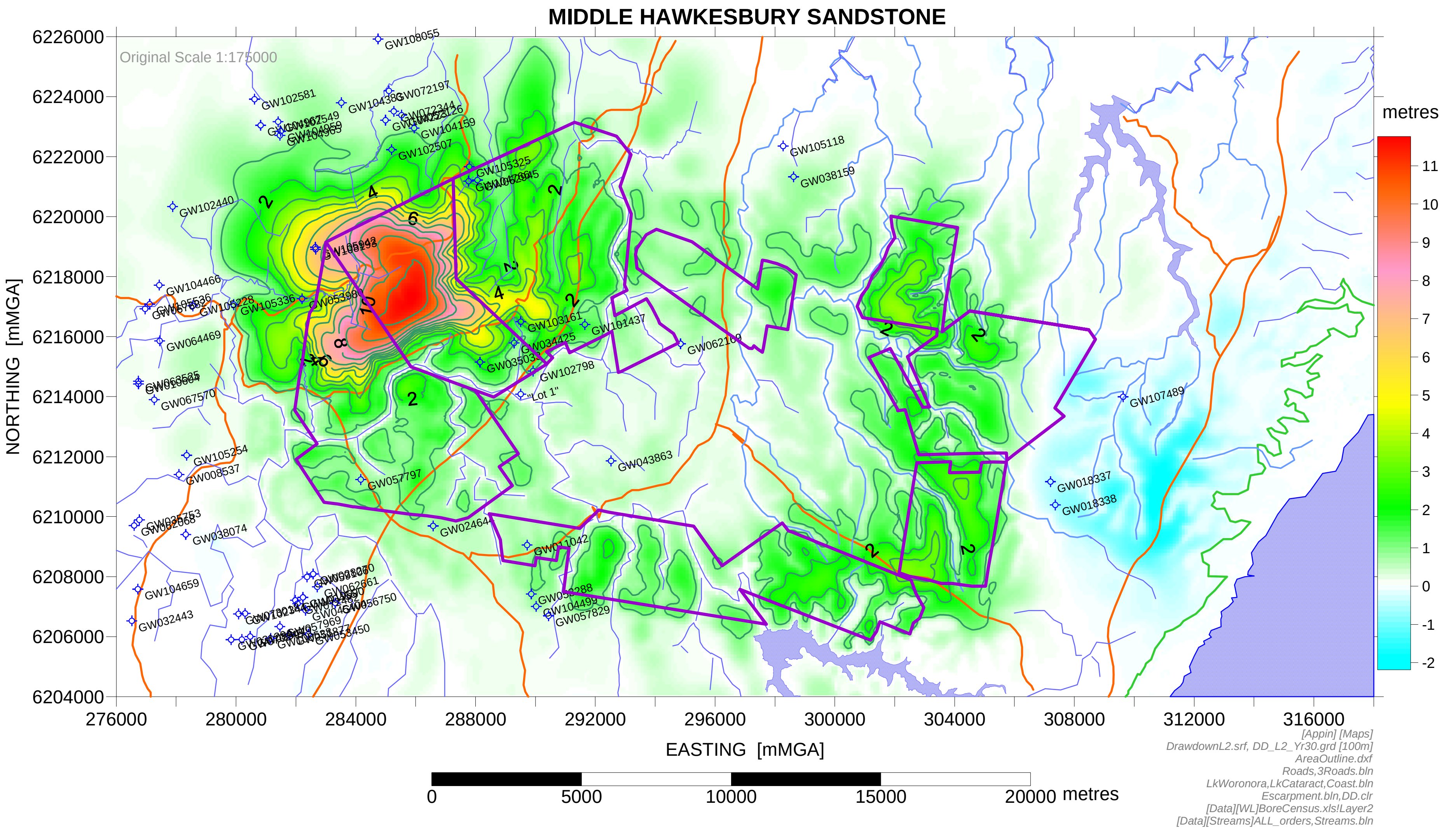


Figure 55. Simulated groundwater levels at the end of the recovery period year 130 (higher storage coefficient): [a] Layer 6 (Lower Bulgo Sandstone); [b] Layer 9 (Lower Scarborough Sandstone); [c] Layer 12 (Bulli Coal Seam).



[Appin] [Maps]
DrawdownL2.srf, DD_L2_Yr30.grd [100m]
AreaOutline.dxf
Roads,3Roads.bln
LkWoronora,LkCataract,Coast.bln
Escarpment.bln,DD.clr
[Data][WL]BoreCensus.xls!Layer2
[Data][Streams]ALL_orders,Streams.bln

Figure 56. Predicted drawdown in the middle Hawkesbury Sandstone in relation to registered production bores after 30 years of mining.

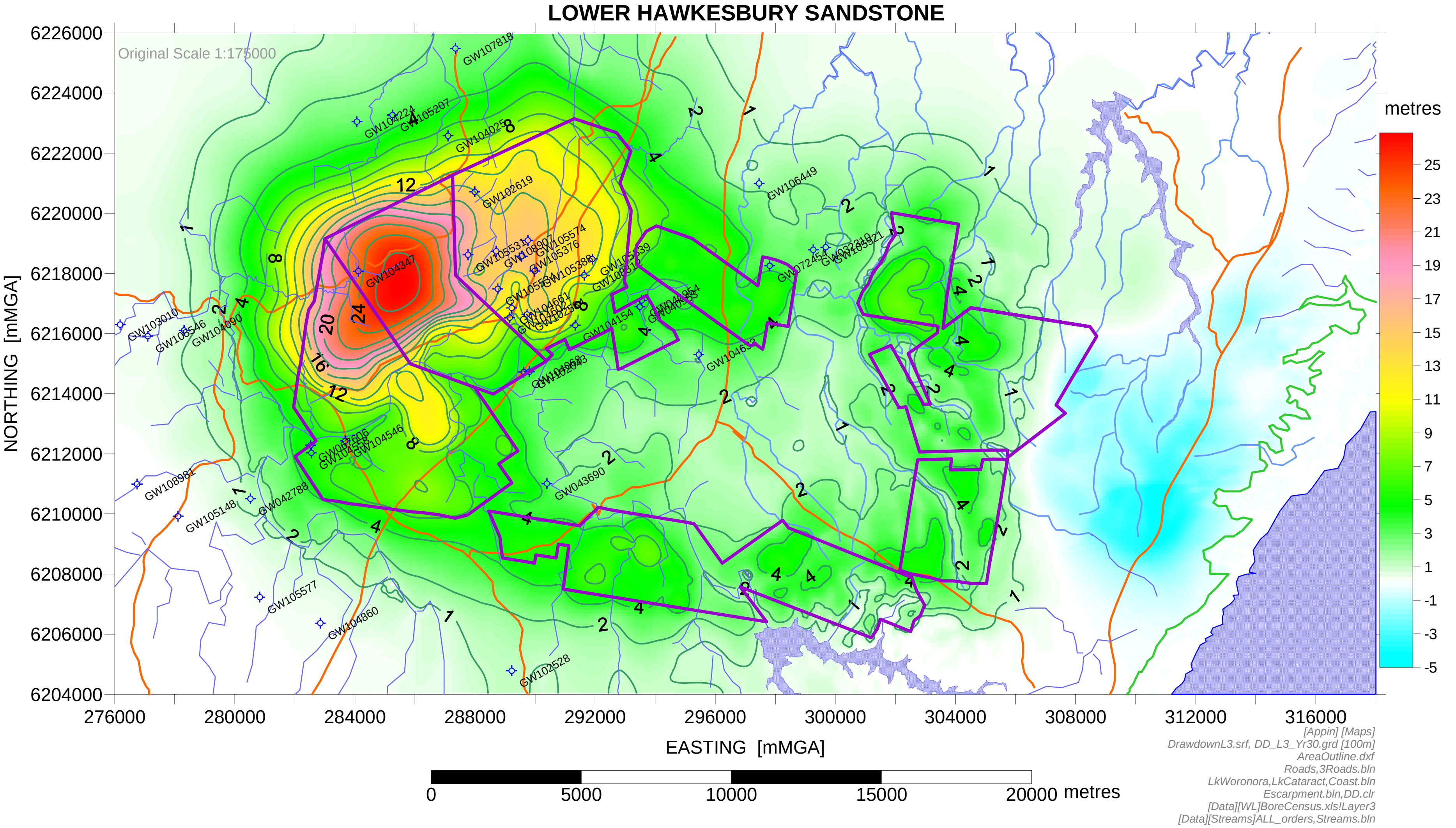


Figure 57. Predicted drawdown in the lower Hawkesbury Sandstone in relation to registered production bores after 30 years of mining.

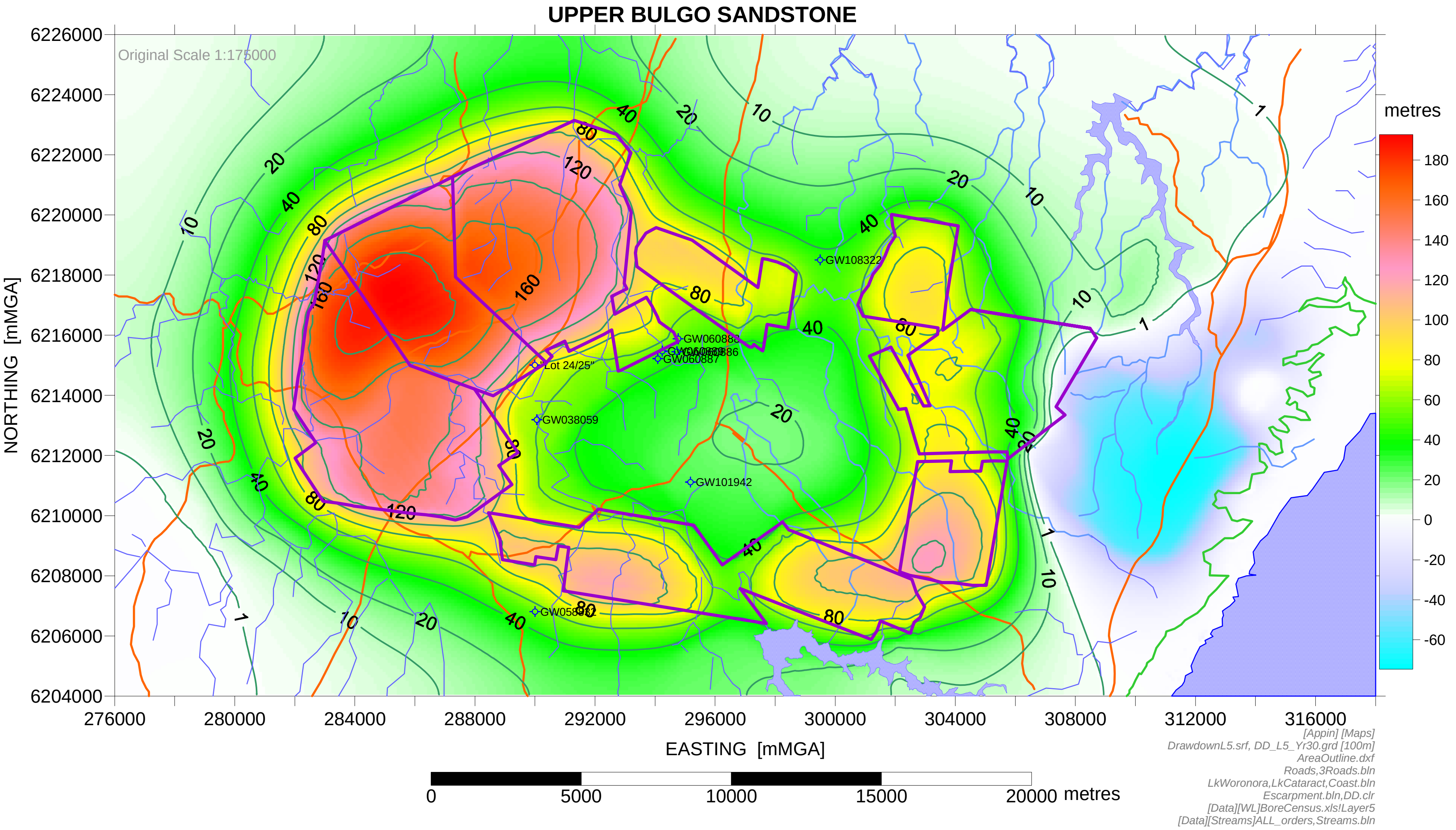


Figure 58. Predicted drawdown in the Bulgo Sandstone in relation to registered production bores after 30 years of mining.

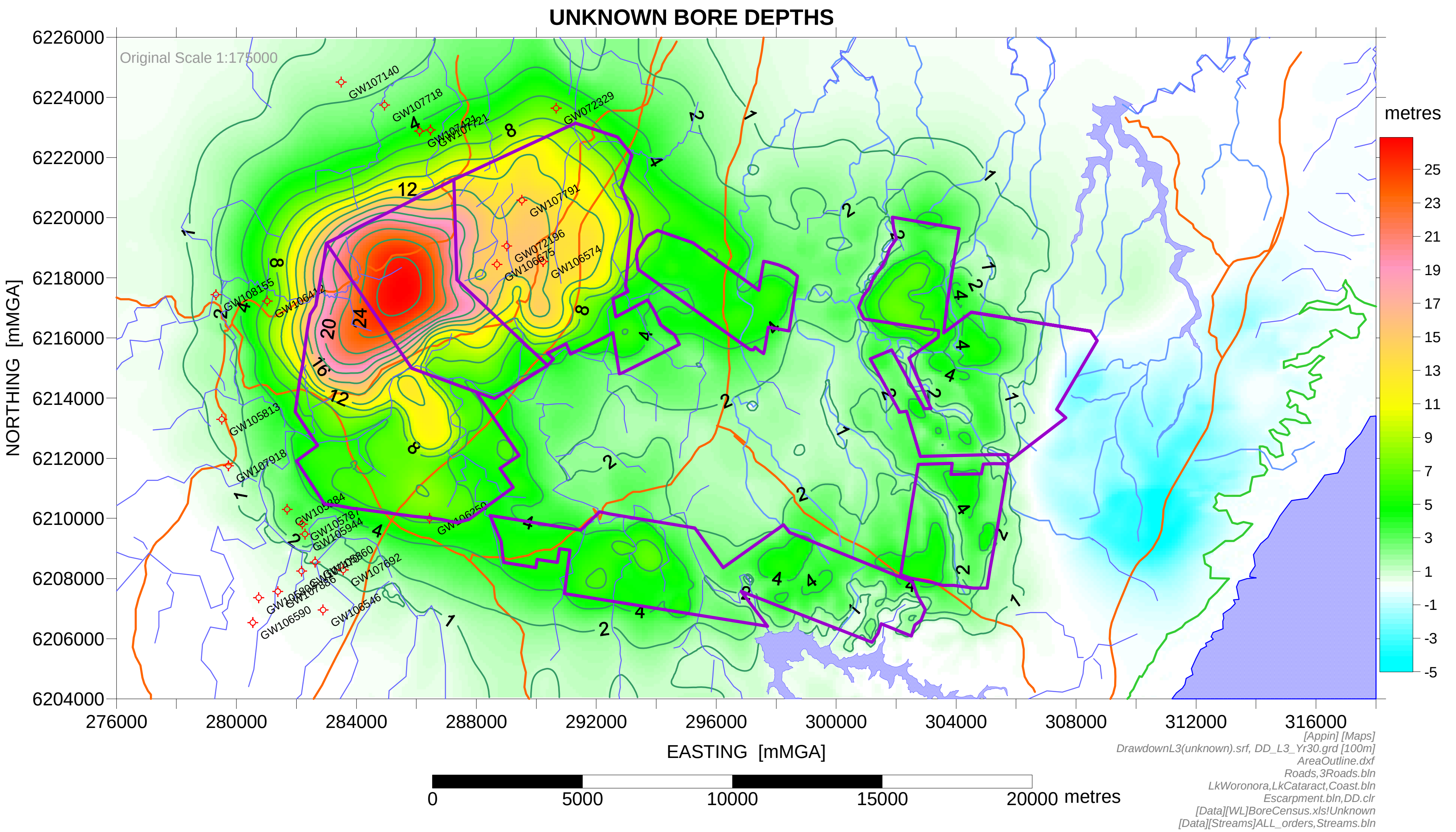


Figure 59. Predicted drawdown in the lower Hawkesbury Sandstone in relation to registered production bores of unknown depth, after 30 years of mining.

ATTACHMENT A

Known Registered Bores in the Vicinity of the Bulli Seam Operations

Table A1. Known registered bores in the vicinity of the Project

Bore ID	Easting (MGA)	Northing (MGA)	Year of Construction	Hole Depth (m)	Elevation (m AHD)	Depth to Water (m)	Water Level (m AHD)	Yield (L/s)	Lithology
005316	295450	6219905	Unknown	36.5	-	-	-	-	Clay to 1.52 m; Shale to end
008537	278094	6211404	1947	65.5	-	-	-	-	-
008548	277204	6210057	1947	65.5	-	-	-	-	-
010496	276518	6211983	1954	40.6	300	28.6	271.4	0.76	Sandstone to 28.04 m; Shale to 29.57 m; Sandstone to end
010604	276742	6214424	1954	76.2	260	28.3	231.7	-	Sandstone with bands of shale to end
010968	276167	6214872	1953	42.6	280	30.4	249.6	0.63	Clay to 4.57 m; Sandstone to end
011042	289722	6209052	1954	47.3	210	26.8	183.2	0.06	Sandstone to 34.14 m; Shale to 41.15 m; Sandstone Shale to end
013282	276732	6209460	Unknown	-	-	-	-	-	-
013855	278231	6218621	1959	33.5	185	1.2	183.8	1.89	Shale to 30.48 m; Sandstone to end
015090	296443	6213115	1949	36.5	240	12.1	227.9	0.25	Sandstone to end
017315	286747	6220544	1938	36.5	-	-	-	-	-
018337	307204	6211165	1945	123.4	-	-	-	-	Clay to 1.8 m; Sandstone to end
018338	307364	6210390	1946	67.6	-	-	-	-	-
018339	307444	6210465	1946	56.3	373	3	370	1.1	-
019590	282236	6207308	1963	80	230	44.1	185.9	-	Clay 1.52 m; Shale to 3.66 m; Sandstone with bands of shale to end
024351	292026	6224053	1966	21.9	-	-	-	-	Sand to 1.21 m; Silt to 9.14 m; Clay with gravel to 19.50 m; Shale to end
024353	291584	6224351	1966	24.4	-	-	-	-	Loam/clay to 22.55 m; Shale to end
024354	291971	6224237	1966	21.3	-	-	-	-	Sand/clay with bands of gravel to 19.20 m; Shale to end
024644	286584	6209690	1964	77.4	-	-	-	-	Sandstone to end
024750	277203	6216593	1968	11.9	-	-	-	-	-
026469	292287	6222703	1965	20.4	-	-	-	-	Sand/Silt to 19.81 m; Clay to end
026470	292985	6222410	1965	1.9	-	-	-	-	Sand/Silt to end
026471	292348	6222272	1965	5.4	-	-	-	-	Silt to 5.02 m; Clay/Sand to end
026473	291756	6222383	1965	19.2	-	-	-	-	Silt with sand traces to 18.28 m; Clay to end
026516	289142	6221184	1965	10	-	-	-	-	Silt to 2.43 m; Clay to 7.62 m; Silt to 9.75 m; Shale to end
026529	286734	6223380	1965	6.7	-	-	-	-	Clay to 6.40 m; Shale to end
026545	291242	6222433	1965	8.5	-	-	-	-	Silt with gravel traces to 3.96 m; Clay to 8.22 m; Decomposed sandstone to end
026551	291232	6224035	1965	11	-	-	-	-	Loam to 0.91 m; Silt to 10.66 m; Shale to end

Bore ID	Easting (MGA)	Northing (MGA)	Year of Construction	Hole Depth (m)	Elevation (m AHD)	Depth to Water (m)	Water Level (m AHD)	Yield (L/s)	Lithology
026557	291730	6222382	1966	28.4	-	-	-	-	Loam to 3.66 m; Sand with silt traces to 28.35 m; Shale to end
028270	282576	6208087	1966	83.8	-	-	-	-	Sandstone to end
031294	279837	6205896	1969	90.2	280	34.1	245.9	-	Sandstone with shale bands to end
032310	299266	6218786	1969	152.4	-	-	-	-	Sandstone with shale bands to end
032443	276520	6206526	1966	130.1	305	26.2	278.8	-	Sandstone with shale bands to end
034425	289289	6215793	1972	70.1	-	-	-	-	Clay to 1.21 m; Shale to 5.48 m; Sandstone Shale to 7.62 m; Sandstone to end
034687	278326	6209190	Unknown	6	-	-	-	-	-
035033	288150	6215151	1973	131	-	14.6	-	0.63	Clay/Shale to 17.67 m; Sandstone to 78.33 m; Shale to 81.99 m; Sandstone to end
035753	276773	6209893	1972	142	-	-	-	-	Sandstone with shale bands to end
035844	277255	6215484	1968	45.7	230	24.3	205.7	-	Shale to 3.20 m; Sandstone to 16.15 m; Shale to 17.06 m; Sandstone to end
038059	290064	6213190	Unknown	304.8	-	-	-	-	-
038074	278321	6209405	Unknown	60.9	-	-	-	-	-
038159	298623	6221330	1974	121.9	-	-	-	-	Clay to 0.60 m; Sandstone to end
040953	293490	6216890	2005	170	-	-	-	2	Sandstone to end
040954	293550	6217100	2005	205	125	21	104	4	Sandstone to 199.00 m; Claystone to end
042788	280522	6210505	1976	148	-	-	-	-	Shale Clay to 1.40 m; Sandstone/Shale to end
043690	290395	6211009	Unknown	132.5	-	-	-	-	Sandstone with shale bands to end
043863	292527	6211858	1974	121.6	190	62.4	127.6	0.15	Shale to 32.00 m; Sandstone with bands of shale to end
045404	282322	6206879	1952	53.3	-	-	-	-	Sandstone to end
051877	281778	6206065	1979	92	255	43	212	-	Shale to 4.50 m; Sandstone to end
052126	285529	6223383	1981	140	-	-	-	-	Clay with bands of gravel to 19.00 m; Shale with clay bands to 112.60 m; Sandstone to end
053288	289861	6207421	1981	92	-	-	-	-	Shale Clay to 3.60 m; Sandstone to 62.20 m; Shale to 62.50 m; Sandstone to end
053449	280474	6206003	1981	105	285	54	231	-	Sandstone with shale bands to end
053450	282418	6206080	1981	120	-	-	-	-	Sandstone with shale bands to end
053980	282209	6217265	1982	154.5	-	-	-	-	Shale to 118.80 m; Sandstone with bands of shale to 121.00 m; Sandstone to end
056750	283315	6207118	1982	68.9	-	-	-	0.25	Clay to 1.52 m; Sandstone to 61.26 m; Shale to end
057797	284167	6211237	1982	106.7	-	-	-	-	Sandstone with shale bands to end
057829	290440	6206694	1983	90	-	-	-	1	Clay to 9.00 m; Sandstone to end
057969	281465	6206335	1983	108	-	-	-	-	Sandstone with shale bands to end

Bore ID	Easting (MGA)	Northing (MGA)	Year of Construction	Hole Depth (m)	Elevation (m AHD)	Depth to Water (m)	Water Level (m AHD)	Yield (L/s)	Lithology
058832	290002	6206808	Unknown	219.5	-	-	-	-	-
059106	282373	6207990	1982	75	-	-	-	-	-
059446	294732	6212872	1984	57	-	-	-	-	Shale to 12.50 m; Sandstone to end
060778	280155	6225140	1986	40	-	-	-	-	Clay/Sand to 16.80 m; Sandstone to end
060886	294727	6215451	1985	381.1	-	-	-	-	Sandstone/Shale to 186.40 m; Mudstone to 220.00 m; Sandstone/Shale to end
060887	294092	6215221	1985	395	-	-	-	-	Shale to 7.50 m; Sandstone with shale and mudstone bands to end
060888	294769	6215883	1986	394.8	-	-	-	-	Sandstone to 165.00 m; Shale to 196.00 m; Mudstone to 226.00 m; Sandstone to end
060889	294240	6215471	1986	400	-	-	-	-	Sandstone/Shale to end
062068	276598	6209704	1986	150	-	-	-	-	Sandstone to 144 m; Mudstone Sandstone to end
062169	294848	6215762	1986	100	-	-	-	-	Sandstone to end
062661	282714	6207659	1985	126.5	-	-	-	-	Clay to 2.40 m; Sandstone with bands of shale to end
062945	288065	6221221	1986	150	-	-	-	-	Clay/Shale to 6.20 m; Shale to 77.80 m; Sandstone to end
063525	276740	6214516	Unknown	91	255	24	231	-	Sandstone to 83.00 m; Shale to 85.00 m; Sandstone to end
063557	277212	6225190	1988	101.8	-	-	-	-	Clay to 10.70 m; Shale to 49.10 m; Sandstone to end
064469	277451	6215859	1987	91	-	-	-	0.5	Sandstone to end
064814	294459	6222997	2005	48	-	-	-	-	-
064815	294460	6222966	1985	64	-	-	-	-	-
064932	290492	6207805	1988	42	260	17.8	242.2	0.3	-
067570	277269	6213898	1988	85	-	-	-	-	-
067606	282526	6212285	1989	150	-	-	-	-	Shale and clay to 4.80 m; Sandstone to end
067682	276964	6216929	1989	66	200	40	160	2	-
070245	280195	6205904	1992	97.5	-	-	-	-	-
072196	289016	6219057	2006	-	-	-	-	-	-
072197	285107	6224194	1994	180	-	-	-	-	-
072329	290665	6223643	1989	-	-	-	-	-	-
072344	285269	6223513	1994	132.5	-	-	-	-	Clay beds to 19.80 m; Siltstone to 33.00 m; Shale to 110.30 m; Sandstone to end
072454	297815	6218253	1994	162	-	-	-	-	-
072482	282057	6207099	1994	96	-	-	-	-	-
073018	280084	6206757	1992	53.3	-	-	-	2.1	Clay to 4.00; Shale to 30.00 m; Sandstone
100455	281982	6207210	1994	96	-	-	-	-	Shale to 0.75 m; Sandstone to end

Bore ID	Easting (MGA)	Northing (MGA)	Year of Construction	Hole Depth (m)	Elevation (m AHD)	Depth to Water (m)	Water Level (m AHD)	Yield (L/s)	Lithology
101437	291651	6216406	1997	128	-	75	-	0.7	Sandstone
101942	295180	6211115	1998	390	-	-	-	-	Sandstone to 214.00 m; Claystone to 240.00 m; Sandstone to end
102043	289809	6214730	1999	192	-	104	-	0.2	Sandstone
102344	280303	6206770	1998	110	270	29	241	2.1	Sandstone with shale bands to end
102405	280736	6225492	1999	36	-	-	-	-	Clay to 13.50 m; Shale to 23.00 m; Sandstone to end
102412	280938	6225651	1999	30.5	-	-	-	-	Clay to 12.00 m; Shale to 30.50 m; Sandstone to end
102440	277883	6220339	1999	138	240	20	220	-	Clays/Mudstone to 8.40 m; Sandstone to 24.50 m; Shale to 28.80 m; Sandstone to end
102481	281137	6213787	1995	27	-	-	-	-	-
102482	281322	6212466	1995	17	-	-	-	-	-
102483	280402	6212383	1995	21.6	-	-	-	-	-
102484	288080	6223965	1995	17.5	-	-	-	-	-
102485	288968	6224386	1995	20.1	-	-	-	-	-
102507	285196	6222235	1999	165	145	19	126	-	Clay to 11.00 m; Gravel and sand to 15.00 m; Shale to 113.00 m; Sandstone to end
102528	289222	6204784	1999	163	-	-	-	-	-
102549	281406	6223165	Unknown	143	-	-	-	-	-
102581	280619	6223917	1990	110	-	-	-	-	Clay to 23.40 m; Shale to 70.50 m; Sandstone to end
102584	289731	6216635	1999	186	-	60	-	0.9	Clay to 9.50 m; Shale to 24.00 m; Sandstone to end
102619	287992	6220715	Unknown	224	-	-	-	-	Shale to 76.40 m; Sandstone with siltstone to 117.40 m; Shale to 164.60 m; Sandstone/Shale to end
102798	289923	6214855	1997	122	-	-	-	1	Sandstone
103010	276182	6216296	2000	138	245	17.5	227.5	-	Sandstone to 127.00 m; Shale to end
103161	289511	6216499	2000	120	-	25	-	0.2	Sandstone
104025	287104	6222579	2000	305	115	58	57	2.9	Clay to 2.00 m; Shale to 113.00 m; Sandstone with bands of shale to end
104068	289624	6214720	2001	180	120	62	58	0.88	Clay to 4.00 m; Sandstone to 178.00 m; Shale to end
104090	278313	6216103	2001	150.5	205	39	166	-	Clay to 6.30 m; Shale to 24.00 m; Sandston with shale bands to end
104092	280328	6225252	2001	41	-	-	-	-	Clay to 13.80 m; Shale to 17.00 m; Sandstone to end
104154	291338	6216278	2000	165	150	74	76	1.3	Clay to 1.00 m; Shale to 11.00 m; Sandstone to 114.00 m; Shale to 116.00 m; Sandstone to end
104159	285950	6222954	2001	195	-	-	-	-	Shale to 151.00 m; Sandstone with bands of shale to 158.00 m; Sandstone to end
104223	284994	6223217	2002	231.5	105	13.7	91.3	70	Clay to 10.60 m; Gravel to 11.00 m; Shale to 115.00 m; Sandstone with bands of shale to end

Bore ID	Easting (MGA)	Northing (MGA)	Year of Construction	Hole Depth (m)	Elevation (m AHD)	Depth to Water (m)	Water Level (m AHD)	Yield (L/s)	Lithology
104224	284068	6223049	2002	257.5	110	24.6	85.4	1.63	Clay to 1.40 m; Shale to 87.00 m; Sandstone to end
104347	284117	6218074	2002	298	220	110	110	0.2	Clay to 3.60 m; Shale to 145.00 m; Sandstone to end
104383	283519	6223800	2002	249.5	120	29	91	1.35	Clay to 4.10 m; Shale to 85.00 m; Slate to 114.00 m; Sandstone with small bands of shale to end
104466	277437	6217718	2002	108	250	23	227	7	Sandstone to end
104499	290025	6207006	2001	103	270	34.6	235.4	0.23	Clay to 3.00 m; Sandstone to end
104546	283678	6212431	2002	186	140	80	60	0.15	Clay to 4.00 m; Sandstone and shale to end
104558	282552	6212031	2002	186	170	103	67	0.26	Clay to 3.00 m; Sandstone and shale to end
104593	277478	6220013	2001	44.3	-	-	-	11	Clay to 10.50 m; Shale to 23.00 m; Sandstone to end
104602	289159	6216528	2002	231	130	42	88	0.75	Clay 2.80 m; Shale to 31.00 m; Sandstone to 226 m; Claystone to end
104633	295456	6215299	2003	141.3	190	38	152	1.5	Shale to 5.50 m; Sandstone/Shale to 42.50 m; Sandstone to end
104659	276722	6207581	2003	132	295	51	244	0.8	Sandstone to 43.00 m; Shale to 44.20 m;Sandstone to end
104661	289223	6216851	2003	219.3	150	68	82	1.05	Clay to 4.50 m; Shale to 36.00 m; Sandstone to end
104766	287768	6221185	2002	192	110	82	28	0.15	Clay to 1.00 m; Shale to 82.50 m; Sandstone with clay and shale bands to end
104860	282850	6206368	2003	204.3	260	81	179	1.1	Siltstone to 8.30 m; Sandstone with quartz and shale bands to end
104959	281493	6222849	2001	180	130	30	100	0.44	Clay to 16.00 m; Sandstone to end
104965	281467	6222712	2001	180	135	25	110	0.23	Clay to 18.00 m; Sandstone to end
104967	280822	6223046	2001	159	-	-	-	0.32	Sandstone to end
105042	277596	6218751	2003	49	225	11	214	0.75	Clay to 6.00 m; Shale to 18.00 m; Sandstone to end
105118	298273	6222356	1996	130	175	70	105	0.29	Sandstone to 125.00 m; Siltstone to end
105148	278111	6209923	1995	120	270	33	237	0.3	Sandstone with quartz and siltstone bands to end
105207	285253	6223270	2003	250	100	24	76	1.8	Clay to 4.80 m; Shale to 110.00 m; Sandstone to end
105228	278556	6217027	2003	63	180	23	157	1.5	Clay to 10.00 m; Shale to 19.00 m; Sandstone to end
105243	280734	6225313	2003	72	105	13	92	8	Clay to 18.00 m; Shale/sandstone bands to 42.00 m; Sandstone to end
105244	280910	6224396	2003	72	-	-	-	11.25	Gravel to 15.00 m; Shale to 60.00 m; Sandstone to end
105254	278351	6212046	2003	163	300	80	220	0.67	Clay to 4.00 m; Shale to 36.00 m; Sandstone with shale bands to end
105325	287790	6221664	2001	159	-	-	-	0.5	Shale to 83.00 m; Sandstone/shale to 125.00 m; Sandstone to end
105336	279922	6217069	2003	130	160	21	139	4.5	Shale to 35.10; Sandstone with small shale bands to end
105339	291907	6218477	2003	238	-	-	-	0.25	Clay to 3.00 m; Shale to 25.00 m; Sandstone with bands of shale to 230.00 m; Bald Hill Claystone to end

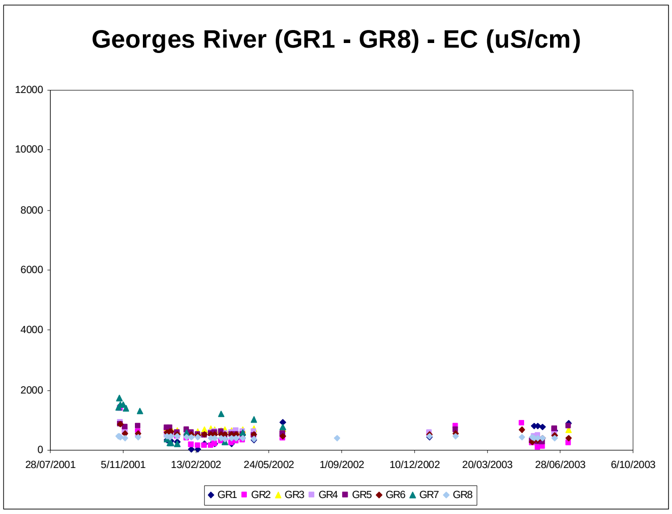
Bore ID	Easting (MGA)	Northing (MGA)	Year of Construction	Hole Depth (m)	Elevation (m AHD)	Depth to Water (m)	Water Level (m AHD)	Yield (L/s)	Lithology
105376	289548	6218570	2002	218.5	150	76	74	1.5	Clay to 2.50 m; Shale to 68.00 m; Slate to 96.00 m; Sandstone with bands of shale to end
105388	289993	6218082	2002	230	145	69	76	0.13	Clay to 1.80 m; Shale to 81.00 m; Sandstones with bands of shale to end
105531	287769	6218620	2003	210	145	79	66	0.15	Clay to 7.00 m; Shale to 69.00 m; Sandstone to end
105534	288760	6217487	2003	207	145	92	53	0.43	Clay to 1.80 m; Shale to 69.30 m; Sandstone to 144.00 m; Slate to 149.50 m; Sandstone to end
105536	277116	6217083	2003	108	210	26	184	1.75	Sandstone to 107.10 m; Shale to end
105546	277102	6215913	2004	163	200	38	162	2.67	Sandstone to 60.00 m; Shale with sandstone bands to 72.00 m; Sandstone to end
105574	289761	6219098	2003	210	-	-	-	0.45	Clay to 4.00 m; Shale to 44.00 m; Sandstone to end
105577	280833	6207231	2003	162	250	21	229	0.8	Clay to 3.00 m; Sandstone to end
105787	282200	6209811	2005	-	-	-	-	-	-
105802	280744	6207363	2005	-	-	-	-	-	-
105813	279513	6213296	2005	-	-	-	-	-	-
105860	282625	6208549	2005	-	-	-	-	-	-
105884	281693	6210302	2005	-	-	-	-	-	-
105921	299682	6218872	2003	183	250	44	206	0.2	Clay to 0.40 m; Sandstone with bands of shale to end
105942	282650	6218981	2002	214	305	11	294	0.13	Clay to 3.50 m; Shale to 158.00 m; Slate with bands of shale to end
105944	282287	6209477	2005	-	-	-	-	-	-
106250	286441	6210001	2005	-	-	-	-	-	-
106281	277123	6210938	2004	48	285	11	274	0.25	Sandstone to end
106412	281027	6217228	2005	-	-	-	-	-	-
106449	297463	6220993	2003	207	-	-	-	-	Clay to 1.00 m; Shale to 4.00 m; Sandstone with bands of shale to 178.00 m; Shale to end
106546	282890	6206955	2005	-	-	-	-	-	-
106574	290228	6218540	2005	-	-	-	-	-	-
106590	280547	6206534	2005	-	-	-	-	-	-
106675	288687	6218445	2005	-	-	-	-	-	-
107140	283493	6224512	2006	-	-	-	-	-	-
107421	286108	6222882	2006	-	-	-	-	-	-
107470	282174	6208247	2006	-	-	-	-	-	-

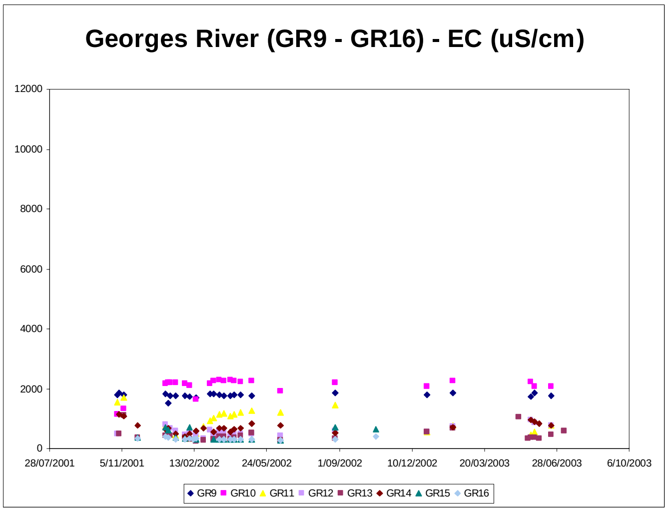
Bore ID	Easting (MGA)	Northing (MGA)	Year of Construction	Hole Depth (m)	Elevation (m AHD)	Depth to Water (m)	Water Level (m AHD)	Yield (L/s)	Lithology
107489	309630	6213995	2003	28	-	-	-	-	Sandstone to end
107692	283560	6208286	2006	-	-	-	-	-	-
107718	284941	6223746	2007	-	-	-	-	-	-
107721	286473	6222918	2007	-	-	-	-	-	-
107791	289520	6220582	2007	-	-	-	-	-	-
107818	287349	6225481	2004	240	90	45	45	1.2	Shale to 94.00 m; Sandstone to end
107886	281381	6207567	2007	-	-	-	-	-	-
107918	279734	6211749	2007	-	-	-	-	-	-
108055	284745	6225924	2007	204	-	-	-	-	Clay to 7.00 m; Shale to 96.00 m; Sandstone with shale bands to end
108155	279317	6217440	2007	-	-	-	-	-	-
108193	282660	6218914	2002	214	305	16	289	0.13	Clay to 3.50 m; Shale to 158.00 m; Slate with bands of shale to end
108312	291639	6217940	2004	175	140	84	56	0.16	Fill to 7.50 m; Shale to 31.00 m; Sandstone to end
108322	299500	6218506	2003	279	265	41	224	-	Clay to 0.30 m; Sandstone with bands of shale to end
108538	281156	6205942	2008	66	-	-	-	-	-
108606	276093	6217209	2008	84	240	21	219	1	-
108863	293843	6222668	2008	20	-	-	-	-	-
108907	288707	6218737	2008	210	120	40	80	1.8	-
108981	276746	6210991	2008	175	290	48	242	0.5	Sandstone with shale bands to 156.00 m; Bald Hill Claystone to end
Lot 1	289510	6214085	1997	96	-	61	-	1.8	Sandstone
Lot 24/25	289995	6215007	Unknown	250	-	-	-	-	Sandstone

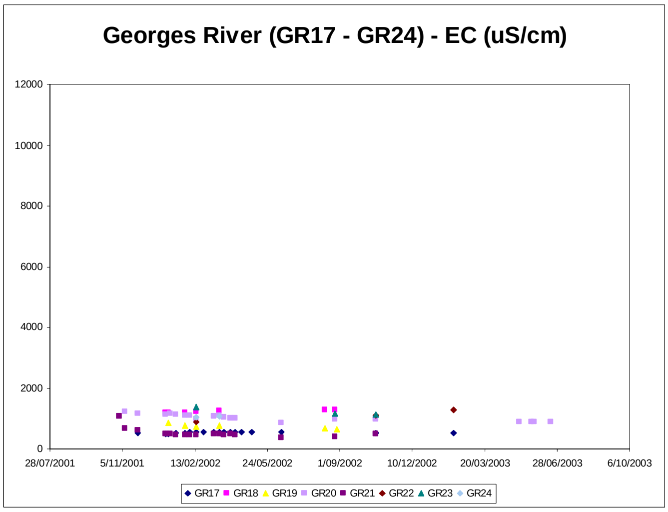
m = metres.
AHD = Australian Height Datum.
L/s = litres per second.

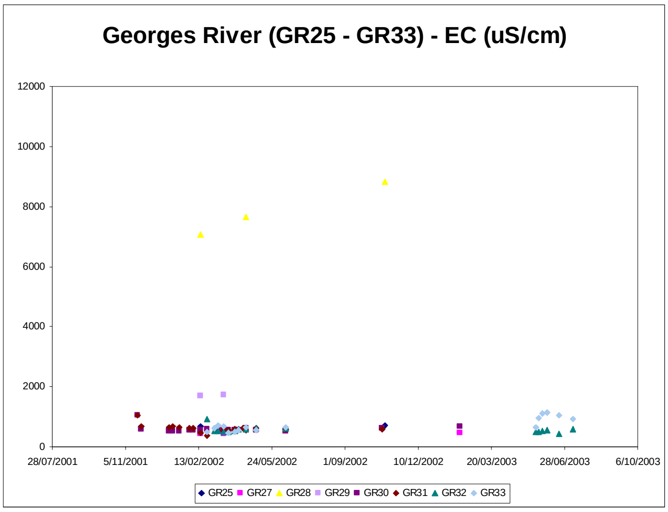
ATTACHMENT B

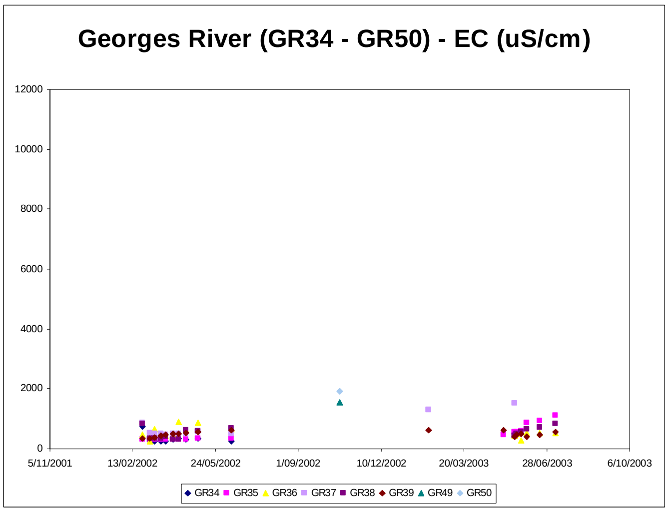
Groundwater Quality Monitoring Results

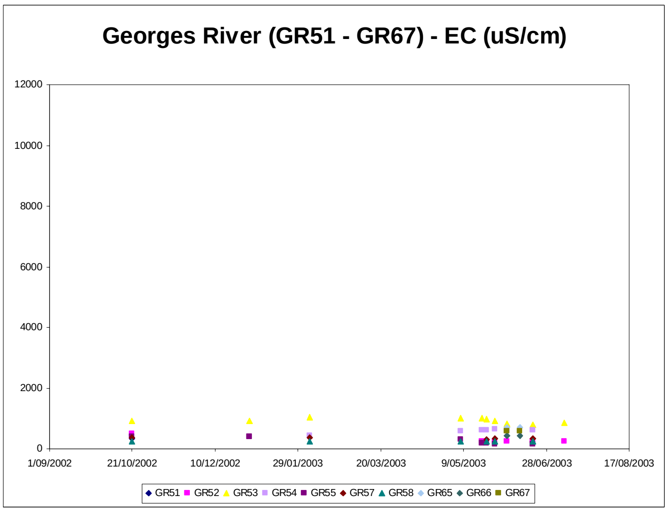




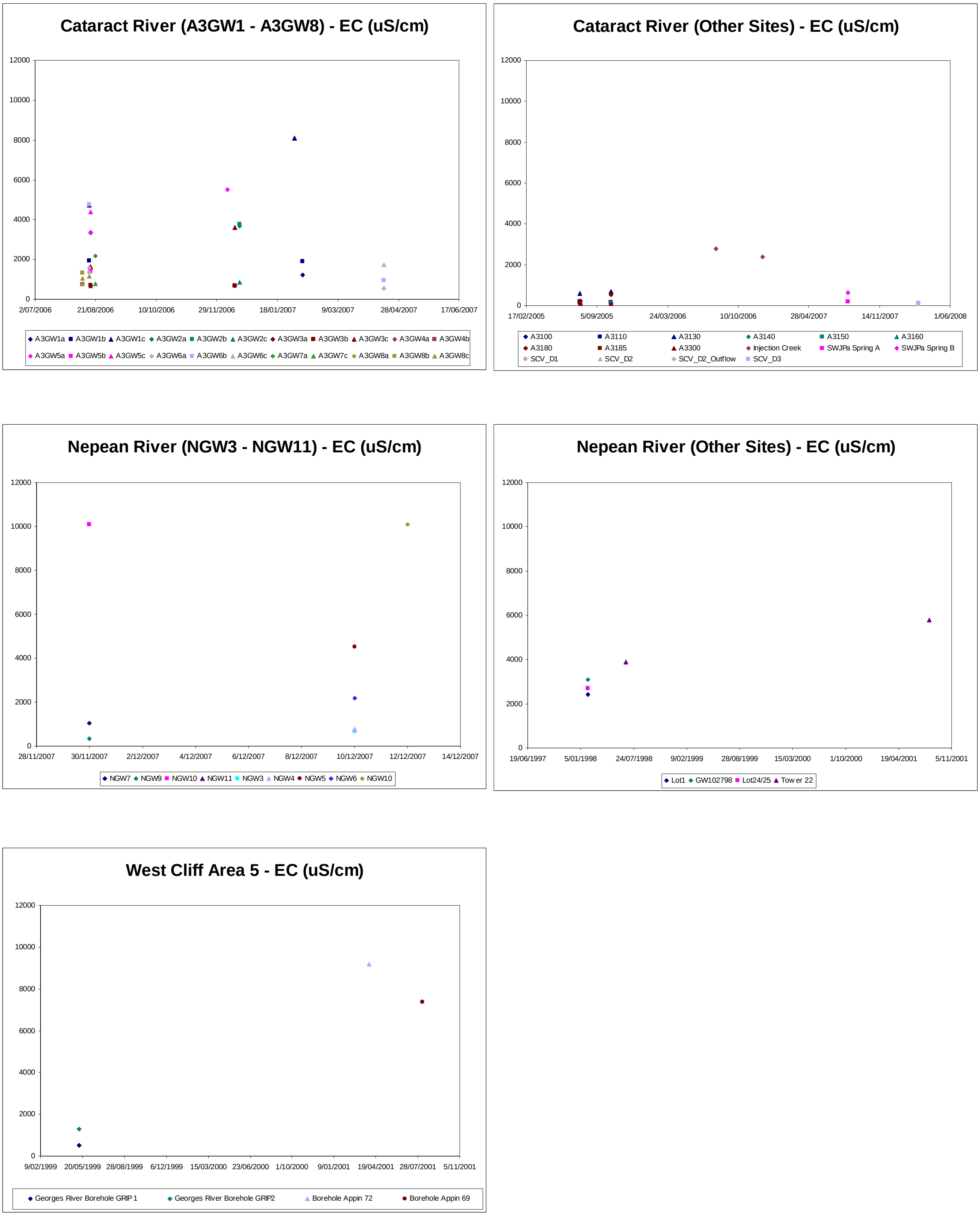




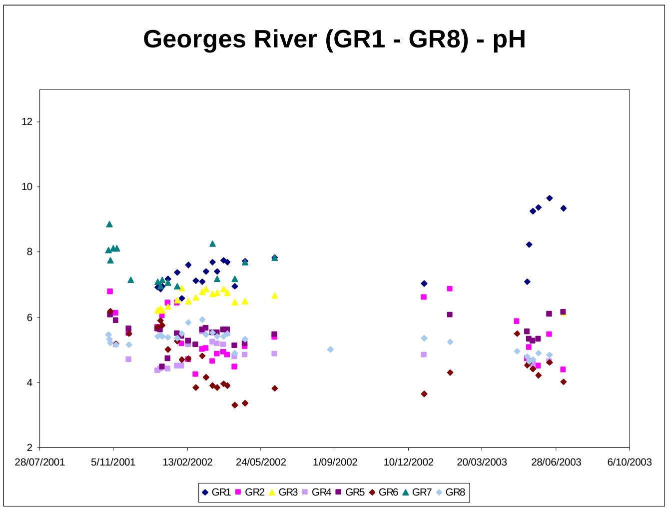


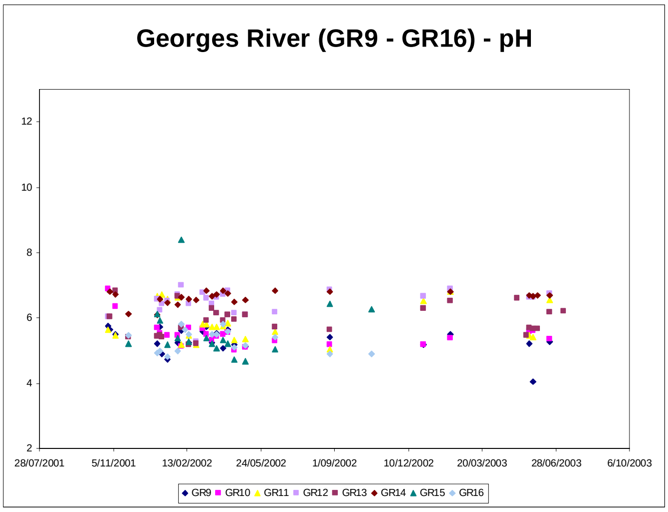


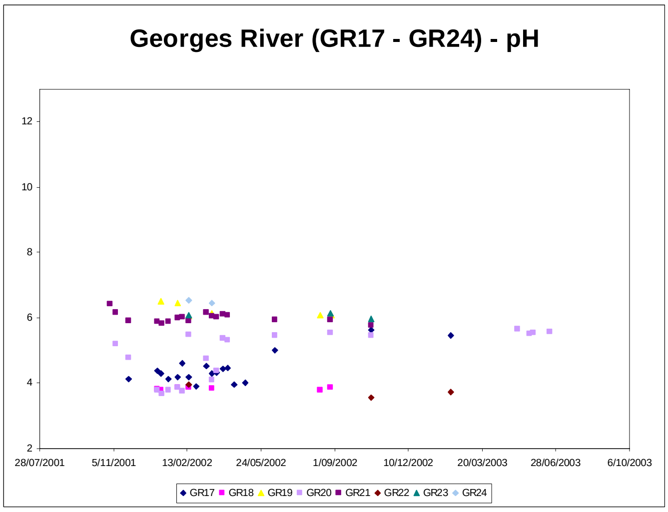
Attachment B1 Observed Electrical Conductivity – Georges River.

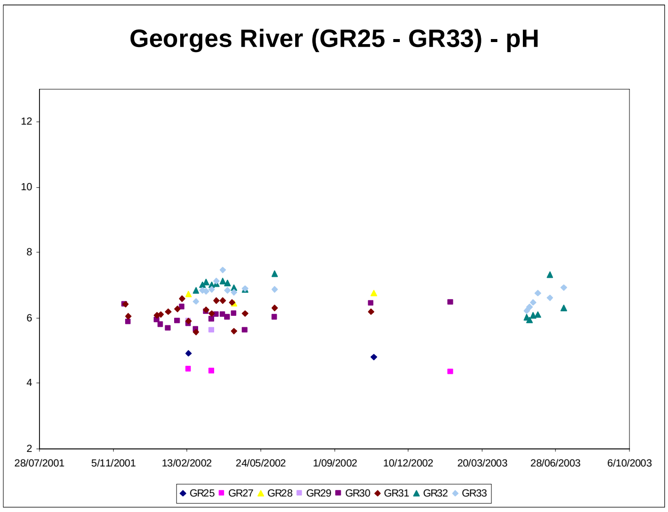


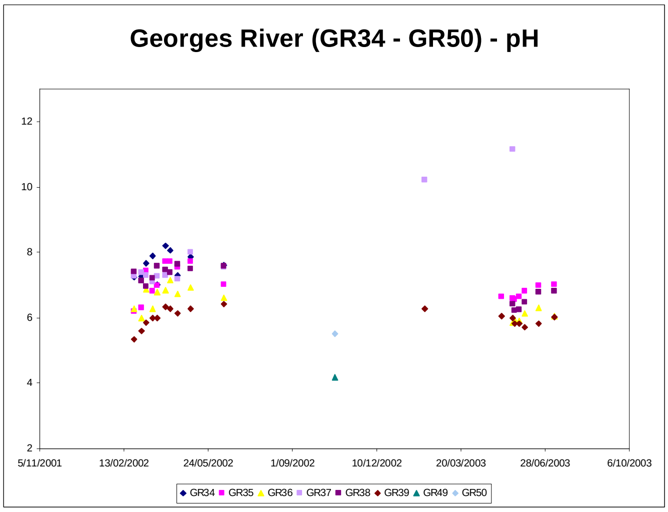
Attachment B1 (Continued) **Observed Electrical Conductivity – Cataract River and Nepean River.**

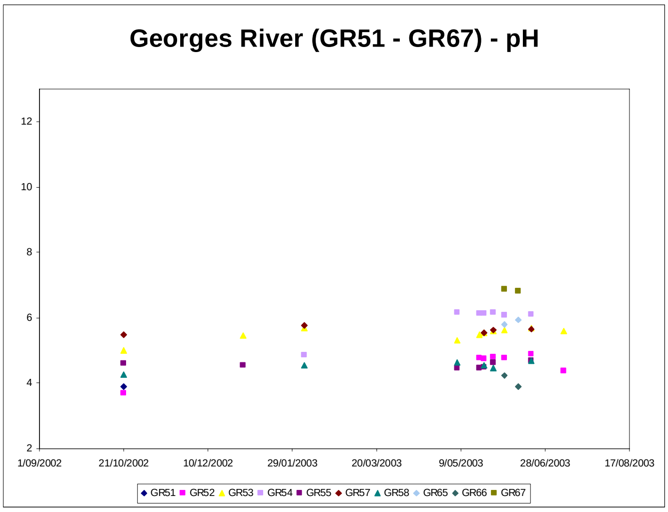




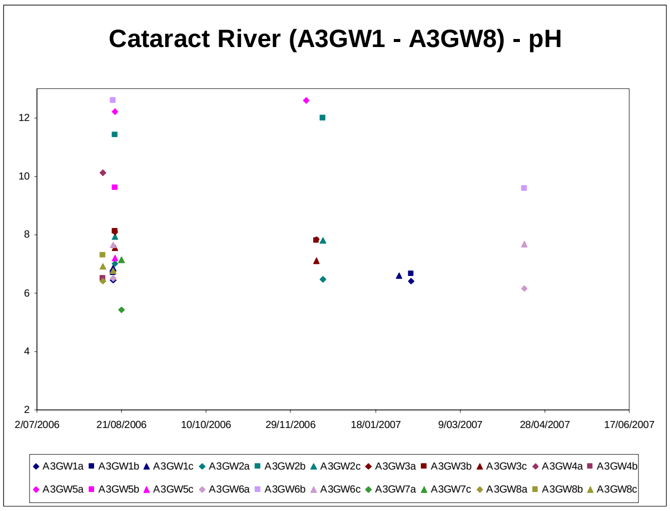


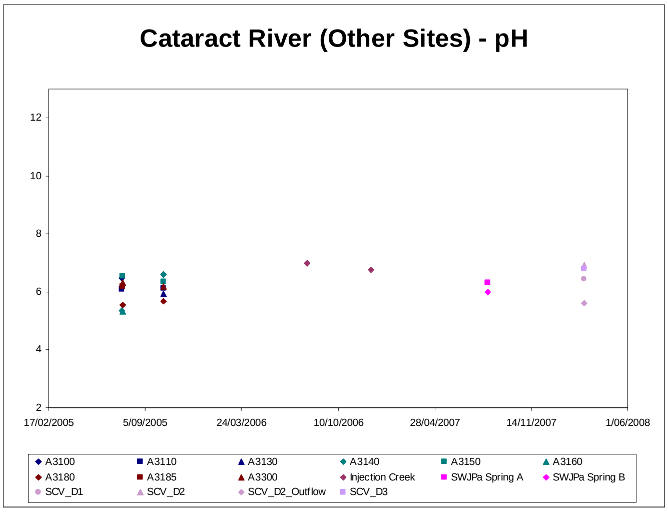


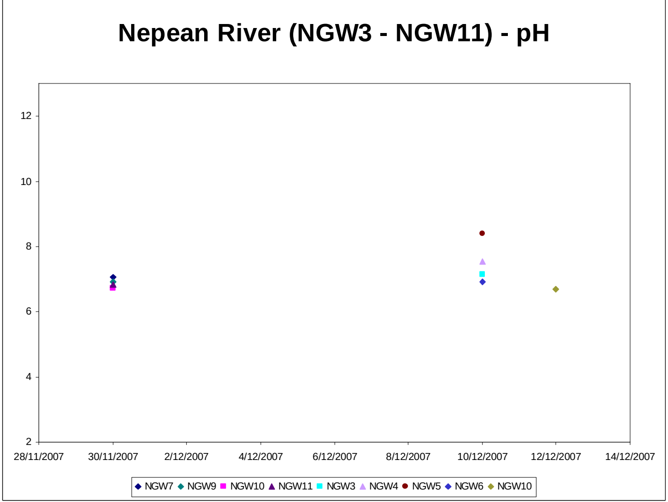


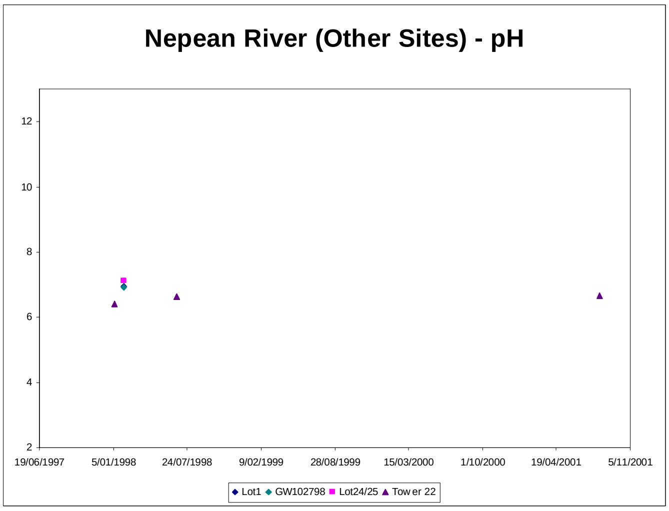


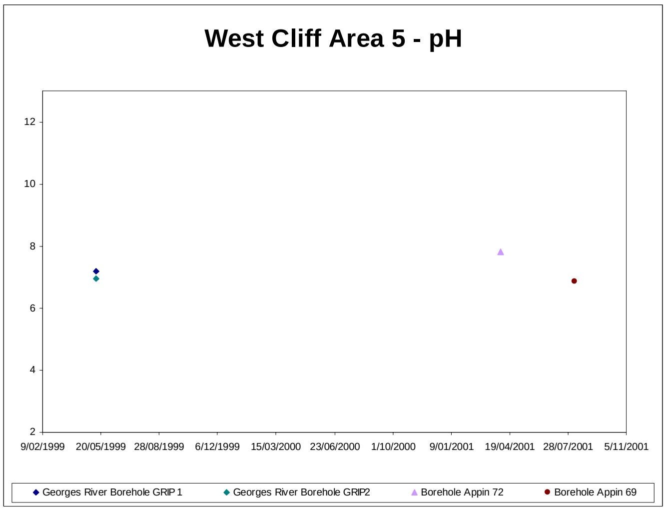
Attachment B2 **Observed pH – Georges River.**



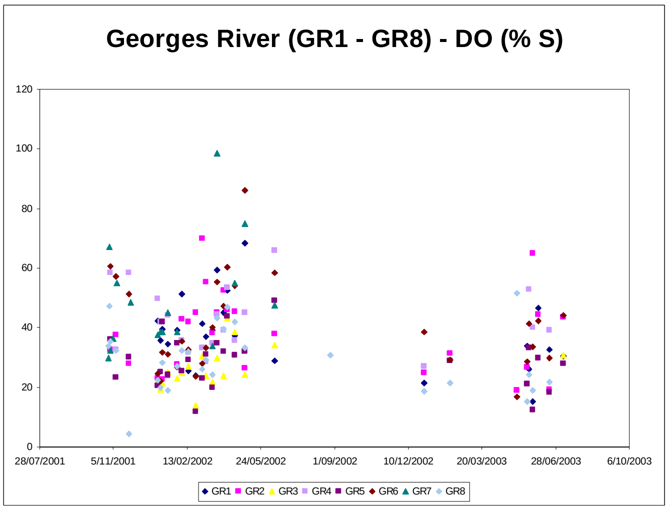


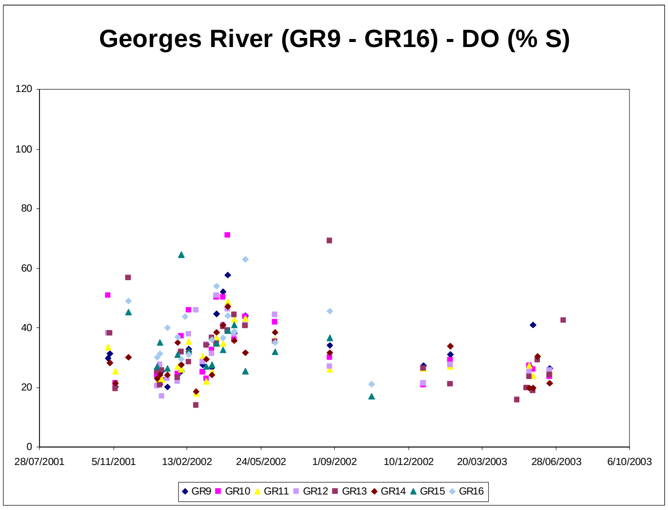


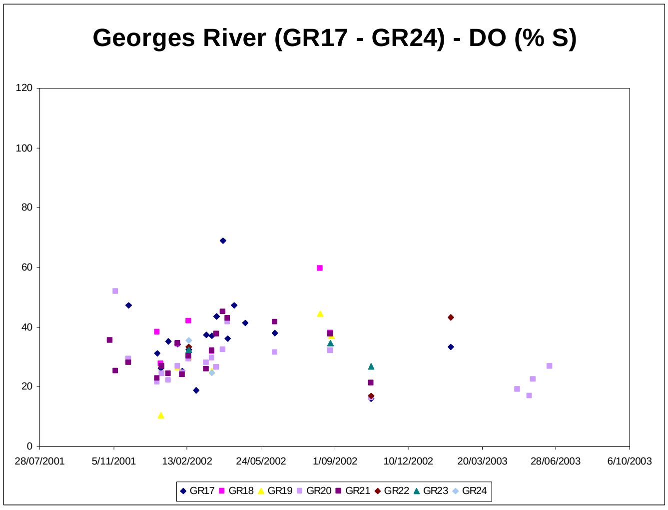


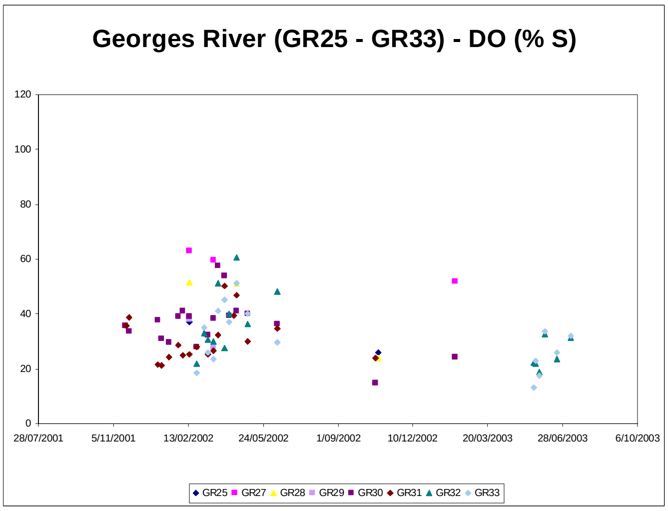


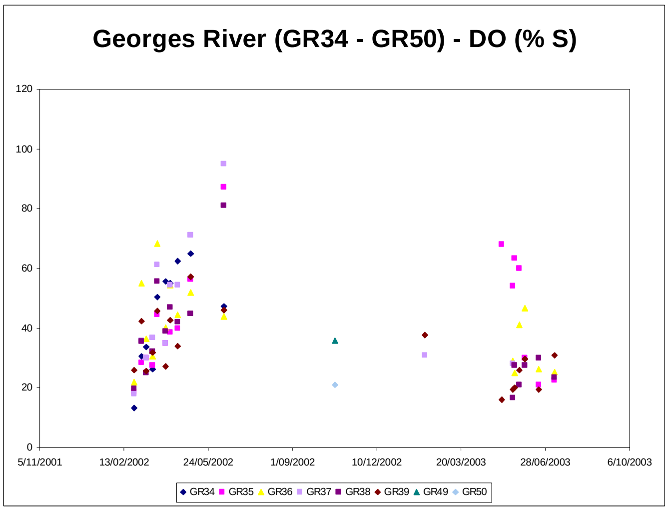
Attachment B2 (Continued) Observed pH – Cataract River and Nepean River.

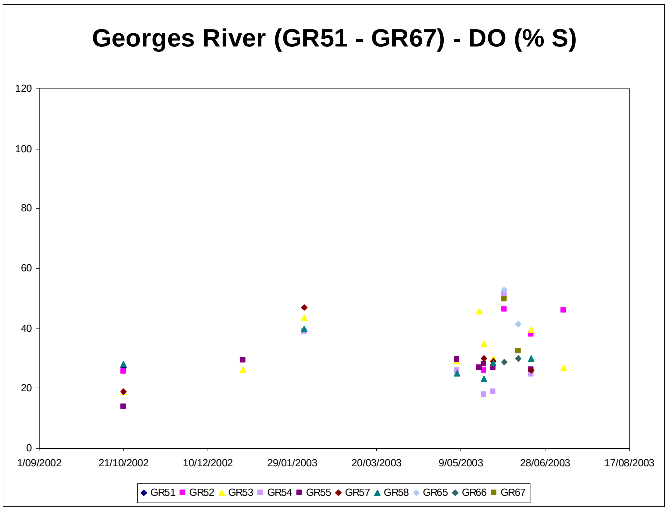




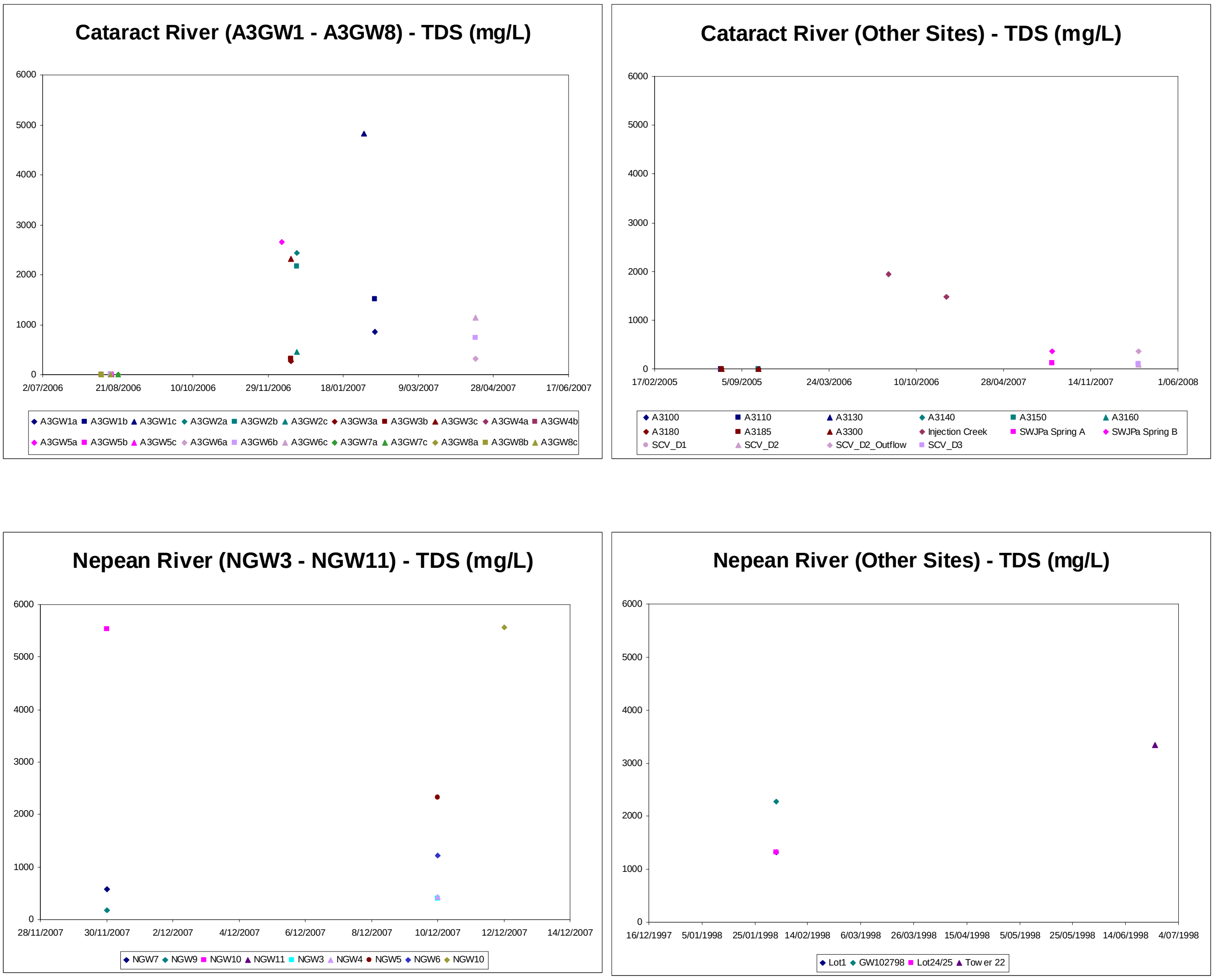




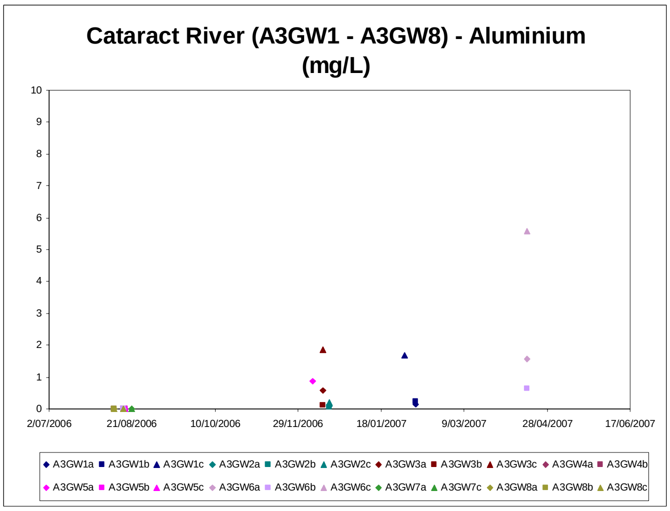


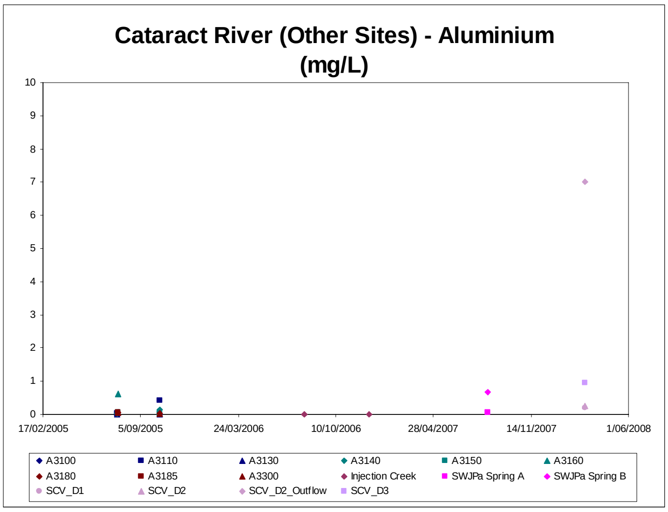


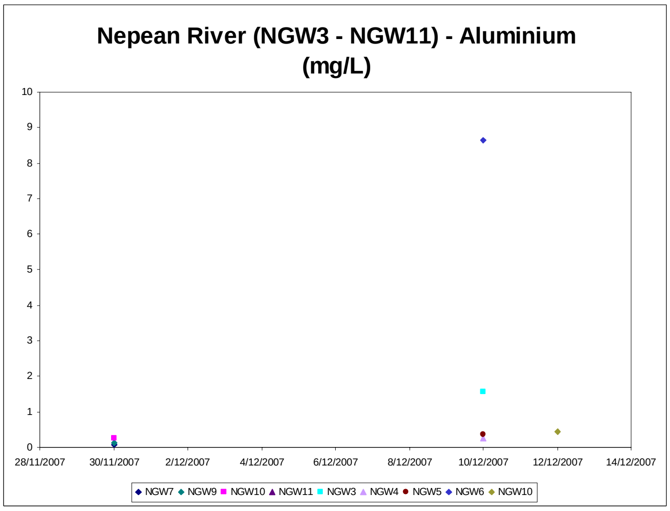
Attachment B3 Dissolved Oxygen – Georges River.



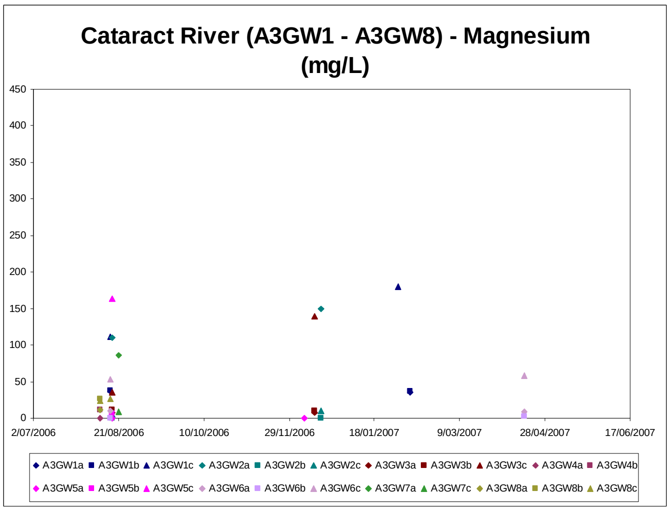
Attachment B4 Total Dissolved Solids – Cataract River and Nepean River.

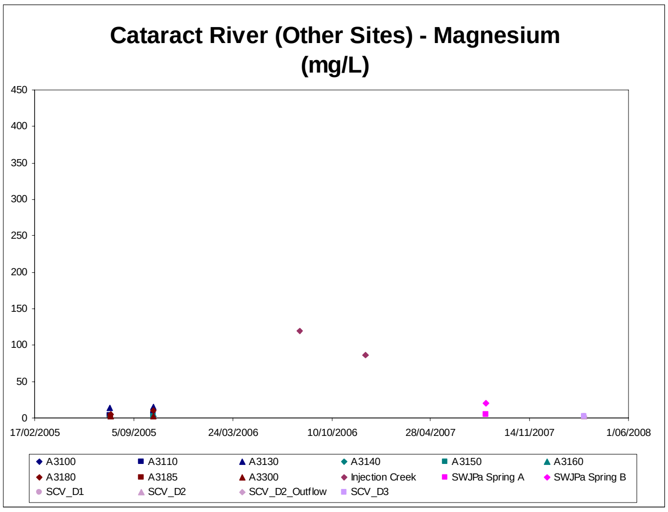


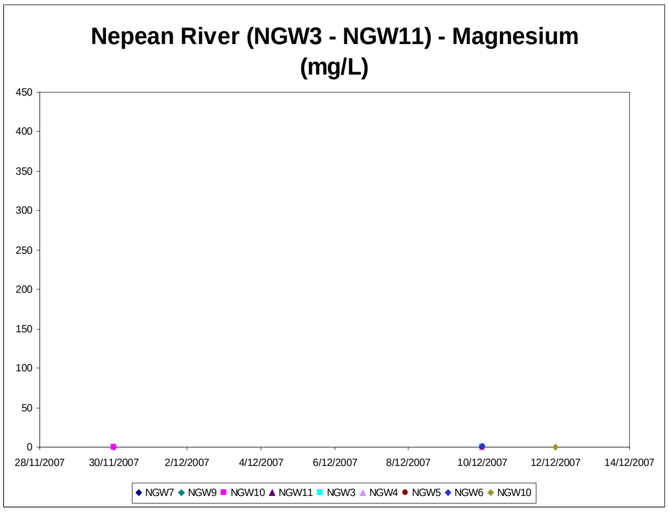


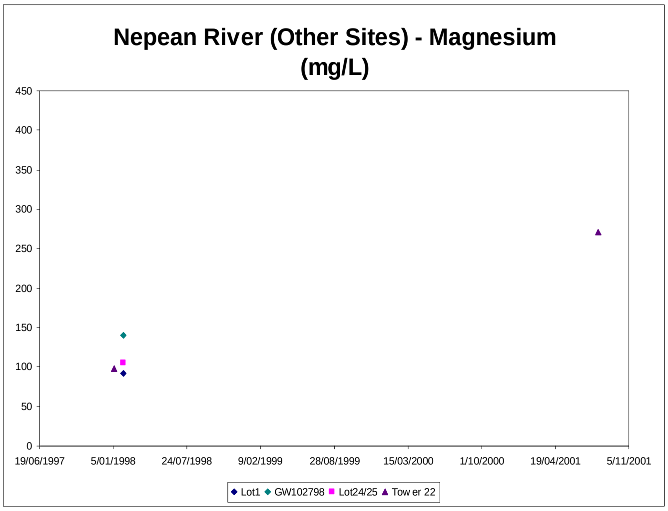


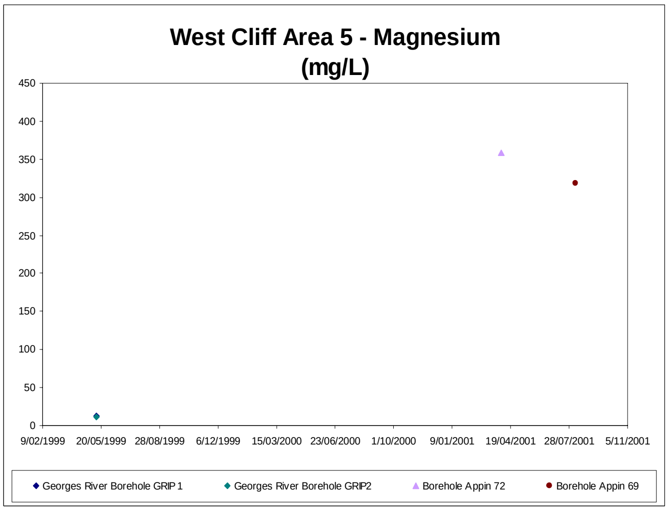
Attachment B5 Observed Total Aluminium Concentrations – Cataract River and Nepean River.



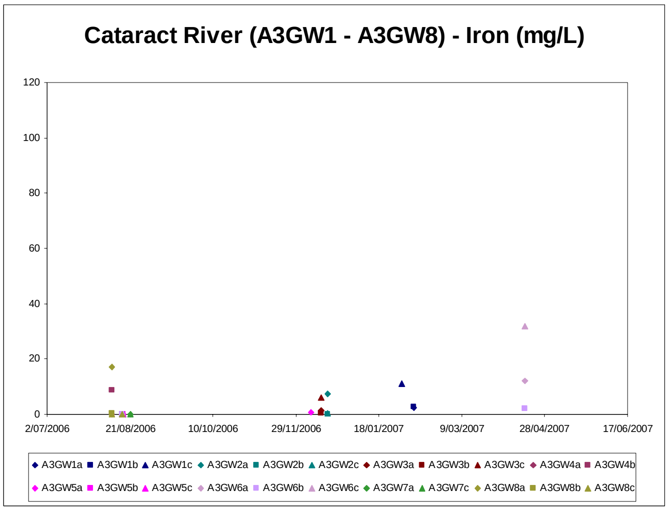


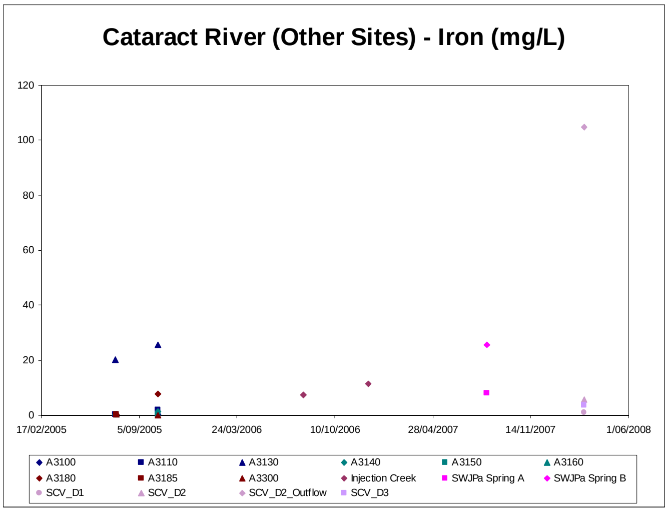


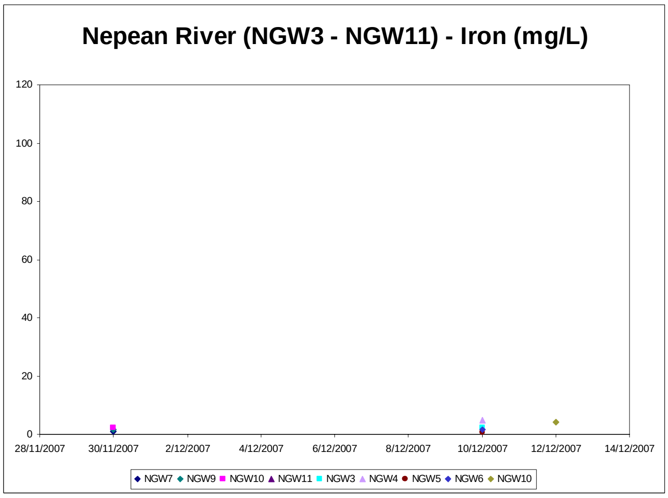


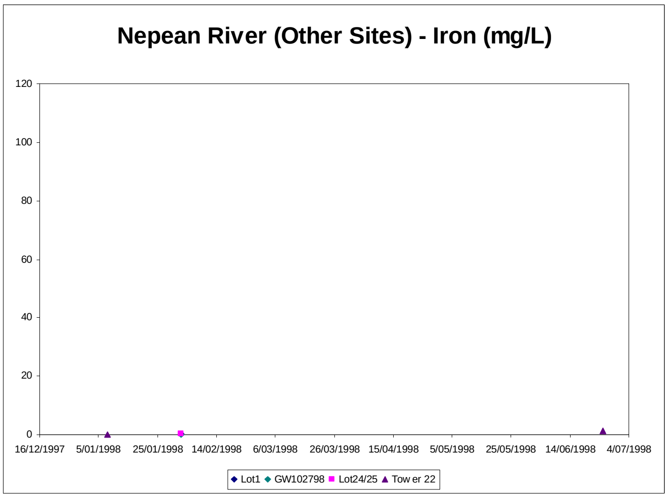


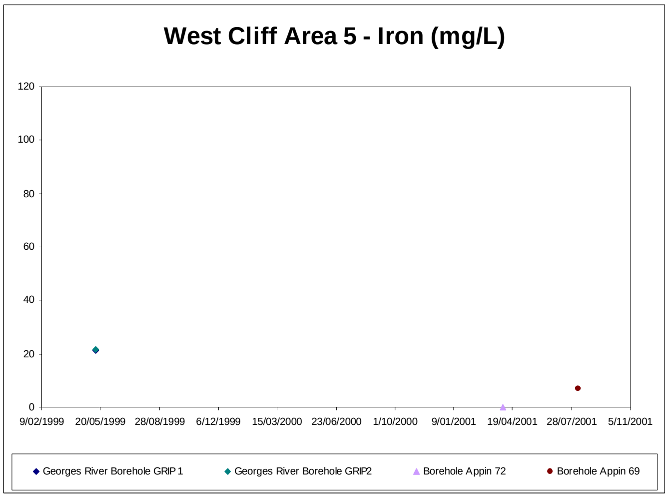
Attachment B6 Observed Dissolved Manganese Concentrations – Cataract River and Nepean River.



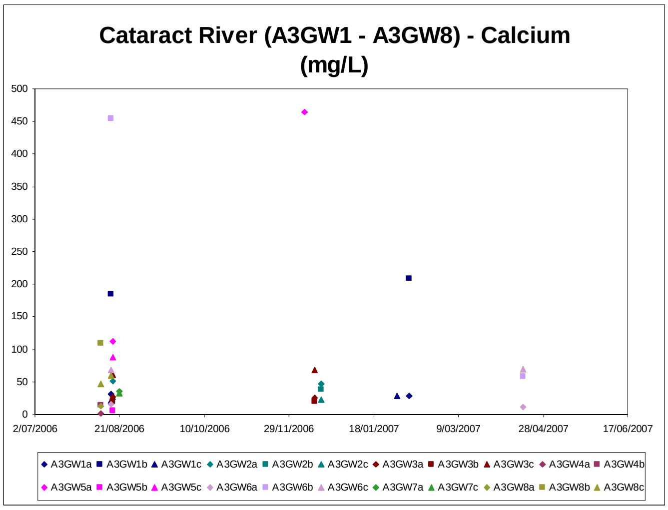


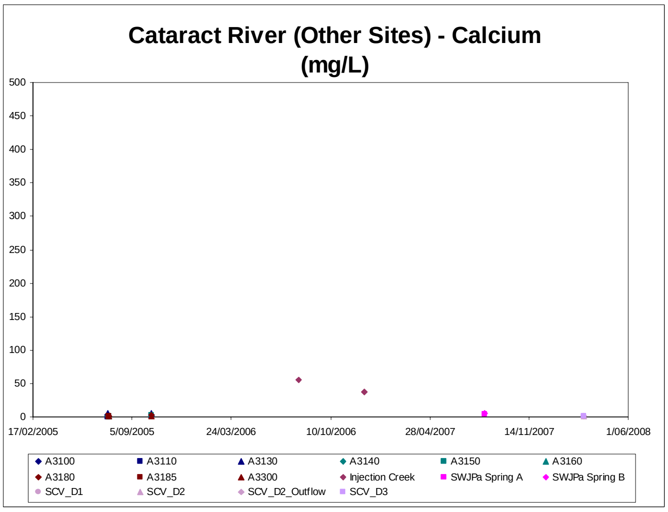


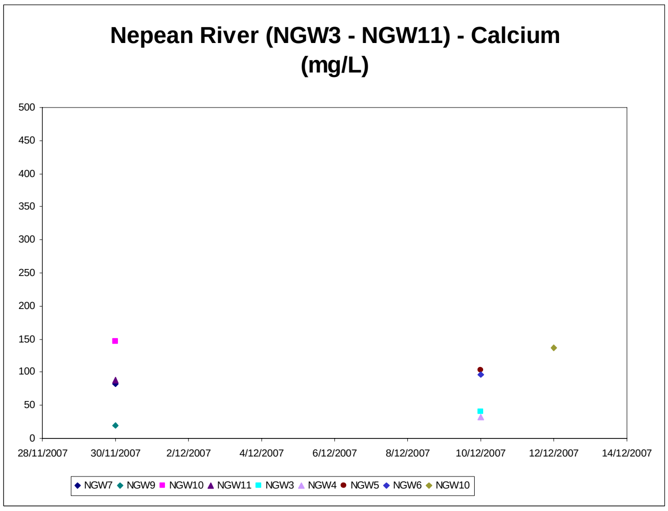


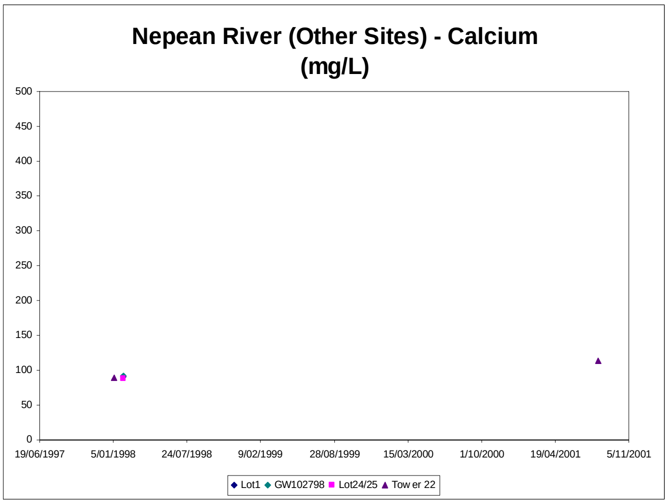


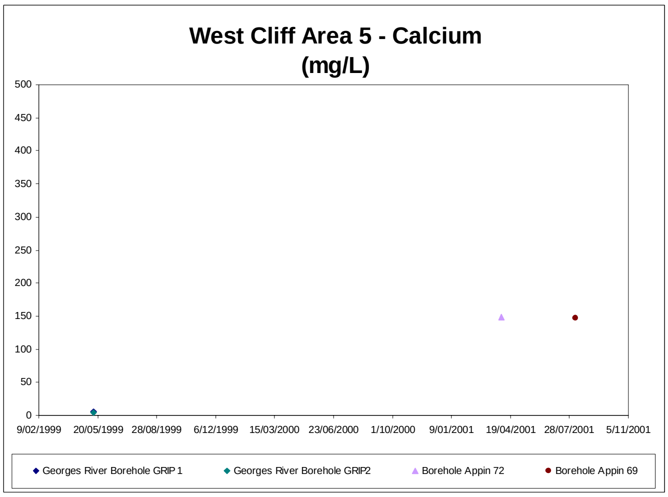
Attachment B6 **Observed Total Iron Concentrations – Cataract River and Nepean River.**



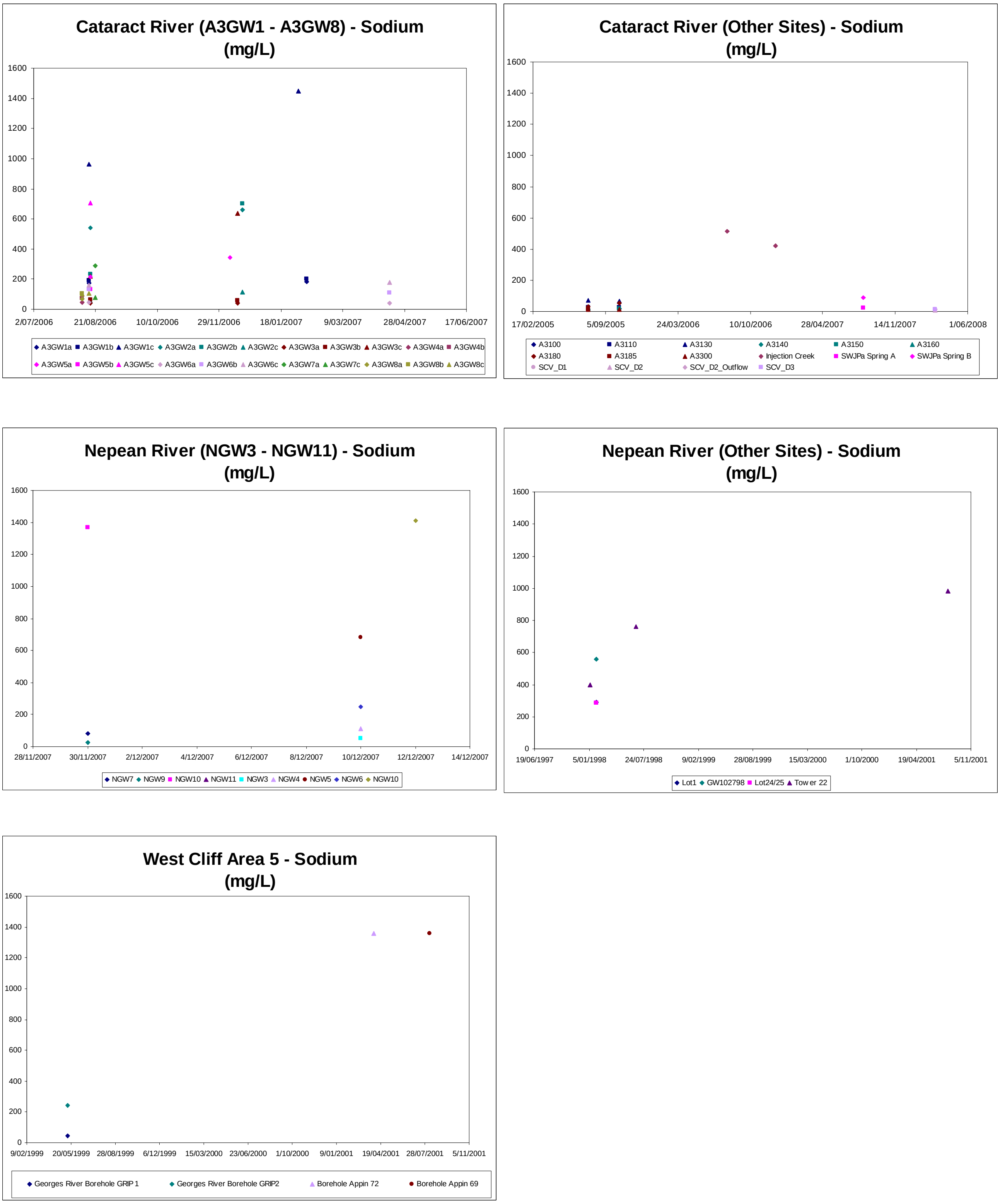




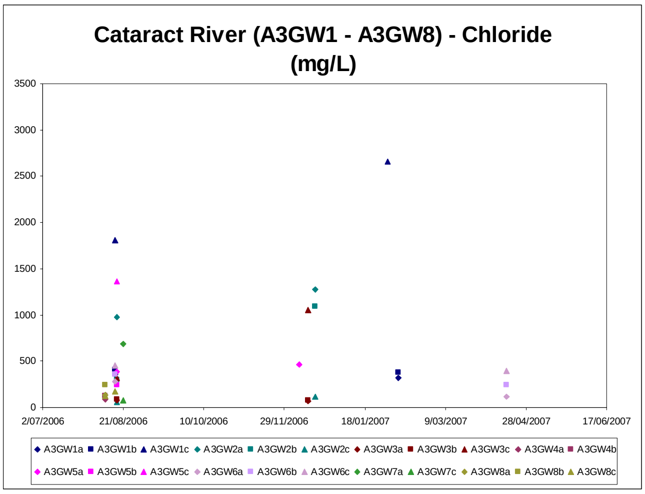


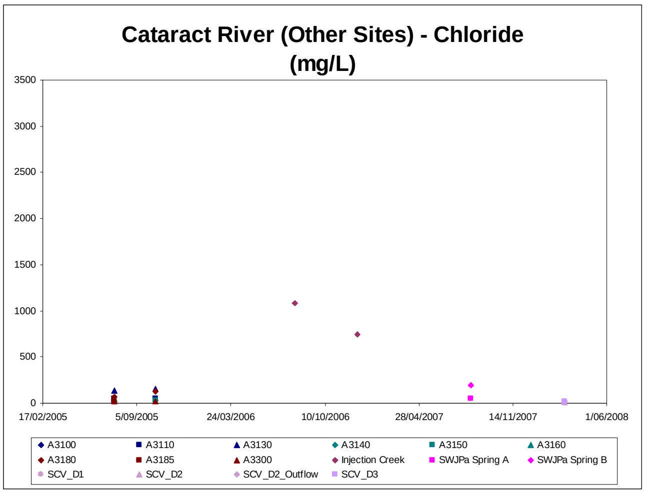


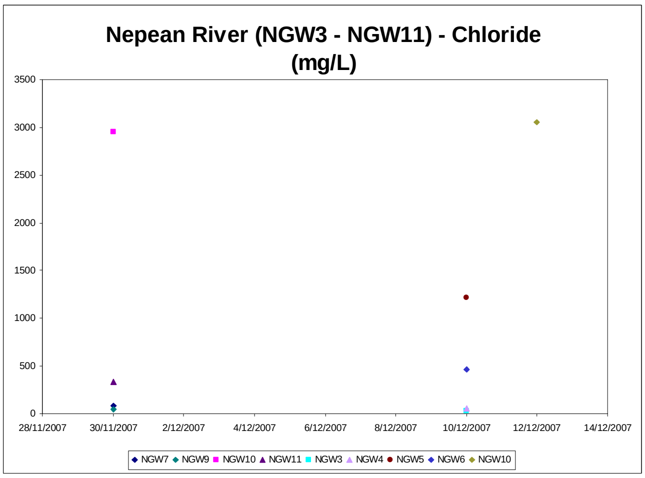
Attachment B7 **Observed Dissolved Calcium Concentrations – Cataract River and Nepean River.**

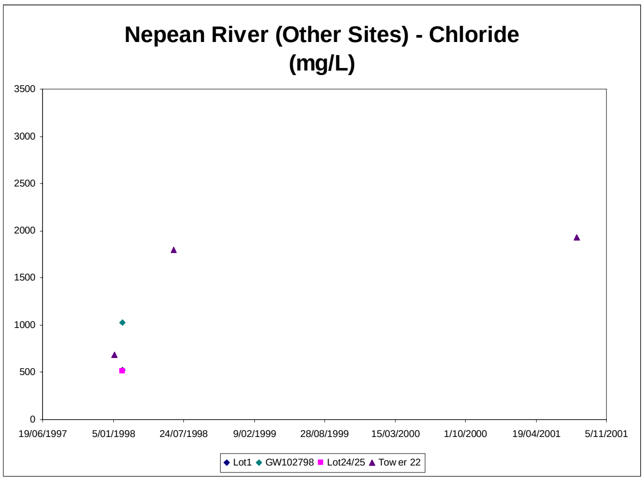


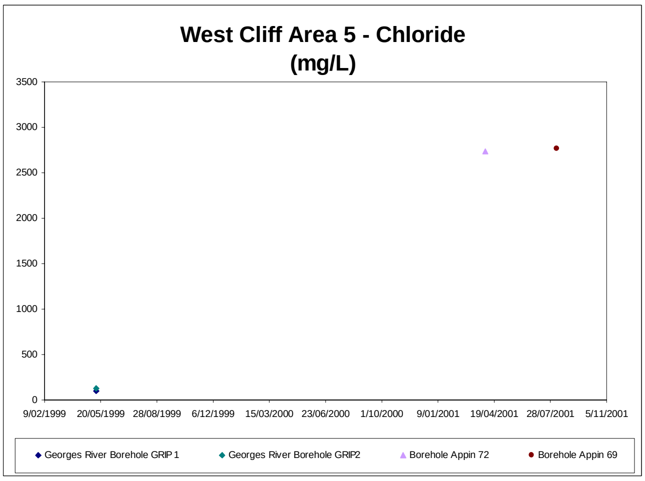
Attachment B8 **Observed Dissolved Sodium Concentrations – Cataract River and Nepean River.**



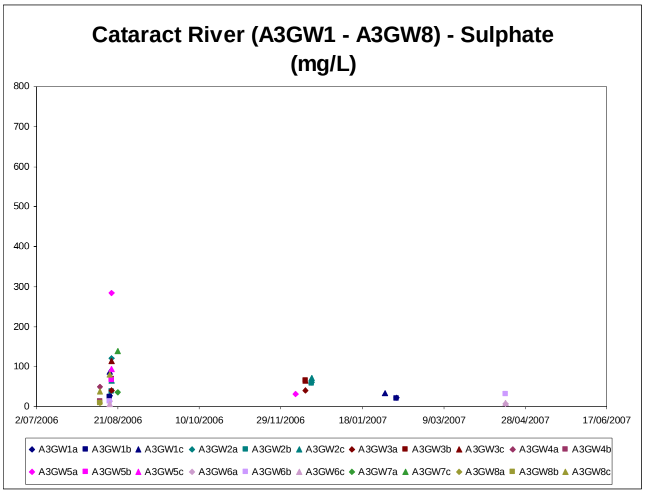


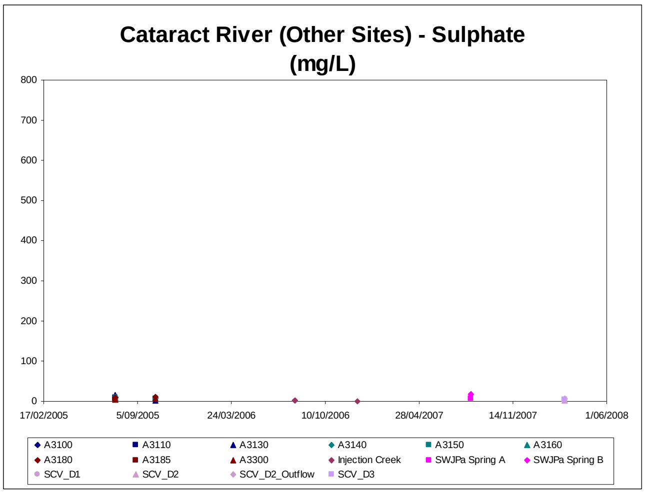


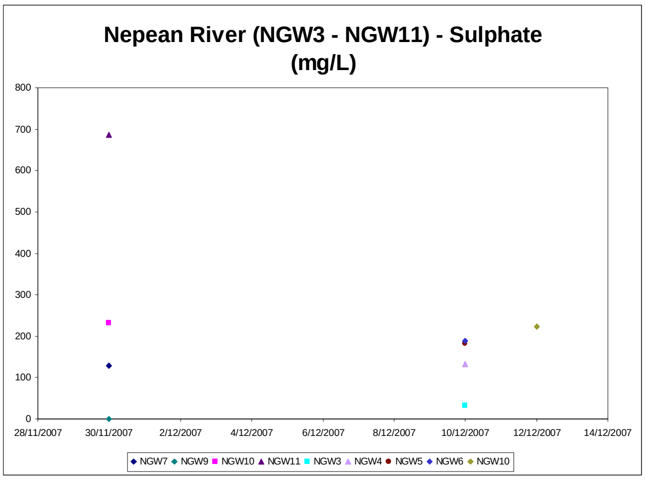


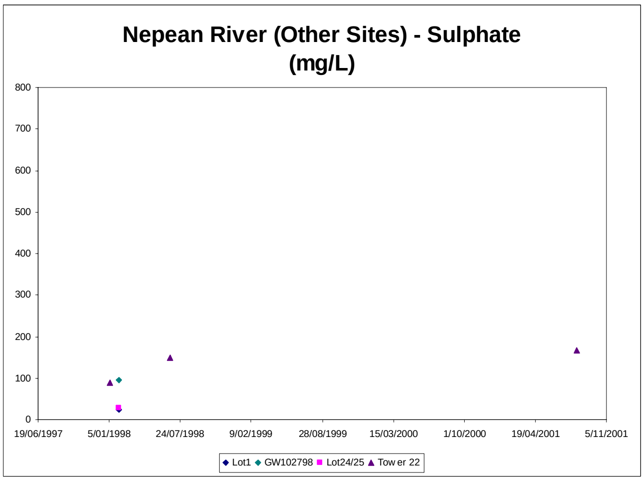


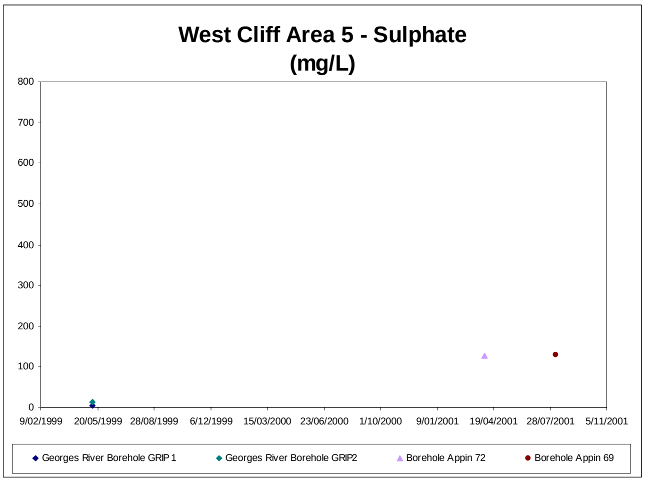
Attachment B9 **Observed Chloride Concentrations – Cataract River and Nepean River.**











Attachment B10 Observed Sulphate Concentrations – Cataract River and Nepean River.