WHITEHAVEN COAL

Narrabri Coal Operations Pty Ltd

ABN: 15 129 850 139

Narrabri Coal Mine
Stage 2 Longwall Project

Hydrogeological Assessment

Prepared by:
Aquaterra Consulting Pty Ltd

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Narrabri Coal Operations Pty Ltd

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Stage 2 Longwall Project

Hydrogeological Assessment

Prepared for:

R.W. Corkery & Co. Pty. Limited
Level 1, 12 Dangar Road
PO Box 239
BROOKLYN NSW 2083

Tel: (02) 9985 8511
Fax: (02) 9985 8208
Email: brooklyn@rwcorkery.com

On behalf of:

Narrabri Coal Operations Pty Ltd
Level 9, 1 York Street
PO Box R1113
SYDNEY NSW 1225

Tel: (02) 8507 9700
Fax: (02) 8507 9701
Email: thaggarty@whitehaven.net.au

Prepared by:

Aquaterra Consulting Pty Ltd
Suite 9, 1051 Pacific Highway
PYMBLE NSW 2073

Tel: (02) 9440 2666
Fax: (02) 9449 3193
Email: andrew.fulton@aquaterra.com.au

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EXECUTIVE SUMMARY

Background

This groundwater assessment report has been prepared by Aquaterra Consulting Pty Ltd (Aquaterra) for R W Corkery & Co Pty Ltd (Corkery) to support an application by Narrabri Coal Operations Pty Ltd (NCOPL) for the Stage 2 Longwall Project at the Narrabri Coal Mine (the Longwall Project).

In March 2007, an Environmental Assessment (EA) was lodged for Stage 1 of the Narrabri Coal Mine (Corkery, 2007), which related to the proposed development of surface infrastructure and initial underground mine development, with coal production by first workings at up to 2.5 Mtpa. Groundwater investigations were undertaken for Stage 1 during 2006 by GHD. That investigation included aquifer testing, hydrochemical analysis and groundwater modelling. Stage 1 of the Narrabri Coal Project was granted project approval by the Minister for Planning on 13 November 2007.

NCOPL is now proposing to develop Stage 2 of the mine, which comprises the development of longwall mining operations for the extraction of coal at up to 8 Mtpa. This groundwater assessment report has been prepared to support the Stage 2 Longwall Project application. The objective of this report is to provide sufficient information on the state of the groundwater environment within the Mine Site (ML1609) and surrounding areas, and to assess the potential impacts on groundwater levels and quality from development of the Longwall Project. This has been done to ensure that any concerns regarding groundwater and surface water resources, groundwater dependent ecosystems and existing groundwater users are addressed to the satisfaction of the Minister for Planning and the NSW Office of Water.

Stage 2 groundwater investigations were undertaken between June 2008 and August 2009. These investigations aimed to verify aquifer parameters by further hydraulic testing of existing boreholes and installation and testing of new monitoring boreholes, and to update impact predictions by further groundwater modelling. The monitoring network has been expanded to 26 bores, which were sampled and tested for groundwater levels, aquifer characteristics and groundwater quality.

Existing Hydrogeological Environment

Based on the findings of the Stage 1 and Stage 2 investigations, the following key conclusions have been drawn about the hydrogeology of the region about the Longwall Project:

- Two distinct aquifer types have been identified within the Longwall Project area:
  - A shallow unconfined aquifer that is found within the regolith layer (weathered bedrock), including occasional fracturing at the top of the underlying fresh rock. It occurs as a semi-continuous layer across the sub-cropping Permian-Jurassic strata. The occurrence of localised fracturing and associated higher permeability is particularly notable in the upper parts of the Garrawilla Volcanics.
  - A deeper fractured rock aquifer system that occurs throughout the stratigraphic sequence, with standing water levels generally at depths greater than 50 m below ground level.

- The Pilliga Sandstone, which forms one of the major intake beds for the Great Artesian Basin (GAB) overlaps the western part of the Mine Site, but is not saturated within the Mine Site area.
- The alluvium associated with the Namoi River to the east does not occur within the Mine Site, and the Hoskissons Seam does not sub-crop beneath the Namoi River alluvium. There is therefore no direct hydrogeological connection between the proposed mine and the Namoi River alluvium.
- Horizontal hydraulic conductivities determined from testing ranged from 3×10^{-4} m/d to 2.5×10^{-1} m/d. The highest conductivity in the rock units was recorded within the Garrawilla Volcanics within the sub-crop zone. The highest conductivities within the deeper aquifers occur within the Hoskissons Seam and underlying Arkarula Formation.
- Although higher hydraulic conductivities have been found within the subcrop zone of the Garrawilla Volcanics, high inflows from this formation have not been encountered during construction of the mine access drifts. This suggests that these more conductive zones are localised.
- Groundwater salinity is variable. Deeper groundwater is generally saline, with measured total dissolved solids (TDS) ranging up to more than 16 800 mg/L. Localised fresher groundwater zones occur in the shallow aquifers, with measured salinities as low as 100 mg/L TDS. Salinity of groundwater in the Hoskissons Seam is variable, ranging from 1350mg/L to 9070mg/L TDS.
- Major ion chemistry within the groundwater samples indicates that there are three distinct zones of water chemistry within the stratigraphic sequence. These distinct differences in groundwater quality indicate that, in the pre-mining condition, there is very little vertical connectivity between the rock strata that occur beneath the Longwall Project.

Prediction of Mining-Related Impacts

The two main potential impacts of proposed longwall mining on the hydrogeological environment were considered to be:

- Localised and to a lesser extent regional lowering of groundwater levels within the Permian-Jurassic strata, due to groundwater inflows to the mine workings, particularly as a result of enhanced permeability of the rock units within the subsidence affected zone above the longwall extraction areas. Some lowering of groundwater levels may also occur as a result of increased rock storativity due to the stress relief fracturing associated with the underground mining.
- Possible impacts on near-surface groundwater, including the alluvial groundwater system of the Namoi Valley, and groundwater baseflow contributions to the Namoi River and other surface drainages.

Subsidence predictions are that maximum subsidence would range from 1.6m in the eastern part of the longwall mining area where cover depth is around 160m, to 2.4m in the west where cover depth reaches 380m. Continuous fracturing associated with this subsidence is predicted to extend from the coal seam to below the base of the Garrawilla Volcanics, but could extend into the Garrawilla Volcanics if adverse geological conditions are encountered. The predicted height of continuous/connected fracturing therefore varies from around 45m below ground level (bgl) in the shallowest parts of the mine to around 200m bgl in the deepest parts of the mine.

The most likely hydrogeological impact is based on the expectation that continuous subsidence fracturing from the longwall panels will not intersect the more permeable sub-crop zone of the Garrawilla Volcanics. Should hydraulically continuous fracturing extend into the Garrawilla Volcanics, it has been assessed that marginally higher inflows could occur. However, the subsidence prediction is that this is unlikely.

Numerical groundwater modelling has been used to predict mine inflows and impacts on groundwater levels and baseflows, both locally and regionally. Principal findings of the modelling include the following:

- The base case predictive modelling simulation predicted that groundwater inflows to underground workings would gradually increase over the first 20 years of mining from an initial 80 ML/a (0.22 ML/d) in Year 1 to a peak inflow rate of 1394 ML/a (3.82 ML/d) in Mine Year 20, before declining steadily thereafter to a rate of 365 ML/a (1.0 ML/d) in the final year of the project.
- Large drawdowns are predicted to occur within the Permian coal measures close to the mine, as a result of groundwater flows into the mine workings. The drawdown cone is predicted to be relatively steep, and drawdowns exceeding 10 m would be limited to around 6 km to 7 km to the west, north and south, and around 2 km to the east of the underground workings. The Permian drawdown impact would extend much less to the east, where it would be limited by the truncation of the coal seam by an overlying unconformity. The region of greater than 1 m predicted drawdown in the Hoskissons Seam extends approximately 20 km to the west, 10km from the mined areas to the south and to the north, but not to the east where the seam is absent.
- Predicted groundwater level impacts in the overlying Triassic Napperby Formation at the end of mining are much less pronounced. Drawdowns of 1m or more are predicted to extend a maximum of approximately 10km to the west of the Mine Site.
- Impacts on Jurassic strata would be extremely small, and there will be effectively no measurable impact above the Purlawaugh Formation aquitard (ie. in the Great Artesian Basin beds).
- Predicted drawdowns in the surficial unconsolidated aquifer at the end of mining are very small, generally less than 1 m except for a small area immediately overlying the mine workings.
- Predicted impacts on river baseflows are very small. The most impacted river reach is the closest section of the Namoi River to the east (model reach 11). Baseflow in this reach is predicted to reduce by a maximum of around 0.22 ML/d, but this is only 2% of the total calculated baseflow contribution to this reach of around 10.3 ML/d.
- Post-mining, baseflows in all reaches of the Namoi River are predicted to recover to levels equal to pre-mining baseflows following 100 years of recovery.

- Post-mining potential for offsite migration of re-injected brine is limited to 1 km in Jurassic Strata and less than 2 km in Triassic-Permian strata after 100 years of recovery. Particle tracking simulation has shown that no saline water will migrate up into the Pilliga Formation.

Overall, these results indicate that the following impacts on water resources may occur due to the Stage 2 Longwall Project:

- There will be negligible impact on groundwater within the Pilliga Sandstone, and hence a negligible (less than 0.03ML/d) impact on recharge to the GAB.
- Negligible impacts on groundwater levels in the Namoi Valley alluvium are predicted, and existing groundwater users will not be affected.
- Continuous/connected fracturing induced by longwall mining has the potential to significantly impact groundwater stored in the fractured rock aquifers above the mine (up to the base of the Garrawilla Volcanics). The potential for impact on other local groundwater users is mitigated by NCOPL's acquisition of several properties within the anticipated zone of impact. However, a commitment to mitigate potential impacts on other groundwater users should be included within the Site Water Management Plan. One bore (WB2) located over LW26 and screened within the Garrawilla Volcanics is expected to be impacted. This bore is located on property owned by NCOPL. No other registered bores are expected to be impacted.

Sensitivity and uncertainly analysis has been carried out to assess the sensitivity of the model calibration to the assumed input parameters and boundary conditions, and the effect of uncertainty on predicted rates and impacts.

Sensitivity analysis was carried out on hydraulic conductivity (horizontal and vertical) and recharge. The model was found to be not highly sensitive to either horizontal or vertical hydraulic conductivity of the in-situ rock strata. However, model-predicted mine inflows are very sensitive to the assumed vertical hydraulic conductivities of the subsidence-affected strata directly above the extracted longwall panels, but is less sensitive to the height of connected/ continuous fracturing assumed in the modelling.

The predicted impacts from the base case model are considered to be best estimates according to experience and a thorough consideration of the hydrogeological conditions of the Longwall Project area. However, as there is no prior history of longwall mining in the Gunnedah Basin, some uncertainty in inflow predictions will remain until mining of the first few longwall panels has been undertaken, and the pattern of subsidence-fracturing and permeability changes has been monitored and evaluated. Accordingly, a range of higher than expected vertical permeabilities has been tested with the groundwater model, to provide an upper limit or worst case assessment of groundwater inflows and impacts. Monitoring of groundwater responses to the Stage 1 continuous miner operation will be of limited value, or there will be no significant subsidence associated with Stage 1. A program of careful monitoring has been recommended for the first 3 longwall panels, to provide definitive data on rock behaviour following subsidence. It is recommended also that assessment of potential mine inflows and re-calibration of the groundwater model should be carried out on a regular basis, with an initial re-evaluation 6 - 12 months after commencement of longwall extraction.

Management and Monitoring of Impacts

Although impacts from the proposed project are generally anticipated to be small, a monitoring programme and contingency response plan will be required to validate predictions and mitigate any detrimental impacts that occur during mining. Proposed recommendations for these programmes are contained within this report, and include:

- Monitoring of mine inflows and water imported into the mine for longwall operation and other underground uses.
- Monitoring of volumes pumped from any water supply or dewatering bores.
- Monthly manual monitoring, or continuous automated monitoring, of water levels/pressures from the network of monitoring bores.
- Water quality monitoring of mine inflows and groundwater in monitoring piezometers.
- Monitoring of Mayfield Spring and other springs located to the south of the mine site.
- Ongoing subsidence monitoring and monitoring of permeability changes caused by subsidence.
- Periodic data review by a suitable, experienced hydrogeologist.
- Periodic review and validation of the groundwater model predictions.

Procedures are presented for investigation and response action if data indicate that impacts on groundwater level or quality are greater than trigger values, or if complaints are received by other groundwater users.

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1. INTRODUCTION

1.1 Background

This groundwater assessment report has been prepared by Aquaterra Consulting Pty Ltd (Aquaterra) for R W Corkery & Co Pty Ltd (Corkery) to support an application by Narrabri Coal Operations Pty Ltd (NCOPL) for the Stage 2 Longwall Project at the Narrabri Coal Mine (the Longwall Project).

The Narrabri Coal Mine is located within Mining Licence (ML) 1609 and is approximately 30 km southeast of Narrabri (**Figure 1.1**).

In March 2007, an Environmental Assessment (EA) was lodged for Stage 1 of the Narrabri Coal Mine (Corkery, 2007), which related to the proposed development of surface infrastructure and initial underground mine development, with coal production by first workings using a continuous miner at up to 2.5 Mtpa.

Groundwater investigations were undertaken for Stage 1 during 2006 by GHD. That investigation included aquifer testing, hydrochemical analysis and groundwater modelling. Stage 1 of the Narrabri Coal Project was granted project approval by the Minister for Planning on 13 November 2007.

NCOPL is now proposing to develop Stage 2 of the mine, which comprises the development of longwall mining operations for the extraction of coal at up to 8 Mtpa.

Stage 2 groundwater investigations have been undertaken between June 2008 and August 2009. These investigations aimed to verify aquifer parameters by further testing of existing boreholes, obtain additional hydraulic data through the installation and testing of new monitoring boreholes, and update impact predictions by further groundwater modelling. The monitoring network has been expanded to 26 bores, which were sampled and tested for groundwater levels, aquifer characteristics and groundwater quality. The bores continue to be monitored regularly as part of an ongoing baseline monitoring program.

1.2 Report Objectives

This groundwater assessment report has been prepared in support of NCOPL’s application for the Longwall Project. The report describes the present state of the groundwater environment within the Mine Site and immediate surrounds, and assesses the potential impacts on groundwater levels and quality, and on groundwater baseflows, from the Longwall Project. This has been done to ensure that any concerns regarding groundwater and surface water resources, groundwater dependent ecosystems and existing groundwater users are addressed to the satisfaction of the Minister for Planning.

This report is structured as follows:

- Section 2 contains a summary of previous groundwater investigations undertaken in the Mine Site, pre- March 2007.
- Section 3 contains the details of the additional groundwater investigations undertaken, specifically in relation to Stage 2, between March 2007 and August 2009.

- Section 4 presents a description of the existing environment in the vicinity of the project.
- Section 5 outlines the mining proposal and gives a brief summary of the proposed operations and water supply demands of the project.
- Section 6 describes the groundwater modelling work undertaken to aid in the assessment of potential groundwater impacts of the proposed project.
- Section 7 contains a detailed outline of the potential impacts of the project on inflows, groundwater levels, groundwater quality, baseflows to Namoi River and other streams, the Great Artesian Basin, existing users, and groundwater dependent ecosystems.
- Section 8 details the monitoring and management recommendations.
- Section 9 presents recommendations for contingency response plans to address any unforeseen adverse impacts on groundwater and/or surface water.
- Section 10 provides a summary and conclusions from this study.
- Section 11 contains a list of references.

1.3 Director General's Requirements

In accordance with Section 75F of the EP&A Act, the Department of Planning has issued the Director General's requirements for the preparation of the Environmental Assessment for Stage 2 of the Narrabri Coal Project. The requirements relating to groundwater have been addressed within this report as detailed in **Table 1.1**.

Table 1.1: Director General's Requirements

Director General's Requirement	Relevant Section of Report
A description of the existing environment	Section 4
Assessment of the potential impacts of all stages of the project including any cumulative impacts associated with the concurrent operation of the project with any other existing or approved mining operation, taking into consideration any relevant guidelines, policies, plans and statutory provisions - Assessment of the potential impacts on the quantity, quality and long-term integrity of the groundwater resources.	Sections 6 and 7
Description of the measures that would be implemented to avoid, minimize, mitigate, rehabilitate/remediate, monitor and/or offset the potential impacts of the project including detailed contingency plans for managing any significant risks to the environment.	Sections 8 and 9

1.4 Relevant State Policies and Guidelines

This report has also been prepared with due consideration of relevant state policies and guidelines including:

- National Water Quality Management Strategy Guidelines for Groundwater Protection in Australia (ARMCANZ / ANZECC).

- NSW Groundwater Policy Framework Document (DLWC).
- NSW Groundwater Quality Protection Policy (DLWC).
- NSW Groundwater Quantity Management Policy (DLWC).
- NSW State Groundwater Dependent Ecosystems Policy (DLWC).
- Murray-Darling Basin Groundwater Quality Sampling Guidelines. Technical Report 3 (MDBC).
- Murray-Darling Basin Commission Groundwater Flow Modelling Guidelines (MDBC).
- NSW Great Artesian Basin Groundwater Sources Water Sharing Plan (DECCW).
- Upper and Lower Namoi Groundwater Water Sharing Plan (DECCW).
- Guidelines for the Assessment and Management of Groundwater Contamination (DEC).

1.5 Water Licensing

Groundwater licences under Part 5 of the Water Act 1912 will be required for the following activities:

- Extraction of water from the underground mine;
- Production bores for water supply or dewatering purposes; and
- Monitoring piezometers for water level and quality monitoring, and test pumping.

It should be noted that Part 5 licences will be required for any extraction of groundwater, including incidental inflows to the mine. Licensing of activities, water use, water works and approvals is currently effected under the *Water Act (1912)*. It is anticipated that the *Water Act* will be repealed in 2010, and will be replaced by the *Water Management Act (2000)* (WMA), and any Part 5 groundwater licences would be transitioned to Access Licences under the WMA.

Any discharge of surplus mine water to the environment will be managed in accordance with the site's Environmental Protection Licence.

2. PREVIOUS GROUNDWATER INVESTIGATIONS

2.1 Previous Investigations

Several previous investigations of groundwater, surface water, geology and geotechnics have been undertaken on the area within and surrounding the Mine Site. Reports that have been produced on those studies include:

- Narrabri Coal Project Groundwater Assessment: Prepared by GHD Pty Ltd, March 2007.
- Bicarbonate Occurrence in Groundwater in the Baan Baa Area, NSW: Prepared by Water Resources Consulting Services, 1997.

- Final Report – Exploration Licence 537: Prepared by ICI Australia Ltd, 1973.
- Narrabri Coal Project Surface Water Assessment: Prepared by WRM Water and Environment Pty Ltd, March 2007.
- Narrabri Coal Project Geological Assessment: Prepared by Belford Dome Resource Assessment, March 2007.
- Narrabri Coal Project Subsidence Assessment: Prepared by Mining Geotechnical Services Pty Ltd, March 2007.
- Narrabri Coal Project Groundwater Management Plan: Prepared by Coffey Geotechnics Pty Ltd, July 2008.

2.2 Lower Namoi Valley: History of Groundwater Modelling

The Namoi Valley is a palaeochannel, 3 to 10 km in width, and contains a sequence of non-marine alluvial deposits of Tertiary and Quaternary age, which range in thickness up to 120 m. The palaeochannel initially trends westerly from the town of Narrabri, and then south-westerly towards Cryon.

A mature numerical groundwater flow model exists for the saturated alluvial aquifer system of the lower Namoi Valley (i.e. the Namoi Valley north of the town of Narrabri). It has undergone a series of revisions since 1982, with changes in conceptualisation, modelling software and computer hardware. It was developed with MODFLOW finite difference software, using the PMWIN Version 5.0 graphic user interface in a Windows environment. Revisions to the groundwater model have been carried out as follows (dates next to each model refer to the timespan covered by the model run, and dates in square brackets refer to the date the model was constructed):

- Narrabri to Merah North, 1969-1981 [1982]
- Narrabri to Cryon, 1969-1982 [1984]
- Narrabri to Cryon, 1981-1986 [1989]
- Narrabri to Cryon, 1987-1994 [1995]
- Narrabri to Cryon, 1980-1994 [1998]
- Narrabri to Cryon, 1980-1998 [1999].

The conceptual model used in historical modelling comprises three aquifers:

- Layer 1: Narrabri Formation;
- Layer 2: Gunnedah Formation; and
- Layer 3: Cubbaroo Formation.

The model has been subjected to post-audit re-calibration on several occasions, and external peer review.

2.3 Upper Namoi Valley: History of Groundwater Modelling

The upper Namoi Valley is that part of the valley upstream (south) of the town of Narrabri. The Namoi River flows in a generally north-north-westerly direction, and passes some 5 km to the east of the Narrabri Stage 2 Longwall Project.

Groundwater models based on MODFLOW software also exist for the Upper Namoi Valley. The valley is flanked by a buried basement ridge on its western side and shallow basement with colluvial cover on its eastern side. Three models exist for the upper Namoi Valley (dates next to each model refer to the time span covered by the model run, and dates in square brackets refer to the date the model was constructed):.

- Upper Namoi, Gunnedah to Narrabri, 1981-1986 [1989]
- Borambil Creek, Zone 1, 1981-1986 [c1997]
- Upper Namoi, Breeza to Gunnedah, Zone 3, 1980-1996 [1999].

2.4 Summary of Groundwater Investigations Undertaken by GHD

GHD were commissioned by R W Corkery & Co Pty Ltd to undertake a groundwater assessment for Stage 1 of the Narrabri Coal Project.

This investigation included the following work:

- Drilling, installation and hydraulic testing of groundwater monitoring bores (piezometers) and test production bores.
- Groundwater level and groundwater quality monitoring.
- Collection of data on registered/licensed and other privately-owned groundwater sources.
- Review of hydrogeological and other relevant reports produced for Narrabri Coal Pty Ltd.
- Numerical groundwater modelling for predicting potential impacts.

The results of this investigation were presented in GHD (2007). RCA (2007) were also engaged to conduct separate hydraulic tests on the Stage 1 piezometers.

2.4.1 Stage 1 Piezometer / Monitoring Bore Installation

Thirteen monitoring bores were installed at nine locations across EL6243. Construction details and the geological formations targeted in each monitoring bore are summarised in **Table 2.1**.

Table 2.1: Stage 1 Groundwater Monitoring Bore Construction Details

Bore ID	Bore Depth (m)	Bore Diameter (mm)	Screen Interval (mbgl)	Target Formation
NC100S	30	150	24 – 30	Garrawilla Volcanics
NC100D	78	100 - 125	72 – 78	Napperby Formation above sill
NC98S	30	150	24 - 30	Garrawilla Volcs / Napperby Formation
NC98D	90	100 – 125	84 - 90	Napperby Formation above sill
NC30S	50	150	44 - 50	Napperby Formation (no sill at bore site)
NC30D	130	100 – 125	118 – 130	Napperby Formation (no sill at bore site)
GWB4S	63	150	57 - 63	Purlawaugh Formation
GWB5S	30	150	24 – 30	Purlawaugh Formation
NC119S	56	150	47 - 56	Purlawaugh Formation
NC119D	146	100 - 125	137 - 146	Garrawilla Volcanics
NC122	146	100 - 125	143 - 146	Hoskissons Coal Seam
NC123R	187	100 - 125	184 - 187	Pamboola Formation
NC127	162	100 - 125	159 - 162	Arkarula Formation

GHD (2007) reported that piezometer locations were distributed across the Longwall Project area with the aim of facilitating sampling, testing and monitoring of groundwater in the Hoskissons Coal Seam (the target seam for coal extraction) and the other lithological units above and below the target seam.

Piezometers targeting the deeper formations (NC30D, NC98D, NC100D, NC119D, NC122, NC123R, and NC127) were installed in existing exploration drill-holes. Shallow piezometers monitoring the water table aquifer (NC98S, NC30S, NC119S, and NC100S) were installed adjacent to four of the deeper piezometers to provide data on shallow groundwater, so that any differences in water level with depth could be assessed, as well as differences in water quality. Two other shallow piezometers were installed, one in the south western quadrant of the site and the other west of the ventilation shaft location (GWB4S and GWB5S respectively).

The logs and construction details for the piezometers installed by GHD as part of the Stage 1 groundwater assessment indicate that they were constructed in accordance with the minimum requirements for monitoring bore construction, as outlined by the National Minimum Bore Specifications Committee (2003).

2.4.2 Stage 1 Hydraulic Testing

Falling Head Tests

With the exception of piezometers NC30D, NC100D and NC119D, each monitoring bore was hydraulically tested using the falling-head, slug permeability test method (GHD, 2007). The test involved the insertion of a solid bailer into the bore, which temporarily raised the water level in the bore. The progressive recovery of the water level back to the equilibrium standing water level was monitored, and the results analysed to determine values of average hydraulic conductivity (permeability).

Results of the bore hydraulic testing undertaken by GHD and RCA are summarised in **Table 2.2**. For reference, the results of all tests are presented in the Stage 1 groundwater assessment report (GHD, 2007; RCA, 2007).

Table 2.2: Falling Head Testing Results (GHD, 2006 and RCA, 2007)

Bore ID	New Bore ID	Screen Interval (m bgl)	Hydraulic Conductivity (m/d)		Target Formation
			GHD – 2006	RCA - 2007	
GWB4S	-	57 – 63	1.1 x 10^{-3}	-	Purlawaugh Formation
GWB5S	P9	24 – 30	4.1 x 10^{-1}	-	Purlawaugh Formation
NC100S	P15	24 – 30	4.7 x 10^{-2}	-	Garrawilla Volcanics
NC98S	P13	24 – 30	6.8 x 10^{-2}	-	Garrawilla Volcanics / Napperby Formation
NC98D	P12	84 – 90	1.6 x 10^{-3}	-	Napperby Formation above sill
NC30S	P11	44 – 50	7.0 x 10^{-4}	-	Napperby Formation (no sill at bore site)
NC122	P18	143 – 146	8.6 x 10^{-3}	8.6 x 10^{-3}	Hoskissons Coal Seam
NC127	P20	159 – 162	1.2 x 10^{-2}	1.2 x 10-^{2}	Arkarula Formation
NC123R	P19	184 – 187	2.1 x 10^{-3}	2.8 x 10^{-3}	Pamboola Formation

Permeability tests undertaken by GHD in March 2006 were evaluated using the Bouwer Rice Method (Bouwer and Rice, 1976) for both unconfined aquifers in the shallow holes and the confined aquifers in the deeper holes. Hydraulic testing undertaken by RCA in February 2007 was evaluated using the Hvorslev method (Hvorslev, 1951).

Sigra Permeability Testing

Drill stem testing (DST) or packer testing was undertaken by Sigra at eight locations in 2006. **Table 2.3** provides a summary of the test locations, tested intervals, hydraulic conductivity results and target formations for the Sigra permeability tests.

Table 2.3: Sigra Permeability Test Results

Location ID	Depth (m bgl)	Hydraulic Conductivity (m/d)	Target Formation	Comments
NC93	301.1 - 313.4	4.21 x 10^{-3}	Hoskissons Coal Seam / Arkarula Formation	Formation Pressure 252.5 m AHD
NC99	179.8 - 210.3	1.26 x 10^{-2}	Hoskissons Coal Seam / Arkarula Formation	Formation Pressure 250.2 m AHD
NC100	147.4 - 130.0	9.17 x 10^{-5}	Dolerite Sill	Negligible Inflow Formation Pressure 261.8 m AHD
NC100	147.5 - 177.3	8.34 x 10^{-6}	Napperby Formation below sill	Negligible Inflow Formation Pressure 248.8 m AHD
NC100	174.6 - 195.0	9.17 x 10^{-5}	Digby Formation	Negligible Inflow Formation Pressure 266.9 m AHD
NC100	197.9 - 212.5	4.00 x 10^{-3}	Hoskissons Coal Seam / Arkarula Formation	Formation Pressure 265.8 m AHD
NC 98	9.7 –24.0	Approx 8	Garrawilla Volcanics	Fast Recovery, very High permeability

Location ID	Depth (m bgl)	Hydraulic Conductivity (m/d)	Target Formation	Comments
NC 98	26.1 - 92.4	8.01 x 10^{-1}	Sill / Napperby Formation / Garrawilla Volcanics	Fast Inflow, High Permeability
NC 98	94.3 - 117.1	8.34 x 10^{-1}	Dolerite Sill	Fast Inflow, High Permeability
NC 98	147.8 - 165.5	1.42 x 10^{-4}	Digby Formation	Negligible inflow Formation Pressure 256.2 m AHD
NC98 1	61.5 - 174.1	3.67 x 10^{-5}	Hoskissons Seam / Arkarula Formation	Approx Formation Pressure 252.7m AHD
NC 110	310.1 - 327.1	1.92 x 10^{-2}	Digby Formation / Hoskissons Seam / Brigalow Formation	Formation Pressure 261.5 mAHD
NC 111	154.4 - 174.0	1.00 x 10^{-2}	Digby Formation/ Hoskissons Seam / Arkarula Sandstone	Formation Pressure 262.4 mAHD
NC 114	356.3 - 368.5	4.09 x 10^{-4}	Digby Formation/ Hoskissons Seam / Arkarula Sandstone	Formation Pressure 271.1 m AHD
NC114	368.0 - 372.2	1.00 x 10^{-1}	Brigalow Formation	Formation Pressure 268.5 m AHD
NC 115	157.7 - 165.3	1.96 x 10^{-3}	Digby Formation / Hoskissons Seam / Arkarula Formation	Formation Pressure 258.0 m AHD
NC 115	166.3 - 171.3	1.15 x 10^{-5}	Arkarula Formation	Formation Pressure 258.9 m AHD

Minor shallow groundwater inflows were reported at NC99 in the Purlawaugh Formation (assumed), while significant inflows were reported in NC98 from 9.7 - 24.0 m bgl, 26.1 - 92.4 m bgl and 94.3 - 117.1 m bgl in the Garrawilla Volcanics, Sill/Napperby Formation/Garrawilla Volcanics, and the Dolerite Sill respectively. It should be noted that the core sample at NC98 was observed by Sigra to be highly weathered and fractured. No groundwater inflows were reported at NC93, NC100, NC110, NC111, NC114 and NC115.

Comparison of falling head test results (GHD, 2007; and RCA, 2007) and drill stem permeability test results (Sigra, 2006) is only possible at NC98. Estimated hydraulic conductivity values differ significantly, with the falling head method (GHD, 2007) giving values two orders of magnitude lower than those estimated using the drill stem method. It is likely that this was due to the different test length used in the two assessments, where GHD testing was conducted over a 6 m interval and Sigra over 14 m and 66 m intervals. Generally speaking the longer the test length interval, the greater the chance that the testing intercepts a zone of higher fracture density, which will result in a much higher recorded permeability.

Core Permeability Testing

Core samples from the Digby Formation, Hoskissons Seam, Arkarula Formation, Brigalow Formation and Pamboola Formation from exploration holes NC123R, NC125, NC126 and NC127 were submitted to CSIRO for permeability testing. Core testing was undertaken to provide data on the matrix permeability of the different formations. However, as groundwater flow is largely dependent on fracture permeability, values of matrix permeability were of limited value in the evaluation of hydraulic conductivity for the numerical groundwater flow modelling.

2.4.3 Other Hydraulic Testing

Aquifer testing was undertaken by ICI in 1973 at registered bore GW017215 (northeast of the Mine Site) and indicated a transmissivity of 0.2 m^2/d in the Pamboola Formation. Bore GW038662 intersected flows of stock quality water at 0.75 L/s at 19 m bgl, and 0.13 L/s sodium bicarbonate water at 128 m bgl (Melville Coal Seam).

To the west of the Mine Site, petroleum companies have drilled numerous wells in the thicker sequences of the Mullaley Sub Basin. **Table 2.4** presents a summary of permeability values derived from testing of the petroleum wells.

Table 2.4: Summary of Permeability Data from Regional Petroleum Wells

Location ID	Test Depth (m bgl)	Permeability (m/d)	Target Formation
Bohena 2 DST6	580	6.3×10^{-2}	Digby Formation
Bohena 2 DST1	671	2.1×10^{-4}	Hoskissons Coal Seam
Bohena 6 DST	671	1.7×10^{-4}	Hoskissons Coal Seam
Wilga Park 1 DST	422	1.4×10^{-1}	Black Jack Group (Sandstone) above Hoskissons Coal Seam
Coonarah 1A DST	516	2.5×10^{-3}	Hoskissons Coal Seam and Arkarula Formation

Comparison of these results with site specific permeability testing undertaken by GHD, RCA and Sigra indicate variable differences, with some tests showing higher permeabilities and some tests showing lower permeabilities within the same formations. Differences are up to two orders of magnitude in the Hoskissons Coal Seam and Arkarula Formation, and three orders of magnitude in the Digby Formation. It should be noted that permeability testing undertaken by the petroleum companies was at depths in excess of 400 m below ground level (bgl) and over unknown test lengths. Therefore limited comparative evaluation of these results can be made.

2.5 Groundwater Flow Regime

GHD (2007) indicated that, based on a report completed by Water Resources Consulting Services in 1997, the regional groundwater flow direction in the Permo-Triassic units of the Baan Baa area is influenced by recharge to the sub-cropping ridges and discharge to local drainage features or overlying alluvials. Water entering the Surat Basin Jurassic sandstone outcrops is described as moving down-gradient or down-dip towards the Surat Basin and the GAB.

GHD also reported that, based on the 1:1,000,000 hydrogeological map of the Darling River drainage basin (AGSO, 1995), groundwater flow in the Jurassic sediments in the western parts of the Mine Site is northwest towards the central area of the Surat Basin. Within and east of the Mine Site in the Permo-Triassic sediments, groundwater flow is east towards the Namoi River. GHD also noted that a groundwater divide between fresher waters of the Jurassic sediments (<500 mg/L TDS) and the brackish waters of the Permo-Triassic sediments occurs within the subcrop area of the Pilliga Sandstone (middle to late Jurassic).

2.6 Surface Water

The Namoi River is located between 3 km and 8 km east and northeast of the Longwall Project. The Mine Site lies within the Namoi Catchment Management Authority Area.

GHD also identified several unnamed ephemeral creeks draining across the Mine Site, flowing east and north-east towards the Namoi River. Other surface drainages include Pine Creek located in the northern part of the site, and Kurrajong Creek in the southern and central part of the site. Flow in these creeks is described as intermittent, with no data on flow rates or water quality available for review at the time the study was undertaken. A surface water divide was identified to the west of the Mine Site, resulting in drainage towards Jack Creek (west) on the western side of the divide and drainage towards the Namoi River on the northern side of the divide.

GHD (2007) reported that surface water consultants WRM Water and Management (2006) made the following comments during a site visit following a rainfall event:

- No evidence of baseflow to the creeks was observed.
- Significant flow velocities are likely to occur, evidenced by erosion in the creek beds.
- No evidence of the presence of wetlands within the Mine Site was observed during site inspection.
- Numerous farm dams located in areas near the Mine Site collect surface water runoff from rainfall for water supply, and may act as localised recharge sources to the water table.

2.7 Groundwater Monitoring Program

2.7.1 Groundwater Levels

Groundwater levels were recorded by GHD in monitoring bores prior to permeability testing and sampling. GHD (2007) reported that RCA also recorded standing water levels in all bores as part of the February 2007 field investigations. Groundwater level data recorded from April 2006 to February 2007 are included, along with data from the current investigations, within **Table 3.1** in the next section of this report.

A water level contour map of the shallow aquifer water table was produced by GHD based on groundwater levels recorded in February 2007 and reduced to the Australian Height Datum (AHD). This map indicates that groundwater in the shallow aquifer is flowing north-east across the site towards the Namoi River. This is consistent with published groundwater flow directions for the shallow Jurassic sediments in the area. No groundwater level contour map was produced for potentiometric levels in the deeper Permo-Triassic Black Jack Formation.

2.7.2 Groundwater Quality

GHD (2007) reported that ten groundwater samples were collected during the 2006 exploration drilling program and submitted for laboratory analysis of pH, electrical conductivity (EC), major anions and cations, heavy metals (As, Cd, Cr, Cu, Ni, Pb, Zn, Hg), iron and manganese.

Groundwater samples were also collected by Water Resources Consulting Services (1997) from six supply bores within 5 km of the Mine Site in 1997. Eastern Star Gas and Whitehaven Coal Mining Pty Ltd provided groundwater quality data for bores intersecting the Hoskissons Coal Seam to the west and approximately 60 km south (Sunnyside Mine) of the Mine Site respectively. No information on sample collection methodology for these groundwater samples was detailed in the GHD report.

The GHD evaluation of groundwater data from the vicinity of the Mine Site indicated pH to be in the neutral to slightly alkaline range (6.0 to 8.7 pH units). Salinity results ranged from fresh (<1000 mg/L TDS) in the Garrawilla Volcanics and Napperby Formation to saline (>15 000 mg/L TDS) in the Purlawaugh Formation and the Basalt Sill.

Table 2.5 presents a summary of these results.

Table 2.5: Summary of Groundwater pH and Salinity Data

Formation	**Number of Samples**	**Groundwater pH**	**Groundwater TDS (mg/L)**
Purlawaugh Formation	4	6.25 – 8.0	1 140 – 16 250
Garrawilla Volcanics	6	6.27 – 8.1	684 – 11 400
Napperby Formation	6	6.65 – 7.9	708 – 10 200
Basalt Sill	3	7.4 – 8.7	1 860 – 16 250
Napperby Formation (below Sill)	1	7.8	8 310
Digby Formation	0	-	-
Hoskissons Coal Seam	1	8.5	1 350
Arkarula Formation	1	7.05	7 740
Pamboola Formation	1	6.01	7 140

It should be noted that no saturated Pilliga Sandstone was intersected within the Mine Site.

A Piper Trilinear diagram of all groundwater data available within a 5 km radius was plotted for comparison of groundwater signatures (reproduced as **Figure 2.1**). GHD identified two groundwater types based on ionic composition, principally the dominant anions. Eight of the 23 groundwater samples analysed indicated bicarbonate as the dominant anion while the other 15 samples were dominated by chloride. The groundwater samples with bicarbonate dominance were representative of a range of formations from the Garrawilla Volcanics through to the Black Jack Group. High bicarbonate groundwater was identified along the outcrop of the Permo-Triassic sedimentary rocks on the eastern margin of the Bohena Trough, likely sourced from dawsonite mineralisation in coal seams. Further discussion about the groundwater geochemistry is provided in **Section 4.5** of this report.

An overall evaluation of water quality results indicated that in general, the groundwater is brackish, with salinity generally ranging from 5 000 to 15 000 mg/L TDS. Localised fresher zones predominate in areas where the Garrawilla Volcanics subcrop, and groundwater in the Black Jack Group formations is generally greater than 7 000 mg/L TDS (brackish). In areas where the Hoskissons Coal Seam is shallow and proximal to the Boggabri Ridge, groundwater is less saline.

2.8 Beneficial Use Assessment

GHD (2007) reported that other potential beneficial uses for groundwater in and around the Mine Site may include:

- Agricultural – including limited irrigation use and some livestock watering which would be dependent upon feed type. It is noted that numerous registered stock bores exist in the region.
- Recreation – groundwater quality results fall within the guidelines for all recreational uses. No data on groundwater discharge to surface drainages is available for evaluation, and therefore it is assumed that these guidelines are applicable.
- Groundwater Dependent Ecosystems (GDE) – no GDEs were identified prior to the GHD study; however provision for future identification has been made based on the known presence of deep-rooted vegetation in the area. These guidelines were therefore deemed applicable.
- Published hydrogeological maps of the area indicate that groundwater present in the Pilliga Sandstone is fresh (<500 mg/L) and may therefore be suitable for potable use. Numerous registered domestic and stock bores west and northwest of the Longwall Project indicate that potable water guidelines are applicable. It should be noted that site drilling indicated that the Pilliga Sandstone is unlikely to be saturated within the Mine Site.

2.9 Census of Groundwater Occurrence and Use

As part of the Stage 1 groundwater investigations, information on existing groundwater occurrence and use was collated by GHD from various sources. These included the NSW Office of Water (NOW)[1] groundwater bore data (information on registered groundwater bores), on-site exploration holes and monitoring bores, off-site exploration holes and monitoring bores, published hydrogeological maps and previous regional hydrogeological investigations. This data was used to identify groundwater supply sources such as bores, wells, soaks and dams, and any naturally discharging springs and soaks, as well as to aid in characterising local and regional aquifer formations.

2.9.1 Registered Bores

GHD identified 18 registered groundwater bores within a 5 km radius of the Mine Site. These bores were grouped into four categories:

- North – Two registered groundwater bores located north of the Longwall Project, which likely intersect the Gunnedah Basin sediments. Groundwater at these bores is reported as being 'very salty' and low yielding (0.6 L/s).

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[1] The NSW Office of Water (NOW) was formerly known as Department of Water and Energy (DWE), and is now incorporated in the Department of Climate Change and Water (DECCW).

- South – Five registered groundwater bores intersecting a range of formations down to the basement volcanics are located south of the site. These bores are typically low yielding (<0.25 L/s) and are used for stock and domestic purposes. Standing water levels range between 10 and 40 m bgl.
- West and Northwest – Eleven registered bores, for stock and domestic use. These bores likely intersect the Pilliga Sandstone and other deeper Jurassic sediments, and report yields ranging between 0.1 and 0.8 L/s. These bores are described as producing 'good' quality water, with water levels ranging from 30 to 80 m bgl.

Thirteen of the above groundwater bores were registered for domestic and stock purposes (three of which were found to have been backfilled). Two of the registered bores were drilled as part of the ICI groundwater exploratory program.

Numerous registered groundwater bores intersecting the Quaternary alluvium of the Namoi River Valley are present east of the Mine Site. These bores are typically shallow and are used for stock, domestic and irrigation purposes. Some are deeper (up to 80 m deep) and are used for irrigation, reported as yielding up to 90 L/s.

2.9.2 Exploration Data

In total, 33 groundwater intersections were noted during drilling, from a total of 98 holes. Airlift tests using a V-notch weir were undertaken at several holes with significant groundwater intersections, and measured flows ranged from 0.13 to 0.78 L/s. The highest frequency of intersections was made between 5 and 45 m bgl (67%), followed by 21% at greater than 100 m bgl, with the remaining 12% between 50 and 75 m bgl. It should be noted that 72% of significant inflows (>0.14 L/s) were reported at depths greater than 50 m bgl. Groundwater intersections were generally associated with fractures, with aquifers being generally laterally discontinuous across the area (Belford Dome, 2006; GHD, 2007).

Table 2.6 presents a summary of groundwater intersection data from exploration drilling (separation into 'minor', 'moderate' and 'significant' inflows is as reported in GHD (2007)).

Table 2.6: Summary of Groundwater Intersections during Exploration Drilling

Formation	No of Groundwater Intersections	Minor (<0.1 L/s)	Moderate (0.1 to 0.14 L/s)	Significant (>0.14 L/s)
Purlawaugh Formation	10	5	1	2
Garrawilla Volcanics	6	1	1	4
Napperby Formation	10	1	-	7
Basalt Sill	4	-	-	3
Napperby Formation (below Sill)	3	-	-	2
Digby Formation	0	-	-	-
Hoskissons Coal Seam	0	-	-	-
Arkarula / Brigalow / Pamboola Formations	0	-	-	-

- Denotes no recorded inflows.

2.10 Stage 1 Groundwater Modelling

A 3-dimensional groundwater flow model was developed by GHD to evaluate impacts from mine dewatering on local groundwater levels and registered groundwater users. Steady state modelling was carried out to simulate pre-mining conditions. Groundwater inflows to the underground workings were simulated using transient modelling. The modelling was carried out using the finite-difference groundwater flow modelling code MODFLOW 2000 (Harbaugh et al, 2000).

2.10.1 Hydrostratigraphy

GHD (2007) used an 11 layer model to simulate the groundwater flow regime for the Stage 1 Project.

Layers 1 to 4 represented the Jurassic Surat Basin formations which comprise the GAB intake beds. Layers 5 to 11 simulated the deeper Permo-Triassic Gunnedah Basin sequence.

Layer 9, representing the Hoskissons Coal Seam, was assigned a uniform thickness across the model. All layers were allowed to vary between confined and unconfined conditions depending on groundwater levels.

Definition of the model layers was based on:

- Stratigraphic logs from the Narrabri Coal NC series drilling
- Summary logs of the DME Narrabri DDH drilling undertaken in the 1980s
- Stratigraphic interpretations from four petroleum wells within the model domain
- Structure contours from the Consolidated Petroleum 1983 report.

2.10.2 Aquifer Parameters

Hydraulic conductivity values used by GHD for model layers were based on the geometric mean of field permeability test results from each formation. Where no site test data was available, GHD adopted regional data or assumed values based on lithology. With the exception of Layer 6, where vertical and horizontal hydraulic conductivities were assigned the same value in order to represent the vertical fracturing observed in the Basalt Sill, vertical hydraulic conductivity values were set at one order of magnitude lower than the horizontal hydraulic conductivity values across the model domain.

Layer 10, representing the Brigalow and Arkarula Formations, the Hoskissons Coal Seam and the Pamboola Formation was divided into 3 north-south bands to reflect the lateral distribution of each of these formations across the Longwall Project area.

The adopted hydraulic conductivity values were used for the steady state model calibration run, and were increased by one order of magnitude in selected model layers for model sensitivity evaluation and potential inflow estimation.

2.10.3 Results

Groundwater inflows into the mine were predicted by GHD to gradually increase to 1.3 ML/d over the first 22 years, reach a maximum of 2.2 ML/d at Year 24 and then decline and stabilise at around 1.9 ML/d to Year 50.

If the hydraulic conductivity of the Hoskissons Coal Seam were increased by an order of magnitude to 0.02 m/d (ie. 1000% increase), predicted inflows increased by only around 30%. Initial inflows of 0.1 ML/d were predicted to increase to a peak rate of approximately 2.9 ML/d at year 25 and then to decrease to 2.2 ML/d by the end of mining (Year 50). Other sensitivity studies undertaken by GHD demonstrated that an increase in the hydraulic conductivity of the Arkarula Formation by an order of magnitude to 0.03 m/d resulted in predicted inflows increasing by only 7%.

The greatest impact from the Stage 1 development was predicted to be in the Gunnedah Basin formations. Groundwater drawdowns in the Hoskissons Coal Seam were predicted to be greater than 100 m within 1 km to 2 km of the underground workings after 50 years. Predicted drawdown rapidly decreased to less than 10 m around 6 km to 7 km to the west, north and south of the underground workings. The drawdown extent to the east was significantly less and was limited by the subcrop of the coal seam. The area of greater than 1m drawdown in the Hoskissons Coal Seam was predicted to extend approximately 10 km to the west and south, and 8 km to the north, after 50 years.

3. STAGE 2 GROUNDWATER INVESTIGATIONS

3.1 Overview and Purpose of Stage 2 Investigations

The Stage 1 investigations assessed impacts from coal recovery by continuous miner, with an annual production rate of up to 2.5 Mtpa. The Stage 2 investigations presented within this report focus on the assessment of impacts resulting from conversion of the approved Narrabri Coal Mine to a longwall mining operation with a maximum production rate of 8 Mtpa.

3.2 Site Investigations

3.2.1 Groundwater Monitoring Bores

Additional monitoring bores have been installed within the Longwall Project area since the completion of the Stage 1 groundwater assessment, increasing the monitoring bore network to 28. Of these, two (NC175 and NC179) are multi level vibrating wire monitoring bores. In addition, eleven registered water supply bores have been identified for inclusion in the monitoring network, subject to access and landholder approval. Details are listed in **Table 3.1**. The monitoring bores target all the principal hydrogeological units, as well as providing a broad geographical network across the Longwall Project area. The locations of all piezometers and registered bores in the monitoring network are shown on **Figure 3.1**.

Twenty-one monitoring bores have been completed as stand-pipe piezometers, from which both groundwater level and groundwater quality data can be collected as part of NCOPL's ongoing environmental monitoring program. Seven coal exploration holes located close to the entry drift of the initial longwall panels have been installed with vibrating wire (VW) piezometers before being grouted up. Five bores have a single VW piezometer, and two are multi-level bores with four or more VW piezometers at different levels. The VW piezometer bores are monitored for groundwater level/pressure only.

All standpipe piezometers were installed in existing coal exploration holes drilled at diameters of 100 mm or 125 mm. Each bore was cased with 50mm diameter PVC casing with a screen adjacent to the desired monitoring interval. The bore annulus was gravel packed over the target monitoring interval, and a bentonite seal set above and below the screened zone to ensure that the screened section was isolated. The remainder of the annulus above the bentonite seal was then backfilled with cement grout. All piezometers were completed at surface with a concrete block, to prevent ingress of surface runoff or contamination, and secured within a padlocked steel monument.

The assessment of which formations are screened by the monitoring bores has been based on geological logs provided by Earth Data and information provided by NCOPL.

Monitoring includes groundwater level and field quality measurements on a monthly to annual basis, and groundwater quality sampling for laboratory analysis on a quarterly to annual basis.

No regulatory guidance for monitoring of groundwater impacts from coal mining within the Gunnedah Basin currently exists. However, it is likely that the principles similar to those set out within the NOW’s draft groundwater monitoring guidelines for the Hunter Region (DIPNR, 2004) will be required by NOW. The number of observation points available for monitoring at the Stage 2 Longwall Project marginally exceeds the minimum requirement within the Hunter Region guidelines.

3.2.2 Census of Groundwater Use

An updated search of the NOW database of registered bores close to the project has been conducted, and revealed that many of the registered bores either were non-existent or could not be found. The age of installation in some cases indicates that they are likely to have been abandoned for some time. Visual surveys have also revealed a number of existing bores, some with active windmills, which are unregistered or missing from the DECCW database. Although unregistered, potential impacts on these groundwater bores needs to be included in the impact assessment.

Table 3.1: Groundwater Monitoring Bores (August 2008)

New Bore ID	Former Bore ID	MGA Coordinates		Bore Depth (m)	Bore Diameter (mm)	Screen Interval	Water Level (September 2008)		Formation
		Easting	Northing			(m bgl)	(m bgl)	(m AHD)	
Standpipe Piezometers:									
P1	NG1	776116	6614694	50	100 - 125	44 – 50	42.82	272.51	Garrawilla Volcanics
P2	NG2	777282	6616355	50	100 - 125	44 – 50	29.88	246.28	Napperby Formation
P3	NG3	780433	6620115	45	100 – 125	34 – 40	9.77	226.43	Pamboola Formation
P4	NG4	777490	6625553	30	100 – 125	24 – 30	17.99	230.8	Napperby Formation
P5	NG5	778180	6628195	30	100 – 125	24 – 30	26.56	209.41	Pamboola Formation
P6	NG6	772726	6626021	90	100 – 125	78 – 90	89.11	237.15	Pilliga Sandstone
P7	NG7	768998	6624338	90	100 – 125	78 – 90	62.87	221.69	Pilliga Sandstone
P8	NC110S	772697	6618421	65	100 - 125	57 – 63	50.53	271.56	Purlawaugh Formation
P9	GWB5S	775127	6620209	30	150	24 – 30	19.66	267.8	Purlawaugh Formation
P10	NC30D	774063	6616444	130	100 - 125	118 – 130	20.03	249.17	Napperby Formation (no sill)
P11	NC30S	774066	6616447	50	150	44 – 50	22.91	280.1	Napperby Formation (no sill)
P12	NC98D	776513	6619964	90	100 - 125	84 - 90	36.49	239.77	Napperby Formation above sill
P13	NC98S	776526	6619972	30	150	24 - 30	9.43	268.13	Garrawilla Volc/Napperby Formation
P14	NC100D	775221	6622816	78	100 - 125	72 – 78		205.41	Napperby Formation above sill
P15	NC100S	775221	6622818	30	150	24 – 30	Dry	N/A	Garrawilla Volcanics
P16	NC119D	772233	6623740	146	100 - 125	137 - 146	50.52	247.29	Garrawilla Volcanics
P17	NC119S	772222	6623712	56	150	47 - 56	57.3		Purlawaugh Formation
P18	NC122	776826	6621802	146	100 - 125	143 - 146	13.16	258.2	Hoskissons Coal Seam
P19	NC123R	776827	6621543	187	100 - 125	184 - 187	16.16	255.9	Pamboola Formation
P20	NC127	776482	6621837	162	100 - 125	159 - 162	13.48	259.15	Arkarula Formation

New Bore ID	Former Bore ID	MGA Coordinates		Bore Depth (m)	Bore Diameter (mm)	Screen Interval	Water Level (September 2008)		Formation
		Easting	Northing			(m bgl)	(m bgl)	(m AHD)	
Vibrating Wire Piezometers (March 2009)									
P21	-	776851	6620363	200	100 - 125	160	22.5	253.82	Hoskissons Coal Seam
P22	-	776745	6620406	180	100 - 125	165	23.84	250.28	Hoskissons Coal Seam
P25	-	776703	6620326	200	100 - 125	165	28.6	246.19	Hoskissons Coal Seam
P26	-	776537	6620528	200	100 - 125	176	28.64	246.77	Hoskissons Coal Seam
P27	-	776531	6620485	180	100 - 125	176	28.29	247.07	Hoskissons Coal Seam
-	NC175	776226	6620693	199	100 - 125	45	24.26	262.74	Garrawilla Volcanics
						120	46.32	240.68	Basalt Sill
						170	36.42	250.58	Digby Formation
						185	39.24	247.76	Hoskissons Coal Seam
-	NC179	776675	6621043	181	100 - 125	36	14.77	259.23	Base of weathering
						112	48.43	225.57	Laminite (?Napperby Fm)
						148	26.86	247.14	Digby Formation
						166	26.64	247.36	Hoskissons Seam
						180	31.96	242.04	Arkarula Formation
DECCW Registered Bores									
WB1	GW038662	777251	6622763	N/A	N/A	?	9	N/A	Alluvium
WB2	GW966836	776382	6619701	N/A	N/A	22 – 26	9	N/A	Garrawilla Volcanics
WB3S	GW030229	779133	6631524	N/A	N/A	8.2 – 8.5	8.6	N/A	Alluvium
WB3D	GW030229	779133	6631524	N/A	N/A	35.1 – 36.3	8.5	N/A	Alluvium
WB4	GW030230	778957	6629746	N/A	N/A	11.3 – 15.9	8.9	N/A	Alluvium
WB5S	GW036004	785892	6618196	N/A	N/A	11 – 14.5	11.1	N/A	Alluvium
WB5D	GW036004	785892	6618196	N/A	N/A	26.5 – 28	11.2	N/A	Alluvium
WB6S	GW036005	786976	6615621	N/A	N/A	11.5 – 13	14.8	N/A	Alluvium
WB6D	GW036005	786976	6615621	N/A	N/A	76.7 – 78	12.2	N/A	Alluvium
WB7	GW038200	784440	6620521	N/A	N/A			N/A	Alluvium
WB8	GW043315	777682	6623409	N/A	N/A	27.4 – 29.8		N/A	Alluvium

3.2.3 Groundwater Levels/Pressures

Monitoring of groundwater levels has been undertaken by NCOPL in accordance with its Groundwater Monitoring Plan. Groundwater levels have been monitored in all 21 standpipe bores, 7 vibrating wire piezometer bores and 11 registered bores (WB1 to WB12).

Groundwater levels in most bores have generally been very stable, with little influence from direct rainfall recharge. Bores that have been monitored, and the relevant formation monitored in each case, are listed in **Table 3.1**. Hydrographs of groundwater levels are included in **Appendix A**.

A number of vibrating wire piezometers located near the mine entry drift have shown a marked drawdown response in the Hoskissons Seam and Digby Formation to pumping from gas drainage test bores between April and July 2009. Drawdowns of up to 40 m have been observed. Hydrographs of groundwater level responses to the gas drainage testing are included in **Appendix K**.

3.2.4 Hydraulic Testing

Testing of aquifer characteristics was undertaken by Aquaterra in August 2008. Tests were conducted on the new monitoring bores constructed during the Stage 2 studies, and some of the Stage 1 monitoring bores were re-tested to verify results recorded during the earlier investigation.

Falling head slug tests were carried out in most instances, involving the introduction of a slug of water, and monitoring the falling heads with a digital data logger. The slug test data were analysed using the Bouwer-Rice method (Bouwer and Rice, 1976) for tests on unconsolidated sediments (alluvium and colluvium), and the Hvorslev Method (Hvorslev, 1951) for tests on the hard rock units. These methods of analysis assume that the entire length of the screened interval in the test well is saturated; however in many cases this condition was not met. In such cases, an adaptation of the Bouwer and Rice method was applied, which accounts for conditions in which the bore is screened across the water table (i.e. where the test interval includes saturated and unsaturated components).

A constant rate test was carried out on bore P13, using a low capacity pump. A successful pumping test was also carried out on one of the station bores on the “Claremont” property.

The results are summarised in **Table 3.2** and the bore test analysis shown in **Appendix B**.

Table 3.2: Permeability Testing Results (GHD - 2006; RCA – 2007; Aquaterra - 2008)

New Bore ID	Former Bore ID	Screen Interval (m bgl)	Hydraulic Conductivity (m/day)				Target Formation
			GHD 2006	RCA 2007	Aquaterra 2008		
					Method		
P1	NG1	44 – 50	-	-	Slug	0.11	Garrawilla Volcanics
P2	NG2	44 – 50	-	-	Slug	0.057	Napperby Formation
P3	NG3	34 – 40	-	-	Slug	0.03	Pamboola Formation
P4	NG4	24 – 30	-	-	Slug	0.004	Napperby Formation
P5	NG5	24 – 30	-	-	Slug	0.002	Pamboola Formation
P6	NG6	78 – 90	-	-	Slug	0.029	Pilliga Sandstone
P7	NG7	78 – 90	-	-	Slug	0.19	Pilliga Sandstone
P8	NC110S	57 – 63	-	-	Slug	0.017	Purlawaugh Formation
P9	GWB5S	24 – 30	0.41	-	Slug	0.032	Purlawaugh Formation
P10	NC30D	118 – 130	-	-	Slug	0.049	Napperby Formation (no sill)
P11	NC30S	44 – 50/ 24 – 40	0.0007	-	Slug	0.00055	Napperby Formation (no sill at bore site)
P12	NC98D	84 - 90	0.0016	-	Slug	0.09	Napperby Formation above sill
P13	NC98S	24 - 30	0.068	-	Constant Rate - Drawdown	0.44	Garrawilla Volcanics/ Napperby Formation
					Constant Rate - Recovery	0.016	
					Slug	0.13	
P14	NC100D	72 – 78	?	?	-	-	Napperby Formation above sill
P15	NC100S	24 – 30	0.047	-	-	-	Garrawilla Volcanics
P16	NC119D	137 - 146	-		Slug	0.003	Garrawilla Volcanics
P17	NC119S	47 - 56	-	-	Slug	0.0028	Purlawaugh Formation
P18	NC122	143 - 146	0.0086	0.0086	Slug	0.013	Hoskissons Coal Seam
P19	NC123R	184 - 187	0.0021	0.0028	Slug	0.023	Pamboola Formation
P20	NC127	159 - 162	0.012	0.012	Slug	0.013	Arkarula Formation
-	GWB4S	57 – 63	0.0011	-	-	-	Purlawaugh Formation
-	Claremont Bore	?	-	-	Constant Rate - Drawdown	T = 150 m^2/d	? Garrawilla Volcanics
					Constant Rate - Recovery	T = 75 m^2/d	

The re-testing of bores P11, P13, P18 and P20 produced average hydraulic conductivities consistent with those determined by earlier testing, however the new conductivity values recorded were an order of magnitude lower at P9, an order of magnitude higher at P19 and two orders higher at P12.

There are several existing station bores nearby which are screened in the Garrawilla Volcanics. They are predominantly equipped with windmill driven pumps used for stock watering purposes, and consultation with property managers revealed that they typically are low-yielding, but are adequate for stock watering purposes. Even though some of these bores are close to exploration holes in which high yields were observed, the stock bores do not appear to have intersected the same high yielding fractures encountered in the exploration drilling.

A pumping test attempted on one of these shallow bores had to be terminated because of the very low yield. However, a second bore located on the Claremont Property was successfully tested. This bore is used to supply water to a dam and is reported to be able to produce a reasonable water supply. It is located approximately 100m from monitoring bore P13 which is screened within the Garrawilla Volcanics. The Claremont bore's construction details and pump setting are unknown, although it is understood that the bore is screened at 30m and the pump set 20m below ground level (mbgl). It is probably also screened in the Garrawilla Volcanics. The pump is powered at the surface by a small diesel engine and is capable of yielding approximately 1 L/s.

The Claremont bore was pumped for 4 hours at 0.95 L/s. The aquifer was not highly stressed during the short test, with only 1.6m drawdown observed in the bore itself and no drawdown at bore P13 100m away.

The calculated average hydraulic conductivity was assessed to be approximately 2 m/d based on a measured transmissivity of 75 m^2/d and an assumed aquifer thickness of 37 m. This result indicates a higher permeability for the volcanic unit than normally encountered and is probably related to localised fracturing.

Details of the pumping test are contained within Aquaterra Report S28_B5_042 Claremont Pump Test, which is reproduced in **Appendix I**.

3.2.5 Groundwater Quality

Groundwater quality monitoring has been conducted on behalf of NCOPL by EA Systems, with samples from all available bores in the monitoring network submitted for laboratory analysis of pH, electrical conductivity (EC), Total dissolved solids (TDS) major anions, major cations and selected heavy metals (As, Cd, Cr, Cu, Ni, Pb, Zn, Hg, V, Mn).

The laboratory analysis results indicated pH to be in the neutral to slightly alkaline range of 6.7 to 8.2 (Stage 1 investigations showed a similar range of 6.0 to 8.7 pH units). Salinity ranged from fresh (<500 mg/L TDS) within the Purlawaugh formations located to the west of the Mine Site (P7 and P8), to slightly brackish (1040 mg/L TDS) in the Garrawilla Volcanics, to strongly saline (up to 16 800 mg/L TDS) within the Napperby Formation. Salinity within the Hoskissons coal seam ranges from as low as 1350 mg/L measured in P18 during Stage 1 hydrogeological assessment to 9030 mg/L TDS measured in recent in seam drilling.

It is noted that field and laboratory measurements of electrical conductivity do not correlate well. It is assumed that the field meter was either faulty or not well calibrated during this sampling campaign.

A summary of the groundwater quality results is presented in **Appendix C**.

3.3 Groundwater Modelling

Groundwater modelling was undertaken to assess the potential impacts of mining activities.

The groundwater model utilised for the Stage 2 Longwall Project is based on the model constructed by GHD for Stage 1. Several modifications have been made to the model structure and parameters to improve the representation of the groundwater and geological environment. The most significant change was an extension of the model domain to the north-east to include the Namoi Valley and the alluvial sediments associated with the Namoi River, so that potential impacts on the Namoi Valley alluvial aquifer could be assessed, as well as potential baseflow impacts on the Namoi River. The Namoi Valley portion of the Stage 2 model was obtained directly from the NOW Namoi Valley model (NOW, 2009).

Other changes to the groundwater model included:

- Refinement of the subcrop geology, incorporating improvements in the geological and geotechnical block models that occurred as a result of additional coal delineation drilling.
- Changes to the specific yield values for the deeper model layers. The specific yield values used by GHD in the Stage 1 modelling were too high for the deeper layers. While this would not cause major impacts where confined aquifers remain saturated, it was considered this error could lead to erroneous predictions of inflow rates where dewatering occurs due to subsidence fracturing above the extracted longwall panels.

A full account of the modelling carried out for the Stage 2 Longwall Project is presented in **Section 6**.

4. DESCRIPTION OF THE EXISTING ENVIRONMENT

4.1 Topographical Setting

The Narrabri Project is located approximately 30 km south-southeast of Narrabri and 10 km north-northwest of Baan Baa. The Mine Site occupies ML 1609, and covers an area of 5 210 ha.

The Mine Site generally slopes gently to the east and northeast, with elevations ranging from over 300 m AHD in the southwest to 270 m AHD in the east. A number of ephemeral surface drainages cross the site in a north-easterly direction.

4.2 Climate

The climate of the region is cool to temperate, with hot summers and cool winters. The average daily maximum temperature ranges from 35.3 ºC in January to 17.0 ºC in July.

4.2.1 Rainfall

Rainfall data is available from Narrabri Airport (Station 54038). Average daily rainfalls are listed in **Table 4.1**.

Table 4.1: Average Monthly Rainfall (mm/day)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
2.18	2.52	1.05	0.91	0.56	2.41	0.92	0.83	0.99	1.23	2.18	3.46	1.60

Source: Bureau of Meteorology (2008)

4.2.2 Evaporation

The nearest meteorological station with long term evaporation data is Tamworth Airport (Station 55054). Average daily evaporation rates are listed in **Table 4.2**.

Table 4.2: Average Monthly Potential Evaporation Rates (mm/day)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
8.6	8.1	6.9	4.6	2.9	2.0	2.1	3.0	4.4	6.0	7.6	8.7	5.4

Source: Bureau of Meteorology (2008)

4.3 Geology

The geology has previously been described in GHD (2007) and the Narrabri Coal Project Geological Assessment (Belford Dome Resource Assessment, 2007). The summary descriptions below are based on these reports.

4.3.1 Regional Geology

The Longwall Project is located within the Permo-Triassic Gunnedah Basin, which forms the central part of the north-south elongate Sydney-Gunnedah-Bowen Basin system. The Narrabri Coal Mine is located near the northern and western boundaries of the Gunnedah Basin and the eastern margin of the Surat Basin, a sub-basin of the larger Great Artesian Basin. Hence, the rocks and sediments beneath and surrounding the Longwall Project can be grouped into:

- Undifferentiated Quaternary sediments;
- Jurassic Surat Basin sequence; and
- The Permo-Triassic Gunnedah Basin sequence.

The Boggabri Ridge, comprising Early Permian volcanic rocks, forms the basement of the Gunnedah Basin. It divides the basin into two parts, the Maules Creek Sub-basin to the east, and the Mullaley Sub-basin to the west.

The Narrabri Coal Project is located within the Mullaley Sub-basin (**Figure 4.1**), which has been described as a series of troughs separated by west-southwest trending structural highs (Tadros, 1988).

In the western part of the Mullaley Sub-basin, the Gunnedah Basin sequence is unconformably overlain by the Jurassic age Surat Basin sequence. The Surat Basin is a sub-basin of the Great Artesian Basin, and contains Jurassic to Cretaceous fluvial, lacustrine and marine sediments (GHD, 2007). Geological units interpreted to be part of the Surat Basin sequence include the Pilliga Sandstone, the Purlawaugh Formation and the Garrawilla Volcanics.

4.3.2 Mine Site Geology

Most of the Mine Site lies within the Mullaley Sub-basin, which contains Permian and Triassic sedimentary and volcanic rocks (**Figure 4.2**). The rocks strike approximately north-south and dip to the west at an angle of less than 10°. Minor variations to the north-south strike may be the result of variable thickness and compaction of the sedimentary units being draped over the faulted and uneven surface on the underlying Boggabri Volcanics. To the east of the Mine Site, the Boggabri Volcanics have been uplifted and faulted along a north-south trending anticlinal structure, the Boggabri Ridge. The Boggabri Ridge is a major control on the outcrop and structure of the local geology (NCOPL, 2009).

Within the Mine Site, there is a low angle unconformity between the Late Permian Black Jack Group and the overlying Triassic Digby Formation.

Figure 4.3 presents an east-west cross-section through the Mine Site, based on delineation drilling undertaken by Narrabri Coal and the 1:100 000 Gunnedah Basin Northern Sheet map. This illustrates the stratigraphic sequence which is intersected within the Longwall Project, as well as the unconformity beneath the Digby Formation, which truncates the underlying late Permian Black Jack Group, including the Hoskissons Seam. Because of this unconformity, neither the Hoskissons Seam nor the remainder of the Black Jack Group are directly in contact with Namoi Valley alluvium in the project vicinity. The regional groundwater level for the Jurassic sediments is shown on **Figure 4.3** for reference.

Each unit in the sequence is described in the following text.

Quaternary Sediments

Undifferentiated Quaternary alluvial gravel, sand, silt and clay overlies the Jurassic and Triassic Sediments. The most significant alluvium occurs in association with the Namoi River, to the east and northeast of the Mine Site. Minor localised and discontinuous alluvium occurs in association with the local ephemeral drainages crossing the Mine Site.

Surat Basin (Great Artesian Basin) Sequence (Jurassic)

The Pilliga Sandstone outcrops along the western margin of the Mine Site. It is up to 60m thick, and consists of medium-bedded, cross-bedded, well sorted fine to coarse grained quartz sandstone.

Beneath the Pilliga Sandstone is the Purlawaugh Formation, which is up to 140m thick and subcrops beneath the central part of the Mine Site. It consists of thinly-bedded, generally fine grained, silty lithic sandstone, siltstone and minor claystone. Thin stony coal seams are present in the lower part of the unit.

Beneath the Purlawaugh Formation is the Garrawilla Volcanics, which consist mainly of alkali basalt flows with very minor intervening mudstone and clastic rocks. The Garrawilla Volcanics are up to 40m thick, and unconformably overlie the Triassic Napperby Formation of the Gunnedah Basin sequence.

Gunnedah Basin Sequence (Permian to Triassic)

The uppermost unit, the Napperby Formation, is up to 140m thick. It consists of a coarsening-up sequence of siltstone-sandstone-siltstone laminate, and fine to medium grained quartz-lithic sandstone.

An intrusive Basalt Sill is present in the lower part of the Napperby Formation in ML 1609. It varies in thickness from 0m to 30m, but is typically 15m to 20m thick, and sits approximately 30m to 35m above the base of the Napperby Formation. It is a dark green alkali basalt and is almost certainly related to the Garrawilla Volcanics. The basalt typically has strongly developed sub-vertical fractures infilled with secondary chlorite and zeolite minerals. The fractures do not continue into the enclosing rocks and may be related to cooling shrinkage.

The underlying Digby Formation is divided into two units, the lower Digby Conglomerate and the upper Ulinda Sandstone. The Ulinda Sandstone is either not present in ML 1609 or the boundary between these units is not clear, with interbedded conglomerate and sandstone common in the top of the conglomerate. Consequently, the whole unit is referred to as the Digby Conglomerate in this area.

The unit consists mainly of thickly bedded, polymictic, lithic, pebble conglomerate with clasts of volcanics, meta-sediments and jasper in a lithic rich matrix. Minor finely to medium bedded, lithic sandstone beds are present towards the top of the unit. The Digby Formation is typically 15m to 20m thick in the Mine Site area.

The boundary with the underlying Black Jack Group is an angular unconformity. In the eastern part of the Mine Site, the unconformity truncates the Hoskissons Seam at a depth of approximately 130m to 160m. In the west, there is up to 20m of Black Jack Group above the Hoskissons Seam (**Figure 4.3**).

The Black Jack Group consists of lithic sandstone, siltstone, claystone and coal with minor tuff. It is up to 70m thick in the western part of the Mine Site but is less than 40m thick in the east due to the low angle unconformity with the overlying Digby Formation. The Hoskissons Seam and the Melville Seam are present beneath the Mine Site. Thickness and quality characteristics are such that only the Hoskissons Seam is currently considered to contain coal resources with mining potential.

Throughout the Mine Site, the Black Jack Group includes the following strata.

- Benelabri Formation – lithic sandstone and siltstone with minor coal. Increases in thickness towards the west due to the unconformity.
- Hoskissons Seam – Dull lustrous coal. Coal consists of a low ash working section (basal 4.2 m) and an upper high ash coal with claystone bands.
- Arkarula Formation – quartzose sandstone and siltstone. Typically forms the upper 10m of the Black Jack Group over the Mine Site.

- Brigalow Formation – coarse sandstone and conglomerate interbedded with the coal seam, which grades laterally into the Arkarula Formation, thickening to the west across the mine site from 2m to 19m.
- Pamboola Formation – lithic sandstone, siltstone, claystone and coal. Continuous over the Mine Site below the Arkarula Formation and Brigalow Formation, with a thickness of between 55m and 75m.

4.4 Hydrogeology

4.4.1 Groundwater Occurrence

Groundwater can occur in all geological units, but most of the hard rock units generally have low hydraulic conductivity.

Quaternary Alluvium

Groundwater monitoring within alluvial sediments associated with the Namoi River, which is located 2-7 km east/north-east of the Mine Site, has a lengthy history, as the alluvial aquifer supports irrigated agriculture within the region. The aquifer is considered to be stressed due to large over-allocations of groundwater extraction. The alluvium associated with the Namoi River valley can exist to depths in excess of 100 m, as is seen in the paleochannel to the north of Narrabri.

Away from the Namoi River floodplain, alluvial/colluvial sediments have a limited occurrence, and form localised surface cover over the sub-cropping Permian-Jurassic stratigraphy, with a thickness that locally can extend to several tens of metres.

Regolith

No groundwater had previously been recorded from the regolith within the Mine Site. However, during construction of the box cut for the portal to the underground mine, groundwater seepage was observed emanating from the base of the weathering profile around most of the box cut perimeter. Groundwater appears to be restricted in the vicinity of the box-cut to small localised ponding on top of the fresh rock at the base of the weathered zone. Seepage rates are low. Similar occurrences may exist elsewhere around the Mine Site area.

The Mine Site is located on land that is topographically higher than the Namoi River floodplain (**Figure 4.3**), and the discontinuous regolith groundwater on the Mine Site is not hydraulically connected with alluvial groundwater associated with the Namoi River.

Permian to Jurassic Hard Rock Units

The Surat Basin Jurassic sediments in the study area form part of the regional Great Artesian Basin (GAB) and correspond to the intake beds (GWMA 601) of the GAB (Ife and Skelt, 2004). Underlying the Surat Basin sediments are units from the Gunnedah Basin sediments. Both the Surat Basin and Gunnedah Basin units contain local groundwater flow systems in fractured rock.

The Pilliga Formation is unsaturated within the Mine Site area.

4.4.2 Groundwater Levels and Flow Patterns

Three groundwater flow systems occur within the Mine Site area. A shallow aquifer system occurs within alluvium associated with the Namoi River, and locally in the alluvium/colluvium and weathered rock (regolith) above fresh rock. Two separate fresh rock groundwater flow systems occur predominantly in open fractures in the underlying fresh rock.

Within the Longwall Project Site, groundwater levels in the shallow alluvium/colluvium/regolith aquifer are generally about 10-20m or more below ground level. Groundwater in this aquifer is localised and discontinuous and is influenced primarily by topography and local surface drainage.

The groundwater flow direction in the shallow groundwater system is therefore similar to the surface topography, ie. east to northeast towards the Namoi River valley. Recharge to the shallow aquifer system is believed to occur by infiltration of rainfall through the surficial alluvium and regolith, with discharge occurring locally to the surface drainages.

Within the deeper hard rock aquifers, groundwater levels are generally in the range 25-50m below surface. The shallower of the two hard rock groundwater systems occurs within the Jurassic sediments, which subcrop beneath the Longwall Project area. The westerly dip on the strata exposes progressively younger units from east to west across the site. A deeper groundwater flow system occurs within the Permian-Triassic sediments which also dip in a westerly direction.

Contours of groundwater levels / pressures have been prepared based on the measured water levels in the monitoring piezometers. With the limited number of water levels from each hydrogeologic unit, contouring has only been possible by consolidating all bores from the Permian-Triassic formations into one group, and the Jurassic formations into another, and contouring each group to produce a representative potentiometric surface for the Permian-Triassic units and water table contours for the Jurassic units. Contours for the two groups are shown on **Figure 4.4**.

The contours on **Figure 4.4** show that the groundwater in the Permian-Triassic units has a hydraulic gradient generally dipping to the north-west. The Jurassic groundwater flows are also to the north-west but are elevated above the lower Permian-Triassic aquifer levels by 20 - 25 m.

The fracture rock aquifer systems are influenced by regional features such as basin structure and regional recharge and discharge processes, and groundwater flow occurs primarily in fractures. Visual inspection of drill core suggests that the stratigraphic units are heterogeneous, with bulk aquifer properties varying depending on the nature and continuity of fractures and joints. The limited number of formation-specific monitoring points over the Longwall Project area makes it difficult to evaluate groundwater flow patterns, but it is expected that flow is more regional in nature than the water table in the shallow flow system.

Recharge to the deeper Permian-Triassic and Jurassic units is believed to occur through downward percolation of rainfall through the surficial regolith layer and/or alluvium into the underlying bedrock units where they subcrop. The groundwater levels then tend to reflect the elevations of these recharge zones, and the discharge areas which may be some distance away, leading to a regional rather than local flow pattern. The head difference between the two fractured rock systems suggests a hydrogeological disconnection between them.

Geophysical logging of resource drill holes revealed temperature variations which can be correlated to specific stratigraphic intervals in the majority of holes. Temperature generally increases steadily with depth, which can be attributed to normal heat flux. However, a relatively steeper increase in temperature was observed in bores NCOPL29, NC0108 and NC0112 (typified by the log of NCOPL29 shown in **Figure 4.5**) at depths which correspond to the Hoskissons Seam, and zones immediately above (base of the Digby Formation) and below (Arkarula Formation). This has been interpreted to correspond to a higher rate of groundwater flow within the coal seam.

Figure 4.6 illustrates temperature logs for NC109 and NC112 which show sharp increases in temperature at depths which correspond to the base of the Digby Formation and within the Hoskissons Coal Seam.

4.4.3 Aquifer Parameters – Estimates of Hydraulic Conductivity

The hydraulic conductivity results shown in **Table 3.2** indicated several zones of elevated hydraulic conductivity in various formations. Relatively high hydraulic conductivities ranging up to 0.4 m/d are found in the Garrawilla Volcanics and the Pilliga Formation. Moderately high conductivity was also found in the Napperby Formation above the sill.

All other units show a wide range of conductivities, but generally quite low, ranging from 0.0005 to 0.03 m/d, with the higher conductivities generally in sub-crop areas. This is consistent with reports of significant inflows and more intense fracturing in some holes at shallower depths.

The mean hydraulic conductivity of the Purlawaugh Formation and Basalt Sill is an order of magnitude lower than the Pilliga and Garrawilla Formations, at 0.01 to 0.02 m/d.

The geological units underlying the Basalt Sill are characterised by low inherent permeability. The hydraulic conductivity of the Napperby Formation (below the sill) and the Digby Formation range from 1×10^{-4} m/d to 8×10^{-5} m/d. These units are typically fine-grained, laminated and cemented with a clayey matrix. Limited groundwater intersections were noted during drilling. These low permeability units separate the overlying permeable Jurassic strata from the underlying Permian Black Jack Formation.

The hydraulic conductivity of the Black Jack Group, comprising the Hoskissons Coal Seam, Arkarula Formation/Brigalow Formation and the Pamboola Formation, ranged from $2 \times 10\text{-}^{3}$ to 3×10^{-2} m/d. Relatively high groundwater pressures were observed in the Black Jack Group indicating that these formations are confined by the overlying Digby Formation and Napperby Formation aquitards.

Table 4.3 shows the values of hydraulic conductivity that were used for each formation in the original GHD model, and initial values in the Aquaterra groundwater model that was developed for the Stage 2 impact assessment.

Table 4.3: Hydrogeological Units and Hydraulic Conductivity Values Used in Groundwater Model Development

Model Layer	Formation	Adopted Horizontal Hydraulic Conductivity Kh (m/d)	Adopted Vertical Hydraulic Conductivity Kv (m/d)
1	Alluvium	0.265 - 5	0.0005 - 0.005
2	Pilliga Sandstone	0.004 - 0.265	0.000015 - 0.0002
3	Purlawaugh Formation	0.004 - 0.02	0.000015 - 0.001
4	Garrawilla Volcanics	0.001 - 0.04	0.000006 - 0.001
5	Napperby Formation (above Sill)	0.001 - 0.04	0.000006 - 0.001
6	Basalt Sill	0.004 - 0.12	0.000006 - 0.001
7	Napperby Formation (below Sill)	0.004 - 0.021	0.000006 - 0.001
8	Digby Formation	0.004 - 0.04	0.000006 - 0.001
9	Hoskissons Coal Seam	0.005 - 0.04	0.000006 - 0.001
10	Arkarula Formation	0.0005 - 0.04	0.000001 - 0.001
11	Pamboola Formation	0.04	0.001

4.5 Groundwater Quality

Groundwater quality across the Longwall Project area is variable, both in terms of key field parameters such as salinity and pH, and also in terms of major and minor hydrochemical constituents. These quality data indicate that a range of groundwater types exists across the site.

All available water quality analysis results are presented in **Appendix C**. Where relevant, results have been compared to the ANZECC (2000) guideline values for freshwater ecosystem protection.

No saturated Pilliga Sandstone was intersected within the Mine Site. The Pilliga Formation is believed to be dry in the Longwall Project area, but becomes partly saturated to the west of (down-dip from) the Mine Site, as the formation dips below the regional water table level. Water quality data for the Pilliga Formation are from west of the Mine Site.

4.5.1 Salinity

Figure 4.7 shows the distribution of salinity (as mg/L TDS) as measured at the boreholes monitored for this project. Groundwater salinity varies considerably, with recorded values of TDS ranging from less than 100 mg/L in the Garrawilla Volcanics and less than 500 mg/L within the Pilliga and Purlawaugh formations, to more than 16,000 mg/L in the Napperby Formation and the Basalt Sill.

Initial sampling from the monitoring network suggested that salinity within the Hoskissons Seam would be around 2000 mg/L TDS, which is lower than overlying Triassic and Permian strata where salinities ranging from 6000 to 8000 mg/L TDS are typical. However, recent testing from inseam drilling program suggests that salinity within the Hoskissons Seam may also be in the order of 8000 mg/L TDS, and that the lower salinity determined from earlier monitoring may be limited to areas close to outcrop/subcrop.

The TDS ranges for each described geological unit, and the average values which have been used to derive mine inflow salinity concentrations later in this report (**Section 7.4**) are based on all available data from the sampling of monitoring bores. The data used includes that from the Stage 1 assessment undertaken by GHD, data gathered prior to this assessment by EA Systems (September 2008) as part of routine monitoring, and recent (July 2009) inseam gas testing where samples have been recovered from the Hoskissons coal seam.

Table 4.4: Summary of Groundwater Salinity Data (TDS mg/L)

Formation	Number of Samples	Minimum	Maximum	Average
Pilliga Sandstone	1	101	101	101
Purlawaugh Formation	4	295	14820	2180
Garrawilla Volcanics	6	109	9400	728
Napperby Formation (above Sill)	4	226	1735	1300
Napperby Formation (below Sill)	5	3160	16800	7234
Digby Formation	N/A	N/A	N/A	7000*
Hoskissons Coal Seam	5	1350	9070	5826**
Arkarula Formation	2	7740	9630	8673

* No sampling has occurred from the Digby Formation, and salinity if assumed to be similar to overlying Napperby Formation

** Initial sampling from the Hoskissons coal seam was limited to a single monitoring bore (P18) which indicated that salinity within the seam was less than 2000 mg/L. Recent data from samples collected during seam gas drainage testing suggests salinity concentrations are as high as 9070 mg/L.

4.5.2 pH

The pH ranges from neutral to mildly alkaline, with recorded pH values from 6.7 to 8.2. Recorded pH values are plotted on **Figure 4.8**.

4.5.3 Dissolved Metals

Laboratory analyses of groundwater samples indicate moderately elevated dissolved metals concentrations. The analysis included aluminium, arsenic, boron, cadmium, cobalt, copper, iron, lead, manganese, mercury, nickel, selenium, silver and zinc.

Dissolved metal concentrations which exceed ANZECC (2000) guideline values for freshwater ecosystem protection are detailed in **Appendix C**. Most bore samples exceed ANZECC guidelines for copper, lead, nickel and zinc, and bores P1, P2, P4, P5, P10 and P11 exceed the guideline for manganese as well.

4.5.4 Major Ion Composition

Major ion composition has been assessed with the aid of a Piper Trilinear plot (**Figure 4.9**). This plot allows each water analysis to be plotted as a unique point based on the relative concentrations of the major cations (calcium, magnesium, sodium and potassium) and major anions (carbonate, bicarbonate, sulphate and chloride). Piper plots allow the assessment of differences in water chemistry applying to different areas and/or different hydrogeological units;

and the relative components of groundwater derived as mixtures of waters from one or more different sources. Interpretation can also be made as to the influence of recharge and discharge processes.

In addition to displaying the relative ionic composition, the Piper plot on **Figure 4.9** has also been prepared to provide a broad indication of groundwater salinity, with the plotted symbols sized according to representative salinity ranges.

Groundwater sampled from the Longwall Project area show variable chemical signatures which are related to the geology.

All waters are low in sulphate, but there is a broad distribution from bicarbonate to chloride dominance among the other anions. Chloride dominance occurs in the higher salinity waters from deeper intersections, particularly in the Pamboola Formation and the Napperby Formation. Bicarbonate dominance is normally associated with low salinity, and is typically an indicator of recent recharge or proximity to recharge in the flow system. The bicarbonate-dominant samples are generally from relatively shallow depths in a range of formations.

However, the waters from the Hoskissons Seam and Arkarula Formation have bicarbonate dominance combined with relatively high salinity. In this case the high bicarbonate is believed to be derived from some mineralisation source in the Permian sequence. Note that the bicarbonate dominance applies to the upper members of the Black Jack Group (i.e. Hoskissons Seam and Arkarula Formation), but not to the deeper Pamboola Formation.

4.6 Recharge and Discharge

The main recharge mechanism for the groundwater within the Longwall Project area is local infiltration of rainfall. Recharge rates are a function of rainfall intensity, evaporation, vegetation coverage and density, topography and the degree of fracturing in the upper surface of the hard rocks, either at ground surface or at the base of the weathered zone.

Recharge occurs by direct infiltration of rainfall and local runoff into the unconsolidated surficial material, comprising the weathered zone of the bedrock (regolith layer) as well as discontinuous occurrence of alluvium/colluvium in low-lying areas. Water percolates downwards until reaching a zone of reduced permeability (top of fresh bedrock beneath the alluvium/colluvium, or the base of weathering), and then flows laterally above this less permeable aquitard layer.

A water-table aquifer may form as either a localised perched aquifer, or more extensive unconfined aquifer, within the surficial unconsolidated materials.

The Jurassic, Triassic and Permian aquifers of the Longwall Project area are also recharged at outcrop or subcrop beneath the alluvium or regolith layer. Where permeable parts of these hard rock units subcrop beneath alluvium, colluvium or highly weathered bedrock, recharge can occur to these hard rock formations by downward percolation from the unconsolidated material.

Natural groundwater discharge occurs through evapotranspiration, seepage and spring flow where the water-table intersects the ground surface, and through baseflow contributions to creeks and rivers, including possible discharge to the alluvium in some locations. Local spring or seepage discharges may also occur wherever a permeable fractured zone within a hard rock unit crops out, such as on hillsides or the flanks of creeks and gullies, if the water level in that unit is higher than the ground surface.

4.7 Groundwater - Surface Water Interactions

There is a very low likelihood for groundwater discharge to surface water systems within the Longwall Project area, with the possible exception of the area proximal to NC98S, where the standing water level is shallow (around 5 m below the ground surface). NC98S (P13) is located on the Claremont property within the sub crop zone of the Garrawilla Volcanics and in a low lying area adjacent to a local drainage channel. Elsewhere, the groundwater is too deep to permit discharge to the surface.

NCOPL has identified a spring discharging to surface the south of the Mine Site (Mayfield Spring) which is utilised for stock watering (**Figure 4.10**). It is believed to be derived from the Purlawaugh Formation. Flow rate is difficult to gauge but appears to be very low (<0.1 L/s). The spring emanates within a low-lying area in a valley. A combination of spring discharge and streamflow from the catchment upstream supports a small wetland area which has been formed by a dam constructed across the drainage channel. Land-owners report that the spring-fed dam is able to maintain permanent water through most extended dry periods due to the groundwater seepage.

Figure 4.10 shows additional springs located well to the south of the Mine Site (Hardys and Eather Springs). Details of these springs are not known and the locations were provided by NOW. Elsewhere there is no evidence of other spring discharges within the Longwall Project area.

More regionally, it is believed that there may be some slow natural discharge from the Triassic-Permian formations to the Namoi Valley alluvium to the east of the Longwall Project, but at low rates relative to the recharge from rainfall, as the alluvium groundwater salinity is much lower than the salinity of the Triassic-Permian groundwater.

The Jurassic groundwater discharges regionally to the west within the GAB.

4.8 Current Groundwater Use

Details of NOW registered bores in the area were provided in Section 2.9 of this report.

Groundwater use in the vicinity of the Mine Site is restricted to a number of low yielding groundwater bores used for stock and domestic purposes. There are 18 registered groundwater bores within 5 km of the Mine Site, all located outside of the Mine Site. All of these are low yielding stock or domestic bores.

Some higher yielding bores do exist within the Namoi Valley alluvium further afield to the east of the project.

5. MINING PROPOSAL

5.1 Longwall Mining Proposal

NCOPL proposes to construct a longwall mining operation with a maximum annual production rate of 8 Mtpa.

Mining would involve the sequential development of north-south longwall panels, with nominal 305m panel widths, extending north and south from the central main development gateroads known as the West Mains. Development headings for the longwalls consist of double-entry gateroads, with a nominal chain pillar width of 37.5m. Longwall panels will extend up to 4.2 km north and 3.8 km south from the West Mains. Coal will be conveyed to the Pit Bottom Area for transfer to the surface via the conveyor drift. The proposed mine layout is illustrated in **Figure 5.1**.

It is envisaged that coal production would be achieved through the combination of a single longwall unit and two or three continuous miners developing roadways. It is envisaged that extraction of each longwall panel would take approximately 12 months.

5.2 Mining Schedule

Figure 5.1 shows the proposed mining sequence for the projected 29 year life of the Narrabri Coal Mine.

A total of 26 longwall panels is included in the proposed mine plan, 13 to the north and 13 to the south of the West Mains. Panels on the northern side (LW1 to LW13) will vary in length from 1450m to 4,150m. Panels on the southern side (LW14 to LW26) will vary in length from 1500m to 3,850m.

Extraction will commence on the northern side of the West Mains, starting at LW1 (eastern updip end) and proceeding westwards to LW13, before commencing the panels south of the West Mains, proceeding from LW14 (western downdip end) updip to LW26.

5.3 Subsidence Predictions

The subsidence assessment was undertaken by Ditton Geotechnical Services Pty Ltd (DGS). It was based on 305m wide longwall panels with a 4.2 m mining height, and cover depths ranging from 160m to 380m. The chain pillars are assumed to be up to 37.5m wide, and gateroad height 3.5m.

DGS (2009) predicted that subsidence impacts affecting formation permeability would extend at least to the base of the Garrawilla Volcanics, and could possibly extend up into that unit as well.

DGS reported that *"… direct surface to seam fracturing is 'unlikely' for cover depths greater than 100m and 'possible' up to 120m if an adverse geological condition, such as fault interaction occurs. Indirect or discontinuous sub-surface fracturing could interact with surface cracks where cover depths are < 215 m.*

"The modelling outcomes also indicate that the continuous fracture heights for the mining layout proposed could extend into the Garrawilla Volcanics, if the unit fails, or be truncated at or near the base of this potentially spanning unit.

"Subsequent groundwater impact studies should consider the above uncertainties in regards to surface and groundwater impacts."

5.4 Mine Water Management

Groundwater entering the underground workings will be allowed to flow to sump areas where it will be pumped to the surface, either for operational use or disposal.

The modelling described in **Section 6** indicates that the inflows are predicted to peak in Years 17 – 18 during mining of LW14 to LW16. As mining proceeds back up dip, water will be able to recover in the goaf areas downdip of the active longwall panel. Hence, net inflow rates are predicted to start declining from Year 20.

Net inflows are predicted to be initially less than the water demand, but from Year 8 excess water will be generated from underground inflows, and a disposal plan will need to be implemented for the excess water.

The base case model using the hydraulic parameters considered to best represent the hydrogeological units both pre-mining and following subsidence indicates that groundwater inflows will peak at around 3.8 ML/d (1400 ML/annum). Uncertainty analysis modelling (described in **Section 6.6**) shows that peak groundwater inflows to the underground mine could be as high as 5.2 ML/day (1900 ML/annum) or as low as 3.2 ML/d (1200 ML/annum).

Water management, including management of inflows in excess of project water demands, are addressed by others.

6. GROUNDWATER MODELLING TO ASSESS POTENTIAL IMPACTS

Groundwater impacts have been assessed with the assistance of a numerical groundwater model which is described in the following sections.

6.1 Model Software

The MODFLOW numerical groundwater flow modelling package (Harbaugh, et al, 2000) has been used for this study, in conjunction with the SURFACT module (SURFACT Version 3, HydroGeoLogic, 2006), operating under the Groundwater Vistas Version 5 graphic interface software package (ESI, 2005).

The MODFLOW package is the industry-leading groundwater modelling software, and has advanced modules for simulating surface water and groundwater interaction which allows for the assessment of impacts on creeks and rivers. However, standard MODFLOW has two limitations when simulating longwall mining. Firstly, the package does not allow aquifer properties to change with time as mining progresses. This is important, as longwall mining causes changes in strata hydraulic properties due to fracturing and deformation above the longwall panels. Secondly, standard MODFLOW cannot routinely simulate free draining conditions in strata above a longwall panel.

To overcome the first constraint, the model simulation has been run in a series of consecutive time slice models, with model hydraulic parameters changed from one time slice to the next to reflect the mining advance and associated subsidence. The second constraint has been addressed by using the MODFLOW-SURFACT module. SURFACT enables simulation of saturated and unsaturated flow conditions and provides for more stable drying and re-wetting of cells in thin model layers (such as coal seams and thin aquitards). The model simulations have used the variably-saturated flow conditions of the pseudo-soil function provided by the MODFLOW SURFACT BCF4 package.

Hence, the MODFLOW-SURFACT numerical code, used in conjunction with time slice modelling, was adopted for this study.

The hydrogeological investigations (including the modelling) were undertaken with reference to the 'Guidelines for Management of Stream/Aquifer Systems in Coal Mining Developments – Hunter Region' (DIPNR, 2005), and the modelling was undertaken in accordance with the best practice guideline on groundwater flow modelling (MDBC, 2001). In accordance with this guideline, it was deemed that the degree of model complexity required to accomplish the study objectives in this case was a medium complexity model.

6.2 Conceptual Model Design

6.2.1 Model Domain and Boundary Conditions

The model used for this project is based on the model constructed by GHD for the Stage 1 EIS assessment, but with extensive modifications. It covers an area which includes the Boggabri Ridge extending west of the Mullaley Sub basin and parts of the Gunnedah, Upper Namoi and GAB intake bed GWMAs. The model domain was extended to include the Namoi River alluvial aquifer system. Topographical and geological information in the Namoi area was provided by DECCW (2007). The model grid is aligned with the MGA grid.

The model domain covers an area of 75km x 52km (3900km^2), with a variable grid size ranging from 50m x 50m in the Mine Site, and increasing gradually up to 500m x 500m near the model boundaries. This gave a grid mesh of 269 rows and 270 columns, or a total of 606,783 active cells for the full 11-layer model. The active model area is 1950km^2.

The non-uniform grid size in the model was selected to optimise the model run time and improve the model efficiency. Maintaining the 50m x 50m grid in the proposed mining area allowed modelling of stream-aquifer interaction processes. The finer grid also allowed better resolution of the dipping layer geometry, and the potentially steep water level gradients close to the mine.

The conceptual hydrogeological model is illustrated in **Figure 6.1**, and which also shows the domain boundaries adopted in the model. Details of model layers and boundary conditions are presented on plans in **Appendix D**.

Boundary conditions have been assigned to represent the regional groundwater flow system in a realistic manner, taking into account stratigraphic and topographic controls. Boundary conditions have on the whole been maintained from the GHD model, although some refinement has been made.

No Flow boundaries have been applied along regional flow lines and the basement outcrop of the Boggabri Ridge.

Bed levels and stage heights for the river boundaries along the Namoi River have been refined based on the inclusion of the NOW Namoi Valley model, referred to in **Section 6.1**.

A General Head (or head-dependent flow) boundary was specified at the north-western defined edge of the model for Layers 1 to 4, which contain the alluvium / regolith layer and the Jurassic strata associated with the GAB intake beds. This allowed heads to be specified based on interpreted groundwater levels ranging from 210 to 220m AHD in Layers 1 to 4. This allows the potential for inflow or outflow to/from the interpreted Great Australian Basin intake beds.

Layer 5 and below are assessed to be part of the Gunnedah basin, and no General Head or Constant Head boundaries have been applied to these layers.

6.2.2 Model Layers

The groundwater model contains 11 active layers, as listed in **Table 4.3**. They represent the major hydrogeological units within the Longwall Project area.

The topographical upper surface of the model corresponds to the ground surface information downloaded from the Geosciences Australia website, with a 25m grid node size. The base of each layer has been taken from geological block modelling within the Longwall Project area (supplied by NCOPL) and interpolated outside this area from stratigraphic elevations interpreted from bore logs published in notes accompanying the Narrabri 1:250 000 Geological Map (DMR, 1971).

The Hoskissons Coal Seam (Layer 9) top and base elevations were interpolated from project specific bore-logs and extended regionally using information from the regional geological maps. The regional structure of the Hoskissons Coal Seam was also based on spot level and general dip information provided with the 1:100,000 geological map (Watkins, et al, 1999).

Model layers have been maintained across the model area to facilitate model output data for each individual hydrogeologic unit. In areas where a particular hydrogeological unit has been eroded away or does not exist, the layer representing that unit has been reduced in thickness to 0.1m and assigned hydraulic properties from the nearest underlying active layer.

A significant change from the GHD model was the direct physical disconnection of lower layers (i.e. Digby Formation and Blackjack Formation) from any direct connection with shallow alluvial sediments associated with the Namoi River. This is in keeping with the geology model for the local stratigraphy, and the recognition that the Digby Formation and the Black Jack Formation have been partly truncated by the overlying Napperby Formation. The Hoskissons Seam has been totally eroded away in areas updip from the Mine Site.

Layer surface elevation data are presented as plots in **Appendix E**.

All layers are defined in the model as MODFLOW-SURFACT Type 3 (equivalent to semi-confined aquifers with variable transmissivity).

The selection of appropriate host permeability values was based on the results of hydraulic testing combined with model calibration to achieve an adequate match to observed groundwater levels.

6.2.3 Baseflow

The numerical model design incorporates river/aquifer interaction features to enable representation of both baseflow discharges from groundwater and recharge from the streams to the groundwater, as well as quantification of the impacts of groundwater pumping on surface water features.

Baseflow contribution to rivers and streams represents one of the primary natural groundwater discharge processes (the other main discharge process applicable to this area being evapotranspiration). In areas where the groundwater levels may be lower than the creek system, the creeks may be “losing” streams, i.e. they may lose water by seepage to adjacent or underlying aquifers. It is possible for larger river / creek systems to provide some recharge to the aquifer at least periodically, when river or creek levels may be temporarily higher than groundwater levels following heavy rainfall events. The model is designed to allow both processes (i.e. baseflow discharge and groundwater recharge) to occur.

The Namoi River is the most significant surface water feature in the area, and it is generally “gaining”, i.e. it receives baseflow discharges from the groundwater system over most of its catchment. The Maules Creek component of the alluvial aquifer system in the far eastern part of the model area (east of the Namoi River) appears to be overall losing water to the alluvial sediments.

Ephemeral creek characteristics are apparent in most of the tributary drainages where the baseflow is insufficient to maintain permanent creek flow, and extensive periods of no-flow occur naturally. Although baseflow within the ephemeral creek systems is considered to be insignificant, alluvium/colluvium associated with these creeks has been included as a veneer within Layer 1 of the groundwater model. This has been included primarily because it plays a key role in local recharge.

The drainages have been represented in the model using the MODFLOW River (RIV) package.

The river stage elevations in the Namoi River were set to 1m below the river bank elevation, and river bed levels set to 0.2m below the stage in the main rivers, while the river stage elevations of the tributary streams have been set to the same level as the stream bed (1m below the river bank elevation). With this arrangement, the minor tributary streams, which are ephemeral, act only as baseflow-fed groundwater discharge features in the model, not potential recharge features; whereas the main rivers/streams can act as either groundwater discharge or recharge features, depending upon whether the simulated groundwater level is above or below the specified stream stage level.

The river bed conductance parameter was set to a high value of 1000 m^2/day, so as not to constrain flow between the streams and the groundwater.

6.2.4 Recharge

Recharge in the Longwall Project area was discussed in **Section 4.6**. The percentages of rainfall that are assumed in the model to recharge the water-table vary depending broadly on the type and extent of surficial outcrop, and local topography. Six rainfall recharge zones were defined in the model.

For the steady-state (long-term average) calibration modelling, the annual average recharge rate has been modelled by applying a spatially-variable effective rainfall percentage to different zones defined on the basis of sub-crop geology and topography.

The same zone percentage recharge rates have been carried forward to the transient (time-varying) calibration model, but they were applied to actual monthly rainfalls recorded at the Narrabri Airport gauge during the 1-year calibration period to September 2008, rather than average annual rainfalls.

For the forward predictions of mine dewatering, the adopted recharge rates have again been applied to the average annual rainfall as a constant value with time in each zone.

6.3 Calibration

6.3.1 Calibration Approach

Model calibration involves comparing predicted (modelled) and observed data and making modifications to model input parameters where required (within reasonable limits defined by available data and sound hydrogeological judgment) to achieve the best possible match.

In the calibration process, independent variables of the model (parameters and boundary conditions) are adjusted, within realistic limits, to produce the best match between simulated and measured data. The realistic limits on parameter values are constrained by the range of measured values from pumping tests and other hydrogeological investigations.

Model calibration performance is evaluated in both quantitative (head value matching) and qualitative (pattern-matching) terms, by:

- Scatter plots of modelled versus measured head, and the associated statistical measure of the scaled root mean square (SRMS) value.
- Hydrographs of modelled versus observed bore water levels.
- Contour plans of modelled head, with posted spot heights of measured head.
- Water balance comparisons.

The SRMS value is the root mean square (RMS) error term divided by the range of heads across the site, and it is the main quantitative calibration performance indicator. An SRMS value below 10% is considered to be an appropriate target for this model, consistent with the groundwater modelling guideline (MDBC, 2001).

Calibration has been carried out by both steady-state (i.e. calibration to assumed long-term equilibrium conditions) and transient (i.e. calibration to the impacts of time-dependent stresses such as pumping and/or climatic variation) approaches.

6.3.2 Steady State Calibration

Model calibration was achieved using a combination of manual and automated parameter techniques.

Initially, the groundwater model was set up and run in steady-state mode, to represent long term average aquifer conditions. The objective was to derive a comprehensive simulation of pre-development steady-state conditions, for use as initial conditions in the transient model calibration run and subsequent transient prediction modelling.

The steady state calibration was achieved through an iterative process by making small manual adjustments to the horizontal and vertical hydraulic conductivity and recharge values until the best fit between the simulated water levels and interpreted actual long-term average water levels was obtained.

However, manual calibration was not able to achieve the head difference seen between Jurassic sediments and underlying strata. Further calibration of the groundwater model was then undertaken with the use of the automated Parameter Estimation or calibration software PEST (Watermark Numerical Computing, 2004) and an improved calibration was achieved. The hydraulic conductivity parameters values were optimised using this program.

Calibration was demonstrated in quantitative and qualitative terms by the following measures:

- **Figure 6.2** shows the scatter plot for Narrabri steady state calibration. This plot shows a normal agreement between the observed and computed heads across most model layers, with a scaled root mean square (SRMS) error of 11.85%, slightly above the target value, and coefficient of determination of 0.98 (**Table 6.1**).
- **Figure 6.2** also shows the steady state head profile comparison for the multiple vibrating wire monitoring bore NC175 against the head profile for the calibrated groundwater model at the same location for the same stratigraphic horizons which are monitored in NC175. It shows a reasonable calibration between observed and simulated model results at this location. The groundwater model demonstrates an elevated head within Jurassic strata in comparison to Permian strata although not as significant a head difference between the observed head in the Garrawilla Volcanics and the Napperby Formation.
- A comparison between observed and modelled heads at each of the 22 target bores is presented in **Table 6.2**. Bores screened across more than one aquifer are listed separately for each model layer in the table. These show generally good agreement at most sites.
- Contour plans of modelled steady state heads for selected layers are shown in **Figure 6.3 to 6.6**.
- A small water balance residual of 0.05% was obtained (**Table 6.3**).

Table 6.1: Steady State Calibration Performance of the Longwall Project Model

Calibration Parameters		Value	
Count	n	22	
Scaled Mean Sum of Residuals	SMSR	-2.56	%
Root Mean Square	RMS	8.21	m
Scaled RMS	SRMS	9.94	%
Root Mean Fraction Square	RMFS	3.43	%
Scaled RMFS	SRMFS	10.33	%
Coefficient of Determination	CD	0.98	

Table 6.2: Steady State Model Calibration – Groundwater Level Targets

Bore	Easting (MGA)	Northing (MGA)	Observed Head (mAHD)	Simulated Head (mAHD)	Head Difference (m)	Layer
NC175	776170	6620700	241.00	250.71	-9.71	7
NC175	776170	6620700	240.00	249.23	-9.23	8
NC175	776170	6620700	246.00	247.74	-1.74	9
NC179	776710	6621050	248.00	248.95	-0.95	7
NC179	776710	6621050	247.00	247.80	-0.80	8
NC179	776710	6621050	245.00	245.67	-0.67	9
NC179	776710	6621050	242.00	240.67	1.33	10
P1	776115.82	6614693.85	264.04	269.70	-5.65	4
P2	777281.82	6616354.7	245.34	251.51	-6.16	5
P3	780432.76	6620115.01	226.40	228.50	-2.11	10
P4	777490.23	6625553.08	230.47	236.15	-5.69	5
P5	778179.7	6628194.59	204.35	223.71	-19.36	10
P6	772726.23	6626021.32	235.98	240.39	-4.41	2
P8	772696.67	6618420.86	271.60	274.23	-2.64	3
P9	775126.55	6620208.85	267.72	261.87	5.85	2
P10	774063.17	6616444.05	286.97	271.60	15.37	5
P11	774066.35	6616447.21	280.22	271.59	8.63	5
P12	776513.46	6619963.98	239.78	243.50	-3.72	10
P13	776526.05	6619971.87	267.98	255.36	12.61	3
P16	772233.3	6623739.68	252.26	256.10	-3.84	4
P17	772221.6	6623711.77	247.29	256.40	-9.12	3
P19	776826.62	6621543.29	251.00	246.66	4.34	8
Average			243.66	247.79	-4.13	
Minimum			204.35	223.71	-19.36	
Maximum			271.60	274.23	5.85	
Range			67.25	50.52		

The overall groundwater balance for the steady-state Narrabri model is summarised in **Table 6.3**.

Table 6.3: Groundwater Budget for Narrabri Model Steady-State Calibration

Component	Groundwater Inflow (ML/d)	Groundwater Outflow (ML/d)
Recharge	26.59	8.46
River Leakage	14.99	24.71
GHB	0	8.48
Well	0	0
Total	41.58	41.65
Discrepancy (%)	0.17	

The total inflows to the aquifer system were around 41.6 ML/d, comprising rainfall recharge (64%) and leakage into the aquifer from the rivers and streams (36%). The total outflows from the Narrabri model (41.65/d) comprised model boundary outflow (20.4%), discharge from groundwater into the river/creek system (baseflow 59.3%) and recharge outflow (20.3%). The water balance discrepancy between the total inflow and total outflow for the steady state simulation was 0.17%.

From **Table 6.3**, it can be seen that, over the total model area, the steady state calibration indicates a net discharge of groundwater to the Namoi River (or baseflow contribution) of 9.7 ML/d.

6.3.3 Steady State Baseflow

Six river reaches, shown on **Figure 6.7**, have been defined as River boundaries in the Narrabri Model. These are located on the Namoi River and its tributaries Maules Creek and Cox's Creek, and Jacks Creek which is an ephemeral drainage to the west of the Narrabri project and joins the Lower Namoi River approximately 15 km to the north.

Model-calculated baseflow contributions to river/stream flow were evaluated separately for each reach. **Table 6.4** summarises the computed baseflow values for each reach, derived from the steady state calibration. Overall, the Namoi River in the model area is a gaining stream, i.e. the groundwater discharges to the river. Two reaches are losing water - Maules Creek (Reach 12) and Jacks Creek (Reach 20).

Table 6.4: River Baseflow - Steady State Calibration

Reach No	Location	Model Layer	Baseflow* (m^3/d)	Gaining / Losing
11	Namoi River, downstream of Maules Creek between Baan Baa and Narrabri	1	10348	Gaining
12	Maules Creek – tributary flowing into Namoi River from the east	1	-1301	Losing
13	Namoi River, upstream of Maules Creek between Baan Baa and Boggabri	1	1333	Gaining
14	Namoi River, upstream of Boggabri	1	425	Gaining
15	Coxs Creek flowing into Namoi River from the southwest at Boggabri	1	1547	Gaining
20	Jacks Creek (ephemeral) west of Longwall Project area	1	-2633	Losing

* Positive values indicate baseflow. Negative values indicate recharge from the stream to the groundwater.

6.3.4 Transient Model Calibration

The aim of the transient calibration was to try to improve the model calibration by means of a history match to the observed groundwater levels during the period November 2007 to September 2008. Although the observed hydrographs show little response to seasonal rainfall variations, the transient calibration did allow storativity values to be assessed, as the storativity parameter cannot be assessed with a steady state model. Baseline water level hydrographs from all the monitored bores across the model area were used in the calibration process. The river stages in the model were held constant during the calibration simulation.

The heads generated by the steady state model were used as the initial head conditions in the transient model calibration. The transient calibration process involved further manual changes to aquifer parameter values (hydraulic conductivity, unconfined specific yield and confined storage coefficient) within reasonable limits (constrained by available data and hydrogeological knowledge of the area), until reasonable matches were obtained between the observed and simulated hydrographs.

The simulated versus observed hydrographs are plotted for all 18 bores used during calibration in **Appendix G**. The hydrographs in most cases illustrate a good replication of actual water level responses to the seasonal recharge pattern. Contour plans of modelled and measured potentiometric head also show good visual agreement, which is also reflected in the scatter plot of modelled versus measured potentiometric heads. The associated statistical measure of the scaled root mean square (SRMS) value was 10.06%, as shown in **Table 6.5**.

Table 6.5: Transient Calibration Performance of the Groundwater Model

Calibration Parameters		Value	
Count	n	155	
Scaled Mean Sum of Residuals	SMSR	-1.82	%
Root Mean Square	RMS	8.36	m
Scaled RMS	SRMS	10.06	%
Root Mean Fraction Square	RMFS	3.68	%
Scaled RMFS	SRMFS	11.09	%
Coefficient of Determination	CD	1.68	

The water budget for the transient model is shown in **Table 6.6**.

Table 6.6: Groundwater Budget for Narrabri Model Transient Calibration

Component	Groundwater Inflow (ML/d)	Groundwater Outflow (ML/d)
Recharge	26.58	8.62
River Leakage	14.88	25.16
GHB	0.00	8.52
Well	0.00	0.00
Storage	2.26	1.52
Total	43.72	43.82
Discrepancy (%)	0.01	

Table 6.6 shows that:

- The major input to the system is rainfall recharge, at 61% of total inputs.
- The major output is leakage from the groundwater to the river-stream system (baseflow) at 57% of total outputs.
- The net baseflow leakage to the rivers and streams is around 10.3 ML/d, comprising baseflow in the gaining reaches of 25.2 ML/d (57% of groundwater outflows) and discharge to groundwater in the losing reaches of 14.9 ML/d (33% of groundwater inflows).
- Other outputs are head dependent outflow at the model boundary (19%).

The water balance shows an acceptable discrepancy between inflows and outflows of 0.01%.

6.3.5 Calibration Outcomes

The calibrated aquifer hydraulic parameters resulting from the steady and transient model calibration are summarised in **Table 6.7**. Detailed maps for the hydraulic parameter zones for each layer are presented in **Appendix F**.

Table 6.7: Calibrated Narrabri Model Aquifer Parameters

Main Layer	Aquifer/Aquitard	Kh (m/d)	Kv (m/d)	Unconfined Sy	Confined Sc
1	Alluvium	0.265 - 5	0.0005 – 0.005	0.1	5E-6
2	Pilliga Sandstone	0.004 – 0.265	0.000015 – 0.002	0.1	5E-6
3	Purlawaugh Formation	0.004 – 0.02	0.000015 – 0.0011	0.001	5E-6
4	Garrawilla Volcanics	0.001 – 0.04	0.000006 – 0.001	0.002	5E-6
5	Napperby Formation (above Sill)	0.001 – 0.012	0.0001	0.001	5E-6
6	Basalt Sill	0.004 – 0.021	0.00005	0.002	5E-6
7	Napperby Formation (below Sill)	0.004 – 0.04	0.000024	0.001	5E-6
8	Digby Formation	0.0005 – 0.04	0.000015	0.001	5E-6
9	Hoskissons Coal	0.005 – 0.04	0.000006	0.001	5E-6
10	Arkarula Formation	0.0005 – 0.04	0.000001	0.0015	5E-6
11	Basement	0.01	0.001	0.005	5E-6

In general, overall simulated transient hydrograph results coincided very well with the actual hydrographs, confirming the model as a good predictive tool to simulate the multi-layer Narrabri aquifer system.

6.4 Sensitivity Analysis

The SRMS value is the major quantitative performance indicator, and is calculated as the RMS value divided by the range of measured heads across the site. Given uncertainties in the overall water balance volumes (e.g. it is difficult to directly measure evaporation, or baseflow into the creeks), it was considered that a 10% SRMS value on aquifer water levels would be an appropriate target for this project, consistent with the Australian best practice modelling guideline (MDBC, 2001). Quantifying the change in SRMS value with individual changes in parameter values is therefore a method of measuring the model sensitivity to specific parameters.

Sensitivity 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 sequentially changing key input parameters or boundary conditions, and evaluating the impacts of the changes on the SRMS calibration statistic. Any parameter change that resulted in a significant change to the SRMS statistic was identified as a sensitive parameter in the model. The base SRMS value for the sensitivity runs was 9.94%.

Sensitivity analysis was carried out on:

- Hydraulic conductivity (horizontal and vertical)
- Recharge.

Table 6.8 summarises the parameters and the spatial zones that were tested during the sensitivity analysis.

Table 6.8: Parameters, Zones and the Multipliers Tested in the Sensitivity Analysis

Parameter	Layer	Calibrated Value	Zone	Model	Multiplier
Horizontal Hydraulic Conductivity	1	5 m/d	2	Steady-state	0.5, 2
	2	0.5 m/d	3	Steady-state	0.5, 2
	2	0.5 m/d	1	Steady-state	0.5, 2
	3	0.2 m/d	4	Steady-state	0.5, 2
	4	0.3 m/d	6	Steady-state	0.5, 2
	8	0.001 m/d	8	Steady-state	0.5, 2
	5	0.05 m/d	12	Steady-state	0.5, 2
	11	0.01 m/d	5	Steady-state	0.5, 2
	9	0.005 m/d	10	Steady-state	0.5, 2
	7	0.008 m/d	7	Steady-state	0.5, 2
	6	0.01 m/d	9	Steady-state	0.5, 2
	6	0.008m/d	18	Steady-state	0.5, 3
	10	0.001 m/d	11	Steady-state	0.5, 2
Vertical Hydraulic Conductivity	1	0.005 m/d	2	Steady-state	0.1, 10
	2	0.0005 m/d	3	Steady-state	0.1, 10
	2	0.0005 m/d	1	Steady-state	0.1, 10
	3	0.0002 m/d	4	Steady-state	0.1, 10
	4	0.0003 m/d	6	Steady-state	0.1, 10
	8	0.000015 m/d	8	Steady-state	0.1, 10
	5	0.0001 m/d	12	Steady-state	0.1, 10
	11	0.001 m/d	5	Steady-state	0.1, 10
	9	0.000006 m/d	10	Steady-state	0.1, 10
	7	0.000024 m/d	7	Steady-state	0.1, 10
	6	0.00005 m/d	9	Steady-state	0.1, 10
	6	0.000008 m/d	18	Steady-state	0.1, 11
	10	0.000001 m/d	11	Steady-state	0.1, 10
Recharge	Applied to Highest Active Layer	1.90%	1	Steady-state	0.5, 2
		1%	2	Steady-state	0.5, 2
		0.50%	3	Steady-state	0.5, 2
		5%	4	Steady-state	0.5, 2
		0.50%	5	Steady-state	0.5, 2
		0.50%	6	Steady-state	0.5, 2

For zone numbers, refer to **Appendix F**

Hydraulic Conductivity

Horizontal hydraulic conductivity zones in the model were tested by firstly decreasing the calibrated model values (multiplier of 0.5) and then increasing the values (multiplier of 2). Due to a greater level of uncertainty with vertical hydraulic conductivity, vertical values were tested by applying factors of 0.1 and 10. The results for the horizontal hydraulic conductivity (Kh) and vertical hydraulic conductivity (Kv) sensitivity analysis are summarised in Table 6.9. Figure 6.9 shows how the SRMS value changed with multipliers applied to each tested model parameter, compared with the steady-state model SRMS.

Table 6.9: Sensitivity Analysis of Horizontal and Vertical Hydraulic Conductivity Values in the Narrabri Model

Formation	Layer	Zone	Horizontal Hydraulic Conductivity (m/d)	Multi-plier	SRMS (%)	Vertical Hydraulic Conductivity (m/d)	Multi-plier	SRMS (%)
Alluvium/regolith	1	2	5	0.5	10.15	0.005	0.1	9.96
				1	**9.94**		**1**	**9.94**
				2	9.79		10	9.94
Pilliga Sandstone	2	3	0.265	0.5	11.47	0.0005	0.1	9.64
				1	**9.94**		**1**	**9.94**
				2	9.87		10	9.94
Purlawaugh	3	4	0.02	0.5	9.96	0.0002	0.1	9.92
				1	**9.94**		**1**	**9.94**
				2	10.05		10	9.97
Garrawilla Volcanics	4	6	0.024	0.5	9.93	0.0003	0.1	9.9
				1	**9.94**		**1**	**9.94**
				2	9.96		10	9.97
Napperby Formation (above Sill)	5	12	0.001	0.5	9.93	0.00001	0.1	9.88
				1	**9.94**		**1**	**9.94**
				2	9.97		10	10.2
Basalt Sill	6	9	0.004	0.5	9.9	0.00001	0.1	10.99
				1	**9.94**		**1**	**9.94**
				2	10.03		10	10.2
Napperby Formation (Sill)	6	18	0.12	0.5	9.93	0.00005	0.1	9.87
				1	**9.94**		**1**	**9.94**
				2	9.98		10	9.95
Napperby Formation (Below Sill)	7	7	0.007	0.5	9.92	0.000008	0.1	9.58
				1	**9.94**		**1**	**9.94**
				2	9.97		10	10.1
Digby Formation	8	8	0.021	0.5	9.94	0.000024	0.1	9.54
				1	**9.94**		**1**	**9.94**
				2	9.99		10	10.22
Hoskissons Seam	9	10	0.004	0.5	9.95	0.000015	0.1	9.96
				1	**9.94**		**1**	**9.94**
				2	9.93		10	9.98
Arkarula Formation	10	11	0.005	0.5	10	0.000006	0.1	10.05
				1	**9.94**		**1**	**9.94**
				2	9.87		10	9.98
Basement	11	5	0.0005	0.5	9.94	0.000001	0.1	10.41
				1	**9.94**		**1**	**9.94**
				2	9.94		10	9.87

Sensitivity analysis for Kh was completed on all 12 model layers. The sensitivity analysis for horizontal conductivity shown in **Figure 6.8** indicates Zone 3 (Pilliga Sandstone Layer 2) to be the most sensitive in comparison to other zones. Multiplying Kh by a factor of 0.5 and 2 in the Pilliga Sandstone (Layer 2 – 0.5m/d calibrated value) caused only a 15.4% and -0.7% change respectively in the SRMS. In some other zones there was a slightly smaller increase in the SRMS when Kh was either doubled or halved. In all other layers, the model was found to be even less sensitive. Hence, overall, the model is not highly sensitive to horizontal conductivity.

Sensitivity analysis results for vertical conductivity are also shown in **Table 6.9** and **Figure 6.8.** All zones show small variations in SRMS values, ranging between 9.54% and 10.99%. The Napperby Formation above the sill (Layer 5) was found to be the most sensitive to a ten-fold increase in Kv, giving small increases in SRMS of 10%. When the Kv was decreased by a factor of 10, the SRMS value for the Napperby Formation above sill (Layer 5) increased by 2.6%, and for the basement an SRMS increase of 6% resulted from increasing or decreasing the calibrated value by a factor of 10. These results show that overall, the model is not sensitive to vertical conductivity.

In summary, the model was not found to be highly sensitive to either horizontal or vertical hydraulic conductivity. However, it was assessed that the model would likely be sensitive to the hydraulic properties that were assumed for the subsidence fracture zone extending up from the goaf that is used for predictive modelling in **Section 6.5.**

Recharge

Model sensitivity to recharge was tested by changing recharge percentages in each of the six recharge zones in turn by factors of 0.5 (decrease) and 2 (increase). The results of the recharge sensitivity analysis are presented in **Table 6.10**.

The sensitivity analysis for recharge shown in **Figure 6.8** indicates that Zone 3 is the most sensitive to recharge value. The SRMS value in Zone 3 (at 12.03%) is 21% higher than the calibrated SRMS value when the base case recharge is doubled.

Table 6.10: Sensitivity Analysis of Recharge

Sensitivity to Recharge				
ZONE	CALIBRATED VALUE	LAYER	MULTIPLIER	SRMS (%)
1	1.9%	Applied to Highest Active Layer	0.5	9.92
			1	**9.94**
			2	9.97
2	1%	Applied to Highest Active Layer	0.5	9.65
			1	**9.94**
			2	10.41
3	0.5%	Applied to Highest Active Layer	0.5	9.67
			1	**9.94**
			2	12.03
4	1%	Applied to Highest Active Layer	0.5	10.62
			1	**9.94**
			2	9.75
5	0.5%	Applied to Highest Active Layer	0.5	9.85
			1	**9.94**
			2	10.06
6	0.5%	Applied to Highest Active Layer	0.5	9.93
			1	**9.94**
			2	9.97

6.5 Predictive Modelling

The overall objective of the predictive modelling was to assess the potential impacts of the Longwall Project on the groundwater environment, specifically with regard to:

- Predicted mine inflow rates;
- Regional changes in groundwater levels, both during mining and after mine closure;
- Changes in baseflow contributions to surface watercourses, particularly the Namoi River system.

Predictions for the Narrabri Model have been carried out in accordance with the proposed mining schedule outlined in **Figure 5.1**. Predictions have also been made for a 100 year period of post-mining recovery.

The “Base Case” simulation of potential mining impacts involved a simulation comprising 14 time slices, with the first time slice representing 3 years and each of the others representing 2 years, for a 29 year total mine life. The calibrated set of boundary conditions and hydraulic properties (**Table 6.7**) was adopted for the Base Case, except that the hydraulic properties of the model cells within the region above the longwall goafs are changed progressively to reflect progressive effects of subsidence fracturing. The approach followed in changing the fracture zone properties is described in **Section 6.5.3**.

Uncertainty in the predicted outcomes has been assessed by re-running the base case model with a range of different assumed values for selected sensitive hydraulic parameters in the subsidence affected zone above mined longwall panels, as described in **Section 6.6**.

6.5.1 Time Scale Selection

In order to simulate the change in hydraulic properties that occurs above extracted longwall panels during mining, it is necessary to be able to change the hydraulic properties of selected model cells during the predictive simulation. Specifically, models cells for the Hoskissons Seam (Layer 9) initially have coal seam properties, then progressively goaf properties as mining develops. Likewise, the overburden in Layers 5 to 8 overlying the coal seam initially has in-situ rock properties, but these change following coal extraction, as fracturing occurs within the overlying subsidence zone.

As indicated in **Section 6.1**, MODFLOW-SURFACT does not allow changing of hydraulic conductivity parameters with time during a single simulation. Hence, successive ‘time slice’ models of short duration (generally 2 years) have been used, to allow parameters to be changed for each time slice in specific areas to represent the underground mining advance and the progressive expansion of the subsidence failure zone.

Two year time slices with 1 year stress periods were used, matched to the mine schedule shown on **Figure 5.1**. The output heads from each time slice model were used as starting heads for the next successive time slice, and hydraulic conductivities changed to reflect subsided strata above the extraction area for that time slice. This process was repeated until the entire mine plan had been simulated.

Fourteen (14) time slices were used to represent the 29 year mining operation. Time slices were split into 1 year stress periods. A stress period is the time frame in the model when all hydrological stresses (e.g. recharge, mine dewatering) remain constant. **Table 6.11** outlines the model stress period set-up adopted for the prediction model runs (i.e. the base case model run). For the purposes of modelling, we have assumed that longwall development will start at the beginning of 2010.

Table 6.11: Narrabri Model Stress Period Setup

Time Slice	Stress Period (Mine Year No)	From	To	Development Headings	Longwall Extraction
Time Slice 1	1	1/01/2010	31/12/2010	LW1	
	2	1/01/2011	31/12/2011	LW2	
	3	1/01/2012	31/12/2012	LW3	LW1
Time Slice 2	4	1/01/2013	31/12/2013	LW4	LW2 LW3
	5	1/01/2014	31/12/2014	LW5 LW6	LW4 LW5
Time Slice 3	6	1/01/2015	31/12/2015	LW7	LW6
	7	1/01/2016	31/12/2016	LW8	LW7
Time Slice 4	8	1/01/2017	31/12/2017	LW9	LW8
	9	1/01/2018	31/12/2018		
Time Slice 5	10	1/01/2019	31/12/2019	LW10	LW9
	11	1/01/2020	31/12/2020	LW11	LW10
Time Slice 6	12	1/01/2021	31/12/2021	LW12	LW11
	13	1/01/2022	31/12/2022	LW13	LW12
Time Slice 7	14	1/01/2023	31/12/2023	LW14	
	15	1/01/2024	31/12/2024	LW15	LW13
Time Slice 8	16	1/01/2025	31/12/2025		LW14

Time Slice	Stress Period (Mine Year No)	From	To	Development Headings	Longwall Extraction
				LW16	
	17	1/01/2026	31/12/2026		LW15
				LW17	
Time Slice 9	18	1/01/2027	31/12/2027		LW16
				LW18	
	19	1/01/2028	31/12/2028		
				LW19	LW17
Time Slice 10	20	1/01/2029	31/12/2029		
				LW20	LW18
	21	1/01/2030	31/12/2030		
				LW21	LW19
Time Slice 11	22	1/01/2031	31/12/2031		
				LW22	LW20
	23	1/01/2032	31/12/2032		
Time Slice 12	24	1/01/2033	31/12/2033	LW23	LW21
	25	1/01/2034	31/12/2034	LW24	LW22
Time Slice 13	26	1/01/2035	31/12/2035	LW25	LW23
	27	1/01/2036	31/12/2036	LW26	LW24 and LW25
Time Slice 14	28	1/01/2037	31/12/2037		LW26
	29	1/01/2038	31/12/2038		

6.5.2 Simulation of Mine Inflows

Mined areas in each time slice model included both development headings and longwall panels. Both areas were represented in the model by drain cells in Layer 9 (Hoskissons Seam) using the MODFLOW drain (DRN) function. Modelled drain elevations were set to 1m above the base of the seam.

The drain cell conductance parameter adopted for underground mining was 1000 m^2/d. The drain conductance value reflects the resistance to flow between the surrounding material and the mined-out seam. The value used in this case is sufficiently high so as not to limit the free inflow of groundwater to the workings.

6.5.3 Simulation of Goaf and Subsidence Fracturing

The development headings were represented only by drains in the seam (Layer 9), whereas the longwall panels were represented by drains in Layer 9 as well as by changed hydraulic parameters in both the seam (Layer 9) and in some of the overlying layers (Layers 5 to 8) in accordance with the panel progression and the predicted heights of subsidence impacts.

Drains were activated in both development headings and extraction panels in advance (i.e. at the start of the simulation for all cells to be mined in that period), whereas changes to hydraulic properties above the panels were delayed until the next time slice (i.e. until after the relevant panel area has been mined).

6.5.4 Predicted Mine Inflow Rates

Mine inflow rates in the Narrabri Model were calculated by the weighted average method, in which the model-calculated inflow rate at the end of each time step is multiplied by the duration of the time step, and the volumes are then summed for all time steps in each stress period, and divided by the stress period time (i.e. essentially a step-wise integration of the area under the inflow curve).

Table 6.13 and **Figure 6.9** show the predicted Narrabri mine inflow rates from the base case model simulation during the 29 years of operational mining. Total predicted mine inflows at Narrabri range from 78 ML/a in Mine Year 1 up to a maximum of 1419 ML/a in Mine Year 18 (i.e. 0.21 ML/d to 3.89 ML/d). It is seen that inflows peak in Years 18 - 20 (2027-2029), during the mining of LW15 - LW17. Thereafter, inflow rates steadily decline, as mining retreats further up-dip to the east and groundwater is allowed to flow back into the down-dip goaf areas.

Figure 6.10 shows the mass balance for the Digby Formation (Layer 8), Hoskissons Seam (Layer 9) and Arkarula Formation (Layer 10) for the area occupied by the mine footprint in the final time slice of the modelled mine schedule (Years 27 – 29). It shows that in the Digby Formation and the Hoskissons Seam, groundwater flow is dominated by migration from above through the fractured zone. There is a relatively small proportion of lateral flow except for early in the time step as the model settles down. Also apparent is the relatively small upward transfer of groundwater from the Arkarula Formation (Layer 10) below the coal seam.

Table 6.12: Predicted Annual Narrabri Pit Inflow Rates (Base Case)

Mine Year	Weighted Average Inflow Rate		
	m^3/d	ML/d	ML/a
1	213	0.21	78
2	226	0.23	83
3	337	0.34	123
4	923	0.92	337
5	914	0.91	334
6	1393	1.39	508
7	1386	1.39	506
8	1746	1.75	637
9	1771	1.77	646
10	2099	2.10	766
11	1999	2.00	730
12	2508	2.51	915
13	2381	2.38	869
14	3118	3.12	1138
15	2901	2.90	1059
16	3554	3.55	1297
17	3328	3.33	1215
18	3889	3.89	1419
19	3773	3.77	1377
20	3837	3.84	1401
21	3807	3.81	1390
22	2623	2.62	958
23	3019	3.02	1102
24	1956	1.96	714
25	2281	2.28	832
26	1559	1.56	569
27	1709	1.71	624
28	1174	1.17	429
29	1454	0.21	531

6.5.5 Recovery Simulation

Post-mining recovery was simulated for a period of 100 years from the completion of mining.

It is understood that following mining, there will be a requirement to dispose of saline water stored within surface containment areas which was pumped from the mine during the mine life. The volume of water required to be disposed of is understood to be 2018 ML. Re-injection of the stored water was simulated within the groundwater model by reinjecting over a two year period into 20 re-injection bores screened within the goaf zone (i.e. Layer 9 – Hoskissons Seam). Selected large diameter gas extraction bores will be used for saline water re-injection.

A 2 year re-injection period was used to ensure that groundwater levels did not rise to elevations which would have allowed saline water to enter the Garrawilla Volcanics via the subsidence zone. This was verified by trial model runs to assess the height of water level rise during re-injection of this volume of brine over selected time periods. With a 2 year re-injection period, it was found that water levels in the goaf area do not rise above the top of the Napperby Formation during the re-injection period.

Hence the first 2 years of the post-mining recovery period involved the re-injection of the brine. The predicted water levels at the end of re-injection (Year 31) were used as the initial conditions for modelling the remaining 98 years of the recovery period.

Goaf and fracture zone parameters were retained in the cells within the longwall panels and the overlying fracture zone throughout the recovery period. All drains had been deactivated prior to commencement of saline water re-injection.

6.5.6 Predicted Water Level Drawdowns

Figures 6.11 and **6.12** show predicted groundwater levels in Model Layer 1 (Alluvium) at the midpoint of the mine life (Year 15) and at end of mining (Year 29).

Figures 6.13 to **6.20** show predicted drawdowns in Model Layer 1 (Alluvium), Layer 4 (Garrawilla Volcanics), Layer 5 (Napperby Formation above the sill) and Layer 9 (Hoskissons Coal Seam) at Year 15 and at completion of mining (Year 29).

Figures 6.21 to **6.24** show predicted residual drawdowns in Model Layer 1 (Alluvium), Layer 4 (Garrawilla Volcanics), Layer 5 (Napperby Formation above Sill) and Layer 9 (Hoskissons Coal Seam) at the end of the recovery period (Year 129).

Hydrographs of predicted water level drawdown and recovery at key Narrabri monitoring bore locations, and two selected locations in the Namoi Valley alluvium between the mine and the valley, set in the alluvium/colluvium/regolith (Layer 1) and the basement layer (Layer 11), are presented in **Appendix H**. In summary, the drawdown plots and hydrographs show the following:

- Drawdowns in the Namoi Valley alluvium (Layer 1) are predicted to be less than 0.1m.
- Drawdowns in the water table within the regolith (Layer 1) at the end of mining are predicted to be less than 1 m outside the mine footprint area and limited to areas close to the mine. Within the mine footprint area, drawdown is limited to less than a maximum of 5 m.
- Within the Napperby Formation above the sill (Layer 5), drawdowns of up to 5m are predicted adjacent to the mine at the end of mining. Predicted drawdowns of 1m or more are limited to the area within 0.5 km of the mine.
- At the end of the 100 year recovery period, water levels in all hydrogeological units are predicted to have recovered to close to pre-mining levels.

6.5.7 Predicted Baseflow Impacts

The impact of mining on groundwater baseflow discharges to Namoi River, Maules Creek and Jacks Creek has been assessed from the results of the Base Case predictive model run. Baseflows were examined separately for each of the six river reaches designated on **Figure 6.7**.

Baseflow impacts have been assessed through the 29 year mining period and the subsequent 100 year recovery period.

Figure 6.27 shows the predicted baseflows and baseflow changes for the six river reaches over the 29 year mining period, and **Figure 6.28** shows the baseflows and baseflow impacts, from the commencement of mining (Year 0) to the end of the 100 year recovery period (Year 129).

Most of the river reach baseflows are stable during the mining period. A small reduction in groundwater baseflow to the closest reach of Namoi River (Reach 11) is predicted, starting in Year 4, and steadily increasing as mining proceeds to a maximum of 0.22 ML/d during mine years 23-24, as shown on **Figure 6.27**. The maximum predicted baseflow impact during mining represents about a 2% reduction in the pre-mining baseflow in Reach 11, but an insignificant percentage of total streamflow in the Namoi River.

It should be noted that Reach 20 (Jacks Creek) is not in the Namoi River valley but is part of an ephemeral drainage system in the western part of the model domain which drains to the Namoi River to the north, outside of the model domain.

6.5.8 GAB Intake Beds

The impact of mining on groundwater outflow to the GAB intake beds has been assessed by means of the outflows from the General Head Boundary cells along the north-western boundary of the model.

The results of the Base Case predictive model run have shown that the project has a very low impact on this flux. Groundwater flux across the general head boundaries in Layers 2 to 4 (Pilliga Sandstone to Garrawilla Volcanics, which constitute the intake beds to the GAB) changes by less than 0.03 ML/d (less than 0.4%) as a result of mining operations. That is, the flux changes from 8.48 ML/d at the start of mining operations to 8.45 ML/d at Year 29.

6.5.9 Particle Tracking

Particle tracking was undertaken on the recovery model to assess the potential for re-injected brine to migrate from the goaf to hydrogeological units of the Gunnedah Basin, Great Artesian Basin and/or Namoi Alluvium Ground Water Management Areas.

For the particle tracking, particles were inserted into each corner of the mine plan in each model layer from Layer 2 to Layer 9, and to a number of other points outside the mine footprint area, to establish the groundwater flow patterns and direction during the 100 year post-mining recovery period. This was done to assess the potential for offsite migration of the injected brine. **Figures 6.25** and **6.26** show particle tracking vectors for the 100 year recovery model for the Jurassic strata (Layers 2, 3 and 4) and Permian – Triassic strata (Layers 5, 6, 7, 8 and 9) respectively.

When mining is completed and dewatering ceases, groundwater will start to flow back into the drawdown zone created by the 29 years of dewatering. Hence, groundwater will flow radially towards the mine area from the outer edges of the drawdown “cone”. However, as the groundwater levels will become elevated within the goaf area during the 2 year brine re-injection period, there will also be an inner region where groundwater will have the potential to initially flow outwards from the goaf area into the drawdown zone. We have therefore concentrated on this inner region, looking at the distances travelled by particles, and also whether there is any upward migration to higher model layers.

Figure 6.25 shows the paths of particles starting at the edges of the goaf, and shows that groundwater flow directions within the Jurassic strata will trend away from the mine footprint except at the northern end of LW1, where initial flow direction is towards the centre of the mine footprint. The distance predicted to be travelled by particles in the simulated 100 year recovery period is limited to less than 1km from the mine area in all directions.

Figure 6.26 shows similar groundwater flow directions within the Permian – Triassic strata, initially trending away from the goaf area. The potential for injected brine to migrate offsite in the 100 year recovery period within the Permian – Triassic strata is limited to less than 2km from the mine footprint area to the north and generally less than 1 km elsewhere. The larger vector from the northern end of LW14 occurs in the highly fractured goaf zone within the coal seam layer (Layer 9) where hydraulic conductivity is highest.

In most cases, the particle tracking shows that particles stay within the layer from which they started. Where interchange between geological units does occur, the movement is downward to the underlying layer. No upward migration to a higher layer occurs.

In summary, the particle tracking has shown that any migration of saline water from brine re-injection will have moved less than 2km maximum, and in most cases less than 1km from the mine, in 100 years after cessation of mining. Importantly, there will be no upward migration to the GAB formations.

6.6 Uncertainty Analysis

Uncertainty analysis is an assessment of the impact that uncertainty in the assumed values of the input hydraulic parameters has on model predictions and model reliability.

The sensitivity analysis (**Section 6.4**) showed that there were no hydraulic parameter values that had a significant impact on the model calibration.

The subsidence prediction (DGS, 2009) included the possibility that continuous fracturing could extend into the Garrawilla Volcanics, although this was considered to be a low probability outcome. Nevertheless, it was considered prudent to assess the impact of this uncertainty on inflow predictions.

Secondly, it was assessed that the model would likely be sensitive to the hydraulic properties assumed for the subsidence fracture zone extending up from the goaf, and in the absence of prior experience with longwall mining in the Gunnedah Basin, it was considered prudent to also carry out an uncertainty run with higher and lower vertical hydraulic conductivities for the portions of Layers 5 to 8 within the longwall footprint.

And finally, it was also assessed that the changed hydraulic parameters assumed within the fracture zone may reduce slightly with time as settling and/or redistribution of fines occurs. In this scenario, fracture zone parameters were reduced to midway between the base case fracturing and the host properties, with a lag factor of approximately 1-2 years.

These three scenarios have been evaluated in the uncertainty analysis modelling. The base case model in each case was modified by incorporating the uncertainty parameters being evaluated. The model was then run through the full 14 time slices representing the 29 year mine life. The hydraulic conductivity values tested in the three uncertainty runs are listed in **Table 6.14**.

Table 6.13: Mine Area Hydraulic Conductivity Values for Uncertainty Analysis Simulations (m/d)

Layer	Unit	Base Case				Higher Kv and Kh in L5 – L8		Subs Zone to Layer 4	Lower Kv in L5 - L8 (Kv x 0.5)
		Outside Subs Zone		Inside Subs Zone					
		Kh	Kv	Kh	Kv	Kh	Kv	Kv	Kv
1	Regolith	5	5×10^{-3}	5	5×10^{-3}	5	5×10^{-3}	5×10^{-3}	5×10^{-3}
2	Pilliga Fm	0.265	5×10^{-4}	0.265	5×10^{-4}	0.265	5×10^{-4}	5×10^{-4}	5×10^{-4}
3	Purlawaugh Fm	0.02	2×10^{-4}	0.02	2×10^{-4}	0.02	2×10^{-4}	2×10^{-4}	2×10^{-4}
4	Garrawilla Volc	0.024	3×10^{-4}	0.024	3×10^{-4}	0.024	3×10^{-4}	6×10^{-4}	3×10^{-4}
5	Napperby Fm (> sill)	0.001	1×10^{-5}	0.008	2.5×10^{-5}	0.008	2.5×10^{-4}	2.5×10^{-5}	2.5×10^{-5}
6	Napperby Fm (sill)	0.008	8×10^{-6}	0.014	2×10^{-5}	0.014	2×10^{-4}	2×10^{-5}	2×10^{-5}
7	Napperby Fm (< sill)	0.021	2.4×10^{-5}	0.016	2.4×10^{-4}	1	0.1	2.4×10^{-4}	1.2×10^{-4}
8	Digby Fm	0.004	1.5×10^{-5}	0.008	3×10^{-4}	5	3×10^{-3}	3×10^{-4}	3×10^{-4}
9	Hoskissons Seam	0.005	6×10^{-6}	10	10	10	10	10	10
10	Arkarula Fm	0.0005	1×10^{-6}	0.0005	1×10^{-6}	0.0005	1×10^{-6}	1×10^{-6}	1×10^{-6}
11	Basement	0.04	1×10^{-3}	0.04	1×10^{-3}	0.04	1×10^{-3}	1×10^{-3}	1×10^{-3}

The uncertainty analysis modelling results are illustrated graphically in **Figure 6.29**. The base case inflow prediction is shown on this figure for comparison. It is seen that extending the subsidence altered zone higher into the Garrawilla Volcanics has only a minor influence on predicted inflows. The peak inflow rate of 3.88 ML/d is very slightly above the base case peak inflow rate.

However, increasing Kh and Kv for all layers (L5 to L8), or reducing Kv for all layers (L5 to L8) within the subsidence failure zone may have a more significant impact. It is predicted that peak inflows could increase to 5.23 ML/d in this if the Kh and Kv of the substantial zone are of an order of magnitude higher than assumed in the base model. A reduction in Kv to mid way between host and base case hydraulic properties causes a predicted peak inflow reduction to around 3.13ML/d.

Due to the lack of prior longwall mining experience in the Gunnedah Basin against which to calibrate the model it is considered prudent to prepare a contingency plan for the event that inflow rates may be up to 5.22 ML/d during the middle period of the project.

In conclusion, the most likely inflow rate is represented by the base case, which reaches a peak rate of 3.82 ML/d. There is a low probability that inflows could be as high as 5.23 ML/d, with the peak inflow rate occurring in Years 18 - 19.

7. POTENTIAL GROUNDWATER IMPACTS OF THE PROJECT

The Stage 2 Longwall Project will impact on the groundwater environment on a local and, to a lesser extent, regional scale. The base-case groundwater model was used to predict the impacts. Modelling results were presented in **Section 6**. The Narrabri mine plan and schedule are as outlined in **Section 5**.

Potential impacts to the groundwater system may include the following aspects, each of which is discussed in further detail in the following sections:

- Groundwater inflows (volume and quality)
- Groundwater level impacts (during and post-mining)
- Potential impacts on groundwater and surface water quality
- Potential impacts on baseflow to Namoi River and its tributaries
- Potential impacts of brine re-injection
- Potential impacts on other groundwater users
- Potential impacts on Groundwater Dependent Ecosystems (GDEs).

This section starts with a discussion of the potential impacts of subsidence cracking on the hydraulic properties of the strata overlying the underground mine.

7.1 Potential Impacts of Subsidence Fracturing from Longwall Mining

Subsidence will occur above the longwall panels, and consequential fracturing of the rock mass within the subsidence zone will result in changes in permeability. The influence of subsidence on permeability as a result of the development of “direct connected cracking” or “discontinuous cracking” has been modelled.

Subsidence modelling undertaken by Ditton Geotechnical Services (DGS, 2009) has predicted that there is a low probability that continuous subsurface cracking would extend past the base of the Garrawilla Volcanics, due to the potential bridging effect of the Garrawilla Volcanics. Continuous fracturing is more likely to be contained within the Gunnedah Basin Permian-Triassic sediments, extending to the top of the Napperby Formation above the basalt intrusion.

The continuous fracturing induced by longwall mining has the potential to increase groundwater inflows into the underground workings, and the effects of this have been built into the groundwater modelling. The Garrawilla Volcanics are reported to have the highest hydraulic conductivity among the hard rock units above the proposed mine, and the consequences of continuous fracturing extending up into that unit have been assessed with the model, and are reported in **Section 6.6**. Although this is considered unlikely, it is in any case predicted to have only a small additional impact. The model reviews that are recommended to be carried out periodically once operational calibration data are available, as discussed in **Section 8**, will allow the predictive model to be modified and future impacts revisited during the early years of mining before the peak inflow period is reached.

Shallow surface cracking and discontinuous subsurface cracking may impact on shallow groundwater such as at the base of the weathered zone within the subsidence zone. It is likely that long-term these affects will not be extensive or permanent as the surface fractures are expected to close up or become infilled with fine sediments over time.

7.2 Groundwater Inflows

Groundwater inflow predictions are for a moderate rate of groundwater inflow, commencing at 0.21 ML/d in Year 1, and increasing to a peak rate of 3.82 ML/d in Year 20. Thereafter, inflow rates are predicted to decline as water is allowed to recover into the goaf areas of completed longwall panels in areas downdip of the active mining.

Modelling has shown that if connected fracturing extends up into the Garrawilla Volcanics, a slight increase in the peak inflow rate to 3.85 ML/d may occur.

In the unlikely event that vertical permeabilities are increased by a significantly greater amount than anticipated in the subsidence zones above the longwall goafs, inflow rates peaking at up to 5.23 ML/d may occur.

There is a high level of uncertainty in the prediction of groundwater inflows as there is no prior experience with longwall mining in the Gunnedah Basin. Consequently, a conservative approach has been taken in the modelling to predict possible inflow rates. Experience from other areas has assisted with the process of assigning realistic hydraulic properties to the subsidence zone above the extracted longwall panels. Examination of drill cores and hydraulic testing results suggests that the hydrogeological properties of the overburden units at Narrabri will be closer to those applying to the central part of the Hunter Valley Coalfields than either the Western Coalfields or the Southern Coalfields. Hence, a greater reliance has been placed on operating experience from that area.

A number of elements of conservatism have been built into the assessment of inflows:

- Firstly, it is possible that representative hydraulic properties assumed for each model layer may be too high. The values used have been influenced principally by the results of hydraulic testing, however this does not acknowledge that the construction of piezometers and the hydraulic testing has been carried out preferentially on bores that intersected measurable groundwater inflows, whereas most drillholes drilled dry below the regional water table or potentiometric level. Hence the dataset is skewed towards the more permeable locations, and ignores the numerous locations that are essentially impermeable.
- Secondly, all model layers have been assumed to be regionally hydraulically continuous. It is likely that hydraulic barrier boundaries will be found to exist within the vicinity of the mine that will at least partly reduce the regional extent or magnitude of drawdown impact and therefore the groundwater inflows as well. These hydraulic barriers which may coincide with either major or minor faults and other geological structures, or with zones of reduced permeability in the rock, are common in practice but can only be identified under extended pumping or dewatering conditions. It is likely that some partial hydraulic barriers will be found to exist in the area of predicted impact that will lead to a reduction in actual inflow rates.

- Thirdly, no allowance has been made in the base case modelling for any subsequent reduction in permeability of the subsidence-affected strata over time, or reduction in lateral flows due to the dislocation of fracture flow paths by the subsidence effects. Some locations in the central Hunter Valley have shown signs of apparent "healing" or infilling of subsidence fractures reasonably soon after subsidence occurs, leading to a reduction in ongoing drawdowns and inflows.

Consequently, groundwater inflows have been based on the available information, but may prove to have been overestimated. It is essential that the first few longwall panels be closely monitored, so that operational experience of longwall mining in the Gunnedah Basin conditions can be gained as quickly as possible. This experience will allow a greater confidence to be placed on forward predictions of both inflow rates and other impacts.

Limited experience will be gained from the gateroad development once the drift reaches the seam level, anticipated around the end of 2009. However, as there will be no subsidence associated with gateroad development, the inflow rates that occur during development will have only limited bearing on the eventual inflow rates that will apply once subsidence occurs during longwall panel extraction.

Recent groundwater extractions from the Hoskissons Seam during gas drainage trials have provided useful information on groundwater level responses in the seam, negating the need to delay assessment of longwall mining impacts until after a period of coal extraction from the gateroad development in 2010.

7.3 Groundwater Level Impacts

The most significant impacts on groundwater levels are predicted to occur within the Permian coal measures, specifically within the Hoskissons Seam. Groundwater inflows will be induced laterally and from adjacent hydrogeological units, and subsidence fracturing above the longwall goafs will allow increased drainage from the units above the longwall panels, extending up to the Napperby Formation, and possibly above into the Garrawilla Volcanics.

Plots of drawdown and recovery in key formations are presented as follows:

- **Figures 6.13** to **6.20** show the predicted groundwater levels and drawdowns for Alluvium / Colluvium / Regolith (Layer 1), the Garrawilla Volcanics (Layer 4), the Napperby Formation (Layer 5) and the Hoskissons Coal Seam (Layer 9), at Mine Years 15 and 29.
- **Figures 6.21** to **6.24** show the predicted groundwater level recovery for Alluvium / Colluvium / Regolith (Layer 1), the Garrawilla Volcanics (Layer 4), the Napperby Formation (Layer 5) and the Hoskissons Coal Seam (Layer 9), following 100 years of recovery after mining is completed.
- A cone of depression centred on the Narrabri mining operation is evident in the Hoskissons Seam (**Figures 6.19** and **6.20** for Years 15and 29 respectively), a less pronounced cone of depression in the Triassic (**Figures 6.17** and **6.18**) and only very minor localised impacts in the regolith (**Figures 6.13** and **6.14**). Further details of impacts on specific formations are provided below.

- Residual drawdowns in Layers 1, 4, 5 and 9 are shown on **Figures 6.21**, **6.22**, **6.23**, and **6.24** respectively. Groundwater levels are predicted to recover to at least present day levels in all units. Predicted groundwater levels 100 years after completion of the mining are shown in **Appendix H** as prediction hydrographs of all existing monitoring locations**.**

Predicted groundwater levels over the 29 years of mining and 100 years of post-mining recovery are shown as hydrographs for all current monitoring locations in **Appendix H.** Contours of predicted drawdowns in each model layer at the end of mining are shown in **Appendix J.**

Drawdown impacts are predicted to extend regionally within the Permian Units. Groundwater features such as springs, wells/bores, dams or soaks, which derive water from the Permian coal measures within the region of predicted drawdown, may be impacted by the Project.

While there are three NOW Groundwater Management Areas in the vicinity of the Longwall Project area, the area of the longwall panels is covered by GWMA 601 (Surat Basin). The main Surat Basin aquifer in this region, the Pilliga Formation, is dry within the Longwall Project area.

Although the mine is not overlain by any significant aquifer, potential impacts on the aquifers that do exist are as follows.

7.3.1 Predicted Impacts on Groundwater Levels in the Permian Coal Measures

The most significant impacts on groundwater levels are predicted to occur within the Permian coal measures (**Figures 6.19** and **6.20**), specifically within the Hoskissons Seam (Layer 9). Mine dewatering will occur through natural inflows to the underground workings, which will be collected in sumps and pumped to the surface. The groundwater pumped from the mine will be used to provide water supply to meet the project's water demands.

Drawdowns of 5m or more are restricted to a distance of 9 km to the west of mine after 15 years of mining and extending to 15 km at the end of mining. Drawdowns of 1m or more are predicted to extend to a maximum of approximately 20km from the mine in a south-westerly direction and by approximately 9 km in a north-westerly direction by 15 years after the start of mining. After 29 years of mining operations, drawdowns of 1m or more are predicted to extend to a maximum of 20km from the mined areas to the southwest and northwest and 10km from the mined areas to the south. Drawdown to the east is limited by the truncation of the Hoskissons Seam in subcrop.

Recovery of groundwater levels/pressures in the Permian coal measures is predicted to occur gradually after completion of mining. It is predicted that 100 years after mining, residual drawdowns of 5m or more is restricted to the southern parts of the mine footprint, with 1m residual drawdown extending to a distance of 7km to the south and west of the mine.

7.3.2 Predicted Impacts on Groundwater Levels in the Triassic and Jurassic Formations

Predicted drawdowns in the overlying Triassic (typified by Layer 5 – Napperby Formation) at the completion of the Longwall Project (Mine Year 30 – 2039) are less pronounced in comparison to the Hoskissons Seam, as shown on **Figures 6.17** and **6.18**. Drawdowns of 1m or more are predicted to extend to approximately 10km from the mined areas to the South-west and north-west, but the maximum drawdown in the immediate vicinity of the mine is limited to around 20m.

Within the Jurassic sediments, drawdowns of greater than 5 m are restricted to the immediate mine area. No significant regional drawdown impacts are predicted in the Jurassic. Within the Garrawilla Volcanics, 1 m drawdown is predicted to extend between 5 and 8 km to the west of mined areas.

Post mining residual drawdown following 100 years recovery of up to 5m are predicted, but restricted to an area within the mining lease. A predicted residual drawdown of up to 1m extends south and west of the mine and up to 5km east of the mine.

The Pilliga Formation is dry within the longwall project area, and there is no predicted drawdown impact in areas downdip to the west.

7.3.3 Potential Impacts on Groundwater Levels in the Quaternary Alluvium and Colluvium / Regolith

Predicted drawdowns in the alluvium, colluvium and regolith (Layer 1) at the completion of mining (Mine Year 30 – 2039) are shown on **Figure 6.14**. Maximum drawdowns are limited to around 5m, and these only occur in the immediate vicinity of the mine workings. Very slight drawdowns of 0.5m are predicted to extend up to 3km from the mine to the north, but drawdown impact is generally limited to the mining lease.

Post mining residual drawdown following 100 years recovery is up to 5 m, restricted to an area within the mining lease. A residual drawdown of up to 1m extends east of the mine footprint to a distance of 2km, but does not encroach on the Namoi River alluvium.

No measurable drawdown impact is predicted in the Namoi Valley alluvium, either during mining or after completion.

7.4 Quality of Groundwater Inflows

The average water quality of mine inflows will be a composite blend of the water qualities from all groundwater sources contributing to inflows. However, it is anticipated that groundwater quality will initially be dominated by the Hoskissons Seam and the underlying Arkarula Formation. Over time, as proportionally more groundwater inflows from the higher Permian-Triassic units and from more distant parts of the area of predicted drawdown impact, the groundwater quality may change to reflect an increased contribution from those areas.

The indicative water quality for groundwater that may flow into the mine has been determined as a weighted average of inflow volumes and salinities from each hydrogeological unit, using a representative salinity for each unit which is an average of all available measurements of salinity from water quality monitoring results for monitoring bores. Only limited analysis results are available from some units, including the Hoskissons Seam.

The water contribution from each layer was determined by extracting the change in groundwater storage within each layer for each 1 year time step in the base case model, and multiplying this volume change by the average salinity for that layer, summing the totals and dividing by the total mine inflow volume for that time step to determine an average salinity value. Thus an average inflow salinity has been calculated for each year of mining.

This method gives equal weight to both close and distant changes in storage in the model, and hence may underestimate the proportional effect of salinity in the Hoskissons Seam and the other Permian units close to the mine.

To limit uncertainty, and to provide a more conservative prediction, the calculation has been made by only using the changes in storage in the Permian and Triassic units within the predicted deformation zone, thus eliminating any influence of the shallower less saline units from the calculation of bulk salinity.

It is also important to recognise that the shallower Jurassic groundwater salinities are lower than salinities from the Permian and Triassic strata at depth and any contribution from these higher units would lower the overall inflow salinity. This approach is expected to be more representative of inflow salinities in early years, but may overestimate the bulk salinity in later years when some groundwater from the less saline shallower units and updip areas may start to reach the mine workings.

The actual average salinity of inflows is therefore likely to be lower than has been calculated here.

Two separate calculations have been made using the above methodology. The first uses an average salinity for the Hoskissons Seam of 6000 mg/L TDS, which includes all available water quality data, including the low salinity site P18 where salinity is around 2000 mg/L TDS. The second uses a salinity of 8000 mg/L for the Hoskissons Seam which places much more weight to the results of recent sampling from inseam gas drilling, from which salinities in the range 8000-9000 mg/L TDS were reported. The actual average salinity of inflows is likely to be between these two calculations.

Figure 7.1 shows the two alternative predicted mine inflow salinities using average salinity for the Hoskissons Seam of 6000 mg/L and 8000 mg/L TDS respectively. It is suggested that the inflow salinity will be somewhere between the upper and lower bound, and we suggest that for planning purposes the average be used.

Both approaches plotted on **Figure 7.1** suggest initial average inflow salinity in the range 7000 to 8000 mg/L TDS, to around 4500 mg/L TDS by the Year 20, then steadily mining again to around 6000 mg/L TDS by the end of mining.

It is also expected that there will be some variation in inflowing groundwater salinity within each year due to periodic short-term inflows of higher or lower salinities as longwall mining progresses. However, day to day inflow concentrations are not expected to vary dramatically.

7.5 Potential Impacts on the Namoi River and its Associated Alluvium

There is a significant barrier of low permeability strata between the Namoi River alluvium and the proposed mine footprint. Neither the Hoskissons Seam nor the other rocks of the Black Jack Group are directly in contact with the Namoi Valley alluvium in the project area, as these units have been truncated by an overlying unconformity. There is the potential for indirect impacts through the intervening low permeability strata. However, predictive modelling showed the project will have negligible impact on the alluvium in the Namoi River valley.

The Namoi River is a gaining river system which is predicted to continue through the proposed mining operation. A small impact on base flows is predicted, to occur, but the model contains a number of conservative features that will tend to overstate the potential baseflow impact, and negligible impact is likely to occur in reality. As discussed in **Section 6.5.7**, the predicted maximum total baseflow impact during mining is approximately 0.22 ML/d, which represents about 2% reduction in the pre-mining baseflow from reach 11, the closest reach to the project. The maximum reduction is predicted to occur in Year 23.

Post-mining, baseflows in all affected reaches of the Namoi River and Jack Creek are predicted to recover to levels equal to pre-mining baseflows, with 80% of recovery to occur within 40 years of completion of mining.

The surface drainages within the Mine Site are all ephemeral streams in which baseflow is either absent, or insufficient to maintain permanent creek flow. Baseflows prior to the commencement of the Narrabri project predicted by the groundwater model were negligible in all drainages within the Mine Site.

7.6 Potential Impacts on Great Artesian Basin Intake Beds

Groundwater modelling has predicted negligible change (less than 0.03ML/d) to groundwater flux at the model's western boundary, representing outflow from the area covered by the groundwater model to the GAB.

The Pilliga Sandstone, recognised as a major intake bed to the GAB, is dry within the Longwall Project area, so that even in the highly unlikely event that continuous sub-surface cracking from longwall mining does extend beyond the floor of the underlying Purlawaugh Formation, which is recognised as a major regional aquitard, the Pilliga Sandstone will be insulated from groundwater depressurisation occurring within the underlying Permian coal measures.

7.7 Potential Impacts of Brine Re-injection

Assessment of the potential for re-injected brine to migrate from the mine's goaf to hydrogeological units of the Gunnedah Basin, the Great Artesian Basin and/or the Namoi Alluvium Ground Water Management Areas was assessed by particle tracking analysis, as described in **Section 6.5.7**.

The particle tracking indicated that the potential for injected brine to migrate offsite in the 100 year recovery period within the Permian – Triassic strata is limited to less than 2km from the mine footprint area to the north, and generally less than 1 km elsewhere. The potential for adverse impacts on the hydrogeological units of the Gunnedah Basin Ground Water Management Area would be limited to within these distances.

The analysis also showed that there would be no upward migration of saline water into the Jurassic GAB intake beds, specifically the Pilliga Formation.

The particle tracking showed that particle vectors in the alluvium/colluvium/regolith (Model Layer 1) reflect the natural groundwater flow directions. Although the analysis showed that there would be no upward migration of saline water into Layer 1, in any case, the particle tracking indicated that the maximum distance travelled by particles in Layer 1 in the 100 year post-mining recovery period would be only 500m from the northern end of LW1 and 850m from the southern end of LW26.

Groundwater salinity within the Gunnedah Basin sediments exceeds 5000 mg/L TDS, and therefore these units have limited beneficial use value. The residual salinity of groundwater within the predicted migration zone will be a mixture of the insitu groundwater salinity (>5000 mg/L TDS) and that of the injected brine (likely to be in excess of 20,000 mg/L TDS). The actual salinity in the goaf is likely to vary over time as the proportions of these two waters varies. Because of the high initial salinity of the in situ groundwater in the hydrogeological units likely to be affected by saline water, any escape of salinity will not cause a reduction in beneficial use value.

7.8 Potential Impacts on Existing Groundwater Users

The Stage 2 Longwall Project has the potential to impact on groundwater in the fractured rock aquifers above the mine up to the base of the Garrawilla Volcanics, with greatest impacts in geological units close to the Hoskissons Seam, and less impact on higher units. Yields and available drawdown may be affected at any existing groundwater bores close to the mine which are screened in the formations predicted to be affected by groundwater drawdowns. Augmentation of affected water supplies may be required.

A search of the NOW database revealed a number of registered bores within the predicted impact zone, but a field inspection showed many to be either non-existent or lost. The recorded age of some of the lost bores suggests that they may have been long since abandoned. The field survey also revealed a number of existing bores with active windmills which are unregistered.

A free-flowing spring has been identified to the south of the Mine Site that is used for water supply, and although it is not expected to be impacted, it may be at risk if drawdowns in the Purlawaugh Formation prove to be greater than predicted. Others have been identified at greater distance to the south. Modelling has shown that predicted drawdown within the upper geological units is extremely small in the vicinity of the springs, so adverse impacts are not expected. These springs should be included in the routine monitoring program described in **Section 8**.

The potential for impact on other groundwater users is to a large degree being mitigated by NCOPL's acquisition of properties within the anticipated zone of impact. However arrangements to mitigate potential impacts on other groundwater users will be undertaken by NCOPL. Assessment of potential impacts will be undertaken on a case by case basis which will require identifying the potential bores or springs impacted and discussing possible mitigating measures with each affected landholder.

It is predicted that none of the Quaternary alluvium water supply sources will be impacted by the Stage 2 Longwall Project. **Figure 7.2** represents the predicted drawdown in Layer 1 (alluvium/colluvium/regolith) at the end of mining along with known groundwater extraction bores within the Namoi River alluvium. It shows that all known extraction bores are outside the predicted zone of impact. **Figure 7.2** also shows the locations of the three springs discussed above. Two dummy bores were used to illustrate the potential impact on the Regolith / Colluvium and alluvium associated with the Namoi River. DB1 located 2 km north of LW1 and DB2 located in alluvium 5 km east of the mine footprint. Hydrographs are shown in **Appendix H** which indicates that there is little discernable impact on alluvium associated with the Namoi River.

7.9 Potential Impacts on Groundwater Dependent Ecosystems

No groundwater dependent ecosystems have been identified within the Mine Site area previously, although deep rooted vegetation with tap roots up to 25 m depth have been cited to occur in the region (GHD, 2006). Groundwater levels range from more than 60 m below ground level to around 10 m below ground level in topographic low points.

It is anticipated that the Purlawaugh Formation will insulate shallow groundwater from any mining-induced groundwater depressurisation of the underlying Permian coal measures. Therefore it is not anticipated that there would be significant impact to groundwater dependent ecosystems due to the Stage 2 Longwall Project.

It is possible that shallow surface cracking may locally impact shallow groundwater such as the sporadic perched systems that exist at the base of the weathered zone that may locally be supporting some vegetation. As suggested above, it is likely that these effects will not be permanent as the surface cracking will not be continuous to the mine workings, and impacts will therefore be limited. Any storage that is drained will be rapidly restored by recharge from rainfall, as the discontinuous fractures close up or become infilled with fine sediment.

7.10 Groundwater Licensing

The Upper Namoi GWMA and GAB Intake Beds GWMA have been identified as high risk aquifers (DLWC, 1998).

An embargo currently exists in the Great Artesian Basin in New South Wales, which prevents the issuing of new industrial bore licences, but does not apply to new stock and domestic bore licences. Any groundwater which derives from the GAB Intake Beds or Upper Namoi GWMA would require the acquisition of offset licences, although it is considered unlikely that any such impact will occur.

Mining activities will be undertaken beneath the existing groundwater table in the Permian Coal Measures. Therefore a groundwater interference licence will be required prior to intersection of the water table in the drift or development headings.

It is not anticipated that groundwater resources within the Great Artesian Basin intake beds will be impacted by mining activities, and predictive modelling has shown that there will be a negligible impact on the alluvium associated with the Namoi River. Purchase of offset licences is not expected to be necessary for the alluvium. However, the predicted small impact on Namoi River baseflow would need to be offset by purchase of a surface water licence.

8. MONITORING AND MANAGEMENT

8.1 Impacts from Groundwater Extraction / Dewatering

It is recommended that the current baseline monitoring program of groundwater quality and bore water level measurement be continued, with a modified network of monitoring points determined prior to commencement of mining.

Data collected will enable NCOPL to establish, and continually assess if mining activities have any impact on other groundwater users or the groundwater environment. Collection of these data will also enable review of any observed impacts against those predicted by the numerical modelling, and will allow further refinement of the groundwater model as the mine develops.

It is recommended that the proposed project monitoring program includes recording of the following:

- Groundwater extraction volumes – weekly totals from all pumping bores, and weekly totals from each underground pumping station and box cut sump.
- Volumes of water introduced to the mine for longwall operation and other requirements.
- Groundwater discharge quality – monthly measurements on site of the EC and pH of samples collected from each groundwater extraction point for either dewatering or water supply purposes, including both bores and underground pumping stations.
- Quarterly sampling from all pumping bores and underground pumping stations for comprehensive hydro-chemical analysis as detailed in **Table 8.1**.
- Monthly manual monitoring, or continuous automated monitoring, of water levels from the network of monitoring bores
- Annual sampling of representative monitoring bores for laboratory analysis.
- Continuous gas monitoring.
- Monitoring of the spring discharges shown on **Figure 4.9**, carried out at the same intervals as the groundwater level monitoring above.

Table 8.1: Recommended Laboratory Analysis Suite for Groundwater

Class	Parameter
Physical parameters	EC, TDS, TSS and pH
Major cations	Calcium, magnesium, sodium and potassium
Major anions	Carbonate, bicarbonate, sulphate and chloride
Dissolved metals	Aluminium, arsenic, boron, cobalt, cadmium, chromium, copper, iron, lead, manganese, mercury, nickel, silver, selenium, zinc
Nutrients	Ammonia, nitrate, phosphorus, reactive phosphorus

8.2 Subsidence Impact Monitoring

The NCOPL Stage 2 Longwall Project is the first longwall mining operation within the Gunnedah Basin and therefore there is little precedent against which to compare predictions of subsidence and associated groundwater impacts.

A comprehensive monitoring program is recommended to investigate the subsidence impacts as they develop above LW1 to LW3. This monitoring will provide definitive information on the behaviour of the rock strata from subsidence, and will provide more reliable data on which to base the changes to hydraulic conductivities resulting from subsidence fracturing. This will enable the groundwater model to be recalibrated and used to improve the certainty of forward inflow predictions and resulting impacts, before inflows lead to significant water excess, which is currently expected to be from about Year 5, during the mining of panels LW2 toLW3.

Some multi-level vibrating wire piezometers are already in place to enable ongoing monitoring. These have been strategically placed within proposed chain pillars between LW1 and LW 2 and just outside LW1. Additional multi-level vibrating wire piezometers and extensometers will be installed. Monitoring of these facilities will be conducted in conjunction with the subsidence monitoring recommended by DGS (2009).

8.3 Review and Reporting

Collated monitoring data should be subjected to an annual review by an approved, experienced hydrogeologist in order to assess the impacts of the project on the groundwater environment, and to compare any observed impacts with those predicted from groundwater modelling.

It is also recommended that, in accordance with industry best-practice (MDBC, 2001), a modelling post-audit and model verification should be carried out 6-12 months after longwall extraction starts. Due to the prediction uncertainty and sensitivity to the vertical hydraulic conductivity of the fracture zone discussed in **Section 6**, it is recommended that the first review be carried out after six months from the commencement of longwall extraction. Following this first review, if necessary, the groundwater model should be re-calibrated and confirmatory forward impact predictions made. Further post-audits should be carried out at least five-yearly through the remainder of the project, and at any other time should inflows or impacts vary significantly from predictions.

Should any review or post-audit indicate a significant variance from the model predictions with respect to either water quality or groundwater levels, then the implications of such variance should be assessed, and appropriate response actions implemented in consultation with DECCW, Department of Primary Industries (DPI) and Department of Environment and Climate Change (DECC) as appropriate.

9. CONTINGENCY RESPONSE PLANS

9.1 Recommendation for Development of Response Plans

It is recommended that a response program be adopted for implementation in the event of unforeseen adverse impacts on either groundwater or surface water from the Stage 2 Longwall Project. The response plans would be in accordance with those outlined in the Groundwater Management Plan developed for the approved Stage 1 project, modified as required to account for issues relating to Stage 2 operations.

The proposed approach to the management of groundwater levels and water quality are detailed below, outlining the criteria by which each would be assessed in order to determine the need to implement mitigation actions as outlined in the response plans. It should be noted that as groundwater levels and quality will naturally vary over time, the setting of specific trigger-levels, for either quality parameters or water-levels, is not considered practical. For example, water levels may vary considerably in response to natural variation or groundwater use by others, not just to the impacts of mine dewatering associated with the Longwall Project or other mining projects. Seasonal variations in water levels and quality as a result of varying rates of recharge may occur. Significant changes in either groundwater levels or quality may also occur as a result of groundwater extraction and irrigation activities within the Namoi Valley that are unrelated to mining.

It is recommended that the assessment is made based on the variation of levels and quality trends from their recorded baseline range or trends, combined with the recorded variation from predicted impacts (for those bores within the zone of influence of dewatering and borefield pumping).

Trigger levels (or trend changes) will be set, for selected sites, to be applied during the initial stage of mine construction and Mining Years 1 to 3, after which time all trigger levels will be reviewed with reference to the baseline data records available at that time, and revised as appropriate through consultation with NOW.

9.2 Water Levels

In the event that groundwater level drawdowns in any bore in the alluvium, regolith or the Garrawilla Volcanics exceed predicted drawdowns by 15% or more for any consecutive three month period, then the monitoring data should immediately be referred to an approved hydrogeologist for review. The reviewer should assess the data to establish the nature of the exceedance and the reasons for it, and should recommend an appropriate response action plan for implementation in consultation with NOW.

In the event that an existing water supply is adversely affected by any exceedance in drawdowns, the response action could involve provision of a replacement water supply, possibly from diversion of part of the dewatering discharge, subject to water quality being suitable for the purpose.

9.3 Groundwater Quality

Should the water quality of the mine inflows or dewatering discharge indicate an inflow salinity of more than 20% above the averages shown on **Figure 7.1**, it is recommended that the nature of the exceedance, and all relevant monitoring data, be provided to an approved experienced hydrogeologist for review and assessment of the impact of such exceedances on other users or the environment. If remedial action is recommended by the reviewer on the basis of the water quality exceedances, the recommended action will be implemented in consultation with NOW, DPI and DECC as appropriate.

10. SUMMARY AND CONCLUSIONS

This groundwater assessment report has been prepared to support the Narrabri Coal Project (NCP) Environmental Assessment (EA) seeking approval of the proposed Stage 2 Longwall Project.

Stage 1 of the NCP was granted approval by the Minister for Planning on 13 November 2007, for a continuous miner operation. NCOPL is now proposing Stage 2 of the mining plan for NCP, which comprises the development of longwall mining operations on EL6243 for the extraction of coal at around 8 Mtpa.

Groundwater investigations were undertaken for Stage 1 during 2006 by GHD. That investigation included aquifer testing using packer tests on coal resource delineation drill holes, geochemical analysis and groundwater modelling.

Stage 2 groundwater investigations were undertaken between June 2008 and June 2009. These investigations aimed to verify aquifer parameters by further testing of existing boreholes, obtain additional hydraulic data through the installation and testing of new monitoring bores, and update impact predictions by further groundwater modelling. Ongoing investigations include baseline monitoring of a network of 28 bores, which are sampled and tested regularly for groundwater levels, aquifer characteristics and groundwater quality.

This report presents the results of the Stage 2 investigations and details assessment of the potential impacts of the Stage 2 Longwall Project.

10.1 Existing Hydrogeological Environment

Based on the findings of the Stage 1 and Stage 2 investigations, the following key conclusions have been drawn about the hydrogeology associated with the Narrabri Coal Mine Stage 2 Longwall Project ("the Longwall Project"):

- Two distinct aquifer types have been identified within the Longwall Project area:
  - A shallow unconfined aquifer that is found within the regolith layer (weathered bedrock), including occasional fracturing at the top of the underlying fresh rock. It occurs as a semi-continuous layer across the sub-cropping Permian-Jurassic strata. The occurrence of localised fracturing and associated higher permeability is particularly notable in the upper parts of the Garrawilla Volcanics.

- A deeper fractured rock aquifer system that occurs throughout the stratigraphic sequence, with standing water levels generally at depths greater than 50 m below ground level.
- The Pilliga Sandstone, which forms one of the major intake beds for the Great Artesian Basin (GAB) overlaps the western part of the Mine Site, but is not saturated within the Mine Site area. This unit becomes partly saturated to the west (down-dip) as the strata dip beneath the regional water table level.
- The alluvium associated with the Namoi River does not occur within the Mine Site, and the Hoskissons Seam does not sub-crop beneath or adjacent to the Namoi River alluvium. There is therefore no direct hydrogeological connection between the proposed mine and the Namoi River alluvium.
- Horizontal hydraulic conductivities determined from testing ranged from 3 x 10^{-4} m/d to 2.5 x 10^{-1} m/d. The highest conductivity in the rock units was recorded within the Garrawilla Volcanics within the sub-crop zone. The highest conductivities within the deeper aquifers occur within the Hoskissons Seam and underlying Arkarula Formation.
- Although higher hydraulic conductivities have been found within the subcrop zone of the Garrawilla Volcanics, high inflows from this formation have not been encountered during construction of the mine access drifts. This suggests that these more conductive zones are localised.
- Groundwater salinity is variable. Deeper groundwater is generally saline, with measured total dissolved solids (TDS) ranging up to more than 16 800 mg/L. Localised fresher groundwater zones occur in the shallow aquifers, with measured salinities as low as 100 mg/L TDS. Salinity of groundwater in the Hoskissons Seam is variable, ranging from 1350mg/L to 9070mg/L TDS.
- Major ion chemistry within the groundwater samples indicates that there are three distinct zones of water chemistry within the stratigraphic sequence. These distinct differences in groundwater quality indicate that, in the pre-mining condition, there is very little vertical connectivity between the rock strata that occur beneath the Longwall Project.

10.2 Prediction of Mining Related Impacts

The two main potential impacts of proposed longwall mining on the hydrogeological environment were considered to be:

- Local and regional lowering of groundwater levels within the Permian-Jurassic strata, due to groundwater inflows to the mine workings, particularly as a result of enhanced permeability of the rock units within the subsidence affected zone above the longwall extraction panels. Some lowering of groundwater levels may also occur as a result of increased rock storativity due to the stress relief fracturing associated with the underground mining.
- Possible impacts on near-surface groundwater, including the alluvial groundwater system of the Namoi Valley, and groundwater baseflow contributions to the Namoi River and other surface drainages.

Subsidence predictions are that maximum subsidence would range from 1.6m in the eastern part of the longwall mining area where cover depth is around 160m, to 2.4m in the west where cover depth reaches 380m. Continuous fracturing associated with this subsidence is predicted to extend from the coal seam to below the base of the Garrawilla Volcanics, but could extend into the Garrawilla Volcanics if adverse geological conditions are encountered. The predicted height of continuous/connected fracturing therefore varies from around 45m below ground level (bgl) in the shallowest parts of the mine to around 200m bgl in the deepest parts of the mine.

The most likely hydrogeological impact is based on the expectation that continuous subsidence fracturing from the longwall panels will not intersect the more permeable sub-crop zone of the Garrawilla Volcanics. Should hydraulically continuous fracturing extend into the Garrawilla Volcanics, it has been assessed that marginally higher inflows could occur. However, the subsidence prediction is that this is unlikely.

Numerical groundwater modelling has been used to predict mine inflows and impacts on groundwater levels and baseflows, both locally and regionally. Principal findings of the modelling include the following:

- The base case predictive modelling simulation predicted that groundwater inflows to underground workings would gradually increase over the first 20 years of mining from an initial 80 ML/a (0.22 ML/d) in Year 1 to a peak inflow rate of 1394 ML/a (3.82 ML/d) in Mine Year 20, before declining steadily thereafter to a rate of 365 ML/a (1.0 ML/d) in the final year of the project.
- Large drawdowns are predicted to occur within the Permian coal measures close to the mine, as a result of groundwater flows into the mine workings. The drawdown cone is predicted to be relatively steep, and drawdowns exceeding 10 m would be limited to around 6 km to 7 km to the west, north and south, and around 2 km to the east of the underground workings. The Permian drawdown impact would extend much less to the east, where it would be limited by the truncation of the coal seam by an overlying unconformity. The region of greater than 1 m predicted drawdown in the Hoskissons Seam extends approximately 20 km to the west, 10km from the mined areas to the south and to the north, but not to the east where the seam is absent.
- Predicted groundwater level impacts in the overlying Triassic Napperby Formation at the end of mining are much less pronounced. Drawdowns of 1m or more are predicted to extend a maximum of approximately 10km to the west of the Mine Site.
- Impacts on Jurassic strata would be extremely small, and there will be effectively no measurable impact above the Purlawaugh Formation aquitard (i.e. in the Great Artesian Basin intake beds).
- Predicted drawdowns in the surficial unconsolidated aquifer at the end of mining are very small, generally less than 1 m except for a small area immediately overlying the mine workings.
- Predicted impacts on river baseflows are very small. The most impacted river reach is the closest section of the Namoi River to the east (model reach 11). Baseflow in this reach is predicted to reduce by a maximum of around 0.22 ML/d, but this is only 2% of the total calculated baseflow contribution to this reach of around 10.3 ML/d.

- Post-mining, baseflows in all reaches of the Namoi River are predicted to recover to levels equal to pre-mining baseflows following 100 years of recovery.
- Post-mining potential for offsite migration of re-injected brine is limited to 1 km in Jurassic Strata sand less than 2 km in Triassic-Permian strata after 100 years of recovery. No upward migration of saline water to the Pilliga Formation is predicted to occur.

Overall, these results indicate that the following impacts on water resources may occur due to the Stage 2 Longwall Project:

- There will be negligible impact on groundwater within the Pilliga Sandstone, and hence a negligible (less than 0.03ML/d) impact on recharge to the GAB.
- Negligible impacts on groundwater levels in the Namoi Valley alluvium are predicted, and existing groundwater users will not be affected.
- Continuous/connected fracturing induced by longwall mining has the potential to significantly impact groundwater stored in the fractured rock aquifers above the mine (up to the Garrawilla Volcanics). The potential for impact on other local groundwater users is mitigated by NCOPL's acquisition of several properties within the anticipated zone of impact. However, a commitment to mitigate potential impacts on other groundwater users should be included within the Site Water Management Plan. One bore (WB2) located over LW26 and screened within the Garrawilla Volcanics is expected to be impacted. This bore is located on property owned by NCOPL. No other registered bores are expected to be impacted.

Sensitivity and uncertainly analysis has been carried out to assess the sensitivity of the model calibration to the assumed input parameters and boundary conditions, and the effect of uncertainty on predicted rates and impacts.

Sensitivity analysis was carried out on hydraulic conductivity (horizontal and vertical) and recharge. The model was found to be not highly sensitive to either horizontal or vertical hydraulic conductivity of the in-situ rock strata. However, model-predicted mine inflows are very sensitive to the assumed vertical hydraulic conductivities of the subsidence-affected strata directly above the extracted longwall panels, but is less sensitive to the height of connected/ continuous fracturing assumed in the modelling.

The predicted impacts from the base case model are considered to be best estimates according to experience and a thorough consideration of the hydrogeological conditions of the Longwall Project area. However, as there is no prior history of longwall mining in the Gunnedah Basin, some uncertainty in inflow predictions will remain until mining of the first few longwall panels has been undertaken, and the pattern of subsidence-fracturing and permeability changes has been monitored and evaluated. Accordingly, a range of higher than expected vertical permeabilities has been tested with the groundwater model, to provide an upper limit or worst case assessment of groundwater inflows and impacts. Monitoring of groundwater responses to the Stage 1 continuous miner operation will be of limited value, or there will be no significant subsidence associated with Stage 1. A program of careful monitoring has been recommended for the first 3 longwall panels, to provide definitive data on rock behaviour following subsidence. It is recommended also that assessment of potential mine inflows and re-calibration of the groundwater model should be carried out on a regular basis, with an initial re-evaluation 6 - 12 months after commencement of longwall extraction.

10.3 Management and Monitoring of Impacts

Although impacts from the proposed project are generally anticipated to be small, a monitoring programme and contingency response plan will be required to validate predictions and mitigate any detrimental impacts that occur during mining. Proposed recommendations for these programmes are contained within this report, and include:

- Monitoring of mine inflows and water imported into the mine for longwall operation and other underground uses.
- Monitoring of volumes pumped from any water supply or dewatering bores.
- Monthly manual monitoring, or continuous automated monitoring, of water levels/pressures from the network of monitoring bores.
- Water quality monitoring of mine inflows and groundwater in monitoring piezometers.
- Monitoring of Mayfield Spring and other springs located to the south of the mine site.
- Ongoing subsidence monitoring and monitoring of permeability changes caused by subsidence.
- Periodic data review by a suitable, experienced hydrogeologist.
- Periodic review and validation of the groundwater model predictions.

Procedures are presented for investigation and response action if data indicate that impacts on groundwater level or quality are greater than trigger values, or if complaints are received by other groundwater users.

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Figures

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PEER REVIEW

of the

Hydrogeological Assessment

Prepared by

Dr N.P. Merrick

(Note: The attached peer review relates to the assessment report submitted to the Department of Planning for adequacy assessment – August, 2009)

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HERITAGE COMPUTING REPORT

REVIEW OF THE NARRABRI COAL PROJECT HYDROGEOLOGICAL ASSESSMENT

FOR

WHITEHAVEN COAL LTD

PO Box 600, Gunnedah, NSW 2380

By

Dr N. P. Merrick

Report Number: HC2009/7
Date: August 2009

DOCUMENT REGISTER

REVISION	DESCRIPTION	DATE	AUTHOR
A	DRAFT	25 AUGUST 2009	NPM
B	FINAL		NPM

EXECUTIVE SUMMARY

A groundwater model of continuous longwall mining of the Hoskissons Coal Seam at the Narrabri Coal Project in the Gunnedah Coalfield of New South Wales has been developed by Aquaterra Consulting Pty Ltd for Narrabri Coal Operations Pty Ltd. The purpose of the modelling is to assess potential impacts on local alluvial and hard rock aquifers and surface water bodies, Namoi River in particular, and to provide an indicative assessment of mine dewatering requirements.

This report provides a peer review of the model according to Australian modelling guidelines (MDBC, 2001). The review is based on a checklist of 36 questions across nine (9) model categories.

The review finds that the model has been developed competently, and is suitable for addressing environmental impacts and for estimating indicative dewatering rates.

The model has adopted a few practices that are at the leading edge of best practice. First, development headings are recognised as early causes of depressurisation and are explicitly represented in the model. Second, pillars between mined panels are retained explicitly in the model because depressurisation above the pillars should not be as severe as it will be in the fractured zone above the goaf. Third, the material property values above the goaf are informed by external subsidence modelling and experience gained elsewhere.

This study has had the benefit of a substantial groundwater monitoring network of 29 bores spread across the proposed mine site, over a good range of screened lithologies. Most water levels are measured approximately monthly by dipping. When Stage 2 mining commences, consideration should be given to installation of additional dataloggers so that mining effects can be tracked in time. Hydrographs to date show no definitive response to rainfall recharge, although a few bores have indications of time-varying responses that might be related to climate. Two multi-level holes with vibrating wire piezometers are particularly important. They show the natural vertical head profile and will show depressurisation effects when Stage 2 mining commences.

Model calibration is limited to steady-state (pre-mining average heads) and a short period of transient observations. As there is no prior mining at the Project area, and no other operating underground mine nearby, there is only weak evidence for anticipated mine inflows. Model predictions will have consequent uncertainty.

Several lines of evidence are provided in support of steady-state calibration in the form of a scatter plot, a table of performance statistics, and a list of residuals at each of 23 targets. Steady-state calibration is generally good, with satisfactory performance statistics. As the pressure head profile at a multi-piezometer site is matched very well, this adds confidence to mine inflow estimates which depend substantially on vertical hydraulic gradients.

Absolute water levels are reproduced well at 16 simulated hydrographs for the transient calibration. Quantitative performance statistics are satisfactory. A longer period of record, preferably with more datalogged records, is required for definitive transient calibration of storage parameters.

Model predictions have been made for mine inflow, baseflow reduction and regional drawdown.

The predicted baseflow reductions at the Namoi River are likely to be minor (0.1 - 0.2 ML/day).

Drawdown predictions indicate that the project will not impact significantly on the Namoi alluvium. There is only one registered bore that is close to the 1 metre drawdown contour at the end of mining, and a possible impact at this bore should be investigated

Predicted peak mine inflow is expected to be no more than 4 ML/day. However, there is considerable uncertainty in this estimate as it relies on characterisation of a fractured zone that will not occur until Stage 2 mining commences.

Sensitivity analysis has been applied to infer the likely uncertainty in mine inflows due to assumptions on the fractured zone permeabilities. This gives an uncertainty in the order of ±1 ML/day.

TABLE OF CONTENTS

1.0 INTRODUCTION

This report provides a peer review of the hydrogeological assessment of longwall mining of the Hoskissons Coal Seam for Stage 2 of the Narrabri Coal Project, a new mining operation in the Gunnedah Coalfield of New South Wales (NSW). Stage 1, granted approval in November 2007, covered first workings and surface infrastructure. The mine is situated at Baan Baa between Boggabri and Narrabri, about 60 km north-west of Gunnedah. The hydrogeological assessment is based on field investigations and a 3D groundwater model developed by Aquaterra Consulting Pty Ltd.

The groundwater modelling forms an important component of the environmental assessment for the project. The purpose of the modelling is to assess potential impacts on local alluvial and hard rock aquifers, as well as possible interactions with the Namoi River. The model also provides an assessment of likely dewatering requirements for the mine as it progresses in time.

2.0 SCOPE OF WORK

This reviewer was charged with the following key tasks:

- Review the groundwater model as documented against the guidelines developed for the Murray Darling Basin Commission;
- Provide feedback to the modelling team during the course of model development; and
- Provide an independent review in the form of a written report.

The model review was conducted progressively. The reviewer has been engaged at several steps of the modelling process, initially at the conceptualisation stage, and subsequently at calibration and revised calibration stages, and during prediction scenarios.

3.0 MODELLING GUIDELINES

The review has been structured according to the checklists in the Australian Flow Modelling Guideline (MDBC, 2001). This guide, sponsored by the Murray-Darling Basin Commission, has become a *de facto* Australian standard. This reviewer was one of the three authors of the guide, and is the person responsible for creating the peer review checklists. The checklists have been well received nationally, and have been adopted for use in the United Kingdom, California and Germany.

The modelling has been assessed according to the 2-page Model Appraisal checklist in MDBC (2001). This checklist has questions on (1) The Report; (2) Data Analysis; (3) Conceptualisation; (4) Model Design; (5) Calibration;

(6) Verification; (7) Prediction; (8) Sensitivity Analysis; and (9) Uncertainty Analysis.

The effort put into a modelling study is often dependent on timing and budgetary constraints that are generally not known to a reviewer. In this case, however, the reviewer is aware that considerable time and funds were expended on the many revisions of the model, and in no way was model development constrained.

4.0 EVIDENTIARY BASIS

The primary documentation on which this review is based is:

1. *Fulton, A., 2009, Narrabri Coal Project - Hydrogeological Assessment. Aquaterra Consulting Report S28/B2/043c [20 August 2009]. Final Report for Narrabri Coal Operations Pty Ltd.*

Earlier versions dated 4 June 2009 [S28/B2/043a] and 20 July 2009 [S28/B2/043b] also were reviewed.

Two Stage 1 documents were made available to support the review:

2. *GHD Pty Ltd, 2007, Narrabri Coal Project Groundwater Assessment. Report 674/05 for Narrabri Coal Pty Ltd. [March 2007];*
3. *Best, R., 2007, Narrabri Coal Project – Review of GHD Groundwater Assessment. Coffey Geotechnics Letter Report to RW Corkery & Co Pty Ltd. 043c [13 March 2007].*

There has been considerable direct communication with the Aquaterra modelling team in the form of emails, telephone conversations, teleconferences and three face-to-face meetings.

The reviewer has a long history of investigation and modelling in the Lower and Upper Namoi Valleys through the state water agency (now DECCW) and the Cotton Catchment Communities CRC.

5.0 PEER REVIEW

In terms of the modelling guidelines, the Narrabri coal model is categorised as an *Impact Assessment Model* of medium complexity, as distinct from an *Aquifer Simulator* of high complexity.

The Australian best practice guide (MDBC, 2001) describes the connection between model application and model complexity 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; and

- ☐ Aquifer Simulator - a high complexity model, suitable for predicting responses to arbitrary changes in hydrological conditions, and for developing sustainable resource management policies for aquifer systems under stress.

The appraisal checklists are presented in Tables 1 and 2 (at the back of this report). The current review has been based mainly on a written report, but some spreadsheet files were examined during the review. Discussion on each modelling aspect is provided in Section 6.

6.0 DISCUSSION

6.1 THE REPORT

The Model Report (Document #1) is a substantial, high quality document of 67 pages in the main body of the report plus 43 figures and 11 appendices. To an external reader with no prior knowledge of the study area, the report is very good as a standalone document. There is very little assumed knowledge.

The objectives of the study are equivalent to the Director General's Requirements stated in Document #1 as:

1. "A description of the existing environment.
2. Assessment of the potential impacts of all stages of the project including any cumulative impacts associated with the concurrent operation of the project with any other existing approved mining operation, taking into consideration any relevant guidelines, policies, plans and statutory provisions.
3. Assessment of the potential impacts on the quantity, quality and long-term integrity of the groundwater resources.
4. Description of the measures that would be implemented to avoid, minimize, mitigate, rehabilitate/remediate, monitor and/or offset the potential impacts of the project including detailed contingency plans for managing any significant risks to the environment."

The report addresses the project objectives satisfactorily. It discusses and presents results in 10 sections: Introduction; Previous Groundwater Investigations; Stage 2 Groundwater Investigations; Description of the Existing Environment; Mining Proposal; Groundwater Modelling to Assess Potential Impacts; Potential Groundwater Impacts of the Project; Monitoring and Management; Contingency Response Plans; and Summary and Conclusions.

In the discussion on previous groundwater investigations (Section 2), mention should be made of two additional Upper Namoi Valley modelling studies (Breeza to Narrabri; Breeza to Quirindi).

Bore details in Table 2.1 and permeability tests in Table 2.3 appear to be unsorted on any attribute. This lessens the opportunity to perceive patterns in the results. Reference should be made in Sections 2.9, 3.2.2 and 4.8 (Census of Groundwater Use) to the subsequent Figure 7.2 that shows the locations of registered groundwater bores. Geophysical logs in Figure 4.5 should include measurement units.

There is comprehensive coverage of the modelling component of the study, with full disclosure in an Appendix of layer elevations, aquifer parameterisation, and assumed boundary conditions.

The report has sufficient description of the modelling process and extensive reporting of modelling results. Water balance estimates are reported globally at steady state (Table 6.3) and for the period of transient calibration (Table 6.6). For prediction runs, water balance reporting concentrates on drawdown, baseflow, baseflow reduction and pit inflows, the primary outputs of the modelling study.

6.2 DATA ANALYSIS

Substantial hydraulic testing by slug tests, packer tests and core measurements has been undertaken. Slug tests by GHD and Aquaterra show poor repeatability, with often an order of magnitude difference. This is not unusual, as the formation is stressed only to a small degree at point scale and in the short term only. Hence, the derived values are not of much use in informing the values that should be adopted in a regional model. Hydraulic responses to large stresses are the best way to infer true permeabilities, but this cannot happen until mining commences. This reviewer agrees that core measurements of matrix permeability are “of limited value” at a regional scale where fracture flow is likely to dominate.

This study has an extensive network of monitored groundwater levels at 29 sites spread across the proposed mine site, over a good range of screened lithologies. Water level measurements, available from November 2007 usually at monthly intervals, show quiescent conditions in the upper sections. The five exploration holes with vibrating wire (VW) piezometers grouted in the Hoskissons Coal Seam show head variations in the order of 50 m due to in-seam gas drilling. When Stage 2 mining commences, consideration should be given to installation of additional dataloggers so that mining effects can be tracked in time.

Of particular importance are two multi-level holes with VW piezometers at four or five depths. They show the natural vertical head profile and will show depressurisation effects when Stage 2 mining commences. They are of particular value for groundwater model calibration. Only the pressure head at one site (NC175) is shown in the report (in Figure 6.2). The potentiometric head profiles are not shown.

Groundwater elevation contours are provided in the upper (Jurassic) and lower (Triassic to Permian) sections in Figure 4.4. While these contours suggest a vertical head difference of 20-25 m between upper and lower sections, the general flow direction to the north-west is inconsistent with subsequent conceptualisation (Figure 6.1) and simulation (Figure 6.3). Lower measured groundwater heads to the south-east and east suggest that the north-west trend swings around to the east on the eastward side of the project area, as the simulations show (e.g. Figure 6.3). Although the spatial distribution of measurements is insufficient for definitive inference of groundwater flow directions, the groundwater flow regime described in Section 2.5 is consistent with conceptualisation and simulation.

The aquifer system appears to suffer very little stress due to natural processes such as rainfall and stream-aquifer interaction. Most hydrographs show a quiescent response, suggesting a minor role for rainfall infiltration. However, the wide sampling interval (~monthly) precludes a definitive conclusion on the significance of rainfall recharge. Piezometers P10, P16 and P19 show a lowering of water levels in late 2008. This effect should be discussed. Comparison with rainfall residual mass should be made to see if there is a climatic explanation. The lower water levels seem to have been excluded from transient calibration, and the entire P10 hydrograph appears to have been excluded.

Quantifying the permeability and storage characteristics of the fractured zone that develops above a mined seam is extremely difficult. This study has been informed by state-of-art subsidence modelling and by experience in other areas.

6.3 CONCEPTUALISATION

The modelling team's conceptualisation is discussed in detail, in terms of geology and key recharge/discharge processes.

An informative perspective view of the conceptual model is given in Figure 6.1. A conceptual model diagram is a simplified 2D or 3D summary picture (without stratigraphic detail) that conveys the essential features of the hydrological system, denoting all recharge/discharge processes that are likely to be significant. The diagram can serve a dual purpose for displaying the magnitudes of the water budget components derived from data sources or from simulation.

6.4 MODEL DESIGN

There is an existing prior model of the mine site developed by GHD [Document #2], but extensive modifications have been made to that model by Aquaterra [Document #1]. The GHD model had very little data for calibration, did not include a fractured zone, and did not document the assumed mine schedule or the post-mining water balance.

The model has been built with Groundwater Vistas software and MODFLOW SURFACT, an advanced version of standard MODFLOW which is regarded widely as a standard, particularly by government agencies. This version was selected to reduce numerical issues with dry cells (common in mining and dewatering operations). The pseudo-soil option was used, rather than full simulation of variable saturation.

One limitation that all versions of MODFLOW have for coal mining simulations is that they do not permit material properties to vary in time. In this study, a stop-start process across 14 time slices has been adopted to allow progressive incorporation of the fractured zone above goaf areas during the model prediction phase. The fractured zone is assumed to extend from Layer 5 (Naperby Formation) to Layer 8 (Digby Formation) in the model, but a sensitivity run examined the effect of fracturing up to Layer 4 (Garrawilla Volcanics).

Discretisation in space is appropriate. Model cells are 50 m square across the mine site, with 500 m at model edges. There are 269 rows and 270 columns. The fine scale has allowed the simulation of development headings as well as discrete pillar widths. The model has been built with 11 layers.

The broad model extent of 75 km by 52 km incorporates the Namoi alluvium and the Namoi River and its tributaries. There are no other existing mines to be taken into consideration for cumulative effects. Boundary conditions are sufficiently distant that assumptions as to their head/flux values will not bias predictions.

Active mining is represented appropriately by MODFLOW “drain” cells which remain active while mining downdip on the northern side; downgradient panels are deactivated as mining progresses updip on the southern side.

6.5 CALIBRATION

Calibration has been performed for both steady-state and transient conditions. Initial calibration was done by manual trial-and-error, but final calibration was done using automated calibration software (PEST) in order to replicate the observed vertical head gradient.

Several lines of evidence are provided in support of steady-state calibration in the form of a scatter plot, a table of performance statistics, and a list of residuals at each of 23 targets. Steady-state calibration is generally good, with satisfactory performance statistics: 10 % SRMS and 8.2 m RMS. The steady-state scatter plot in Figure 6.2a (Document #1) shows a mild bias towards underestimation of heads. Mine inflow estimates depend mostly on replication of the vertical pressure head gradient, which is matched very well (Figure 6.2b).

Less substantive lines of evidence are provided for transient calibration. The main performance indicator is qualitative comparison of 16 simulated and observed hydrographs. Absolute water levels are reproduced well, but there appear to be no simulated water level fluctuations even though seasonal rainfall has been imposed. This leads to horizontal strings of data points in the scatter plot offered in Appendix G. Performance statistics are satisfactory: 10 % SRMS and 8.4 m RMS. However, some time-varying data from P10, P16 and P19 seem to be excluded from analysis.

Calibrated material properties (Table 6.7) and rain recharge rates (Table 6.10) are generally plausible. Rain recharge rates range from 0.5% to 1.9%, similar in magnitude to values adopted in other Namoi Valley models.

There is full disclosure of calibrated property distributions in an Appendix. Horizontal to vertical permeability anisotropy ratios range from 40 (Layer 11) to 1000 (Layer 1).

6.6 PREDICTION

Predictions are based on transient simulation for 29 years of continuous mining followed by 100 years of recovery after the cessation of mining. No natural dynamic stresses from rainfall or river flow are applied during prediction, so that the hydrological effects of mining can be isolated. Separate schedules are followed for development headings and longwall panels.

For each 1-year stress period, development headings and longwalls are specified in advance as active drain cells. Enhanced permeability in fractured zone cells is specified in arrears for each new time-slice. There are 14 time slices of two years duration (3 years for the first one).

The adopted horizontal permeabilities for fractured formations are listed in Table 6.12 of Document #1. The values are based solely on professional judgement, as there is nothing on which to calibrate, and there are no sufficiently close neighbouring mines to reliably constrain the consequent predicted mine inflows. In the absence of measurement of mining-stressed hydraulic gradients, standard practice is to apply a multiplier to derive a fractured Kh from the host Kh. The multipliers adopted by Aquaterra are 8 (Layer 5) and 2 (Layers 6, 7, 8). These multipliers are reasonable. At a mine in the Southern Coalfield, where mining-stressed hydraulic gradients were available, unconstrained automated calibration gave multipliers of 1.1 to 1.8 for Kh.

The base-case vertical permeabilities for fractured formations are derived by applying multipliers to host Kz values. The multipliers adopted by

Aquaterra are 2.5 (Layers 5 and 6), 10 (Layer 7) and 20 (Layer 8). These multipliers are reasonable. Again, the values are based on professional judgement and the conceptualisation that the fractured zone is essentially uninhibited and free draining. While the adopted fractured zone Kz values make sense conceptually, there is nothing on which to calibrate these values, other than an expectation of mine inflow magnitude.

There is no standard practice for fractured zone Kz estimates. At a mine in the Southern Coalfield, where mining-stressed vertical hydraulic gradients were available, unconstrained automated calibration gave multipliers ranging from 1.5 at the top of the fractured zone to about 20 above the coal seam, with a median of 6 and an average of 8.

The model predicts a peak mine inflow a little less than 4 ML/day. It must be recognised that mine inflow estimates are very sensitive to adopted permeabilities for the fractured zone (as stated in Section 7.2 of Document #1).

The model predicts regional drawdowns that do not impact significantly on Namoi alluvium or registered production bores by the end of mining. After 15 years, the 0.5 m drawdown contour is no closer than 4 km from the nearest alluvial boundary (Figure 6.13). At the end of mining (29 years), the 1 m drawdown contour impinges on the alluvial boundary to the immediate north of the mine (Figure 6.14). There is one production bore that requires assessment for possible impact (Figure 7.2).

There is an acknowledgement in Section 7.3 that some springs derived from Permian strata might be impacted by depressurisation.

The model predicts a minor reduction in Namoi River baseflow in the order of 0.2 ML/d at the end of mining, settling at about 0.1 ML/day reduction 30 years after the cessation of mining.

The model has been used also to assess the likely time-varying salinity ranges of mine water, and the potential for reinjection of saline stored water. These scenarios are constructed sensibly.

For the recovery simulation, it is not clear what storage parameters have been assumed.

6.7 SENSITIVITY ANALYSIS

The degree of sensitivity analysis that can reasonably be done is limited by the long run-time of each simulation. Accordingly, sensitivity analysis has been done with steady-state analysis rather than transient simulation. Performance has been measured by the SRMS statistic for groundwater heads.

There has been an extensive analysis of the effects of varying (in separate runs) the horizontal and vertical hydraulic conductivities in each layer, and the rainfall recharge across six zones. No significant parameters have been omitted from sensitivity analysis.

Compared to the 9.94% SRMS statistic for the simulation with the calibrated data set, the best sensitivity runs achieved only minor improvements in performance: 9.79% (higher Kh in Regolith), 9.54% (lower Kz in Digby Formation), 9.65% (lower rain recharge on alluvium).

Rainfall infiltration is sensitive in Zone 3 (Pilliga outcrop to the west) and Zone 4 (Garrawilla Volcanics outcrop to the east). Horizontal hydraulic conductivity is sensitive in Layer 2 (Pilliga Sandstone) and Layer 5 (Naperby Formation). Vertical hydraulic conductivity is sensitive when it is reduced in about half of the layers.

Instead of the conventional perturbation approach, the sensitivity analysis for transient simulation has been done using alternative models, as discussed in the section on Uncertainty Analysis.

6.8 UNCERTAINTY ANALYSIS

Uncertainty analysis has been performed on transient prediction outputs by the use of alternative models having different values for fractured zone permeabilities, and different heights for the fractured zone. The analysis illustrates the range of uncertainty in baseflow impacts, mine inflow and mine water salinity. Negligible effects resulted from raising the height of the fractured zone.

A conservative approach has been adopted wherever uncertain decisions had to be made in the model, as described in Section 7.2 of Document #1. This approach is likely to overestimate mine inflows and environmental impacts indicated by far-field drawdowns and baseflow reductions.

To account for re-consolidation with time, experiments were conducted for some permeability reduction in the fractured zone for cells that were enhanced in all but the previous time slice. As the base case does not include this feature, resulting inflow predictions will be conservatively high.

7.0 CONCLUSION

The Narrabri Coal groundwater investigation has been thorough and extensive, and the associated groundwater model has been developed competently. It is a suitable model for addressing likely environmental impacts from longwall mining of the Hoskissons Coal Seam, and for estimating indicative mine inflow rates.

The model has adopted a few practices that are at the leading edge of best practice. First, development headings are recognised as early causes of depressurisation and are explicitly represented in the model. Second, pillars between mined panels are retained explicitly in the model, as depressurisation above the pillars is not as severe as it is in the fractured zone above the goaf. Third, the material property values above the goaf are informed by external subsidence modelling and experience gained elsewhere.

This study has had the benefit of a substantial groundwater monitoring network but too few of the bores have automatic dataloggers. As a result, hydrographs to date show no definitive response to rainfall recharge, although a few bores have indications of time-varying responses that might be related to climate.

Predicted baseflow reductions at the Namoi River are likely to be bracketed in the range 0.1 - 0.2 ML/day.

Predicted peak mine inflow is expected to be no more than 4 ML/day, but there is considerable uncertainty in this estimate as it relies on fractured zone permeabilities that cannot easily be measured. No fractured zone will occur until Stage 2 mining commences. The best way to estimate the enhanced permeabilities is by inference using automated calibration of several multi-piezometer data records.

Drawdown predictions indicate that the project will not impact significantly on the Namoi alluvium. There is only one registered bore that is close to the 1 metre drawdown contour at the end of mining, and a possible impact at this bore should be investigated.

8.0 REFERENCES

Best, R., 2007, Narrabri Coal Project – Review of GHD Groundwater Assessment. Coffey Geotechnics Letter Report to RW Corkery & Co Pty Ltd. 043c [13 March 2007].

Fulton, A., 2009, Narrabri Coal Project - Hydrogeological Assessment. Aquaterra Consulting Report S28/B2/043c [20 August 2009]. Final Report for Narrabri Coal Operations Pty Ltd.

GHD Pty Ltd, 2007, Narrabri Coal Project Groundwater Assessment. Report 674/05 for Narrabri Coal Pty Ltd. [March 2007]

MDBC (2001). Groundwater flow modelling guideline. Murray-Darling Basin Commission.
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Table 1. MODEL APPRAISAL: Narrabri Coal

Q.	QUESTION	Not Applicable or Unknown	Score 0	Score 1	Score 3	Score 5	Score	Max. Score (0, 3, 5)	COMMENT
1.0	THE REPORT								
1.1	Is there a clear statement of project objectives in the modelling report?		Missing	Deficient	Adequate	[✓ Very Good]			Director General's Requirements.
1.2	Is the level of model complexity clear or acknowledged?		Missing	No	[✓ Yes]				Section 6.1: Impact Assessment Model, medium complexity
1.3	Is a water or mass balance reported?		Missing	Deficient	Adequate	[✓ Very Good]			Steady state (Table 6.3); transient (Table 6.6) – global. Detail for predicted mine inflow.
1.4	Has the modelling study satisfied project objectives?		Missing	Deficient	Adequate	[✓ Very Good]			Subject to stated limitations.
1.5	Are the model results of any practical use?			No	Maybe	[✓ Yes]			Uncertainty in mine inflows due to anticipated permeability/porosity changes in subsidence zone.
2.0	DATA ANALYSIS								
2.1	Has hydrogeology data been collected and analysed?		Missing	Deficient	[✓ Adequate]	Very Good			
2.2	Are groundwater contours or flow directions presented?		Missing	[✓ Deficient]	Adequate	Very Good			Data are not definitive as to regional flow directions. Presented in Figure 4.4, but inconsistent with Figure 6.3 (prediction).
2.3	Have all potential recharge data been collected and analysed? (rainfall, streamflow, irrigation, floods, etc.)		Missing	Deficient	[✓ Adequate]	Very Good			Rainfall is the only significant recharge source.
2.4	Have all potential discharge data been collected and analysed? (abstraction, evapotranspiration, drainage, springflow, etc.)		Missing	Deficient	[✓ Adequate]	Very Good			No significant stresses.
2.5	Have the recharge and discharge datasets been analysed for their groundwater response?		Missing	[✓ Deficient]	Adequate	Very Good			There is some comment on minor climate influence evidenced by low natural fluctuations. Lower water levels in late 2008 are not discussed for P10, P16, P19. Not compared to rain events or residual mass trend.

2.6	Are groundwater hydrographs used for calibration?			No	Maybe	[✓ Yes]			16 hydrographs over 1 year. Some (of 29 maximum) are excluded. Deep piezos are affected by in-seam gas drilling which is not part of the modelling objectives.
2.7	Have consistent data units and standard geometrical datums been used?			No	[✓ Yes]				
3.0	CONCEPTUALISATION								
3.1	Is the conceptual model consistent with project objectives and the required model complexity?		Unknown	No	Maybe	[✓ Yes]			
3.2	Is there a clear description of the conceptual model?		Missing	Deficient	Adequate	[✓ Very Good]			
3.3	Is there a graphical representation of the modeller's conceptualisation?		Missing	Deficient	Adequate	[✓ Very Good]			Perspective view Figure 6.1.
3.4	Is the conceptual model unnecessarily simple or unnecessarily complex?			Yes	[✓ No]				Sensible stratigraphic division.
4.0	MODEL DESIGN								
4.1	Is the spatial extent of the model appropriate?			No	Maybe	[✓ Yes]			75km x 52km. Extent is defined by Namoi alluvium and GAB overlap. 50-500m cell size is fine enough to represent development headings, pillar width and panel width. 11 layers, 269 rows, 270 columns.
4.2	Are the applied boundary conditions plausible and unrestrictive?		Missing	Deficient	[✓ Adequate]	Very Good			General head boundary to north-west; no flow elsewhere. River package for streams.
4.3	Is the software appropriate for the objectives of the study?			No	Maybe	[✓ Yes]			Groundwater Vistas and MODFLOW SURFACT. Pseudo-Soil option to reduce numerical effects of dry cells. Cannot handle time varying material properties directly – done in time slices.

Table 2. MODEL APPRAISAL – Narrabri Coal

Q.	QUESTION	Not Applicable or Unknown	Score 0	Score 1	Score 3	Score 5	Score	Max. Score (0, 3, 5)	COMMENT
5.0	CALIBRATION								
5.1	Is there sufficient evidence provided for model calibration?		Missing	Deficient	Adequate	[✓ Very Good]			Several lines of evidence: scattergram for steady state (Fig 6.2a) and transient (Appendix G); performance statistics for steady state (Table 6.1) and transient (Table 6.5); lists of observed and simulated steady state heads (Table 6.2); vertical pressure head profile; hydrograph comparisons. Done manually initially; improved by auto PEST.
5.2	Is the model sufficiently calibrated against spatial observations?		Missing	Deficient	[✓ Adequate]	Very Good			9.9% SRMS and 8.2m RMS.
5.3	Is the model sufficiently calibrated against temporal observations?		Missing	Deficient	[✓ Adequate]	Very Good			Absolute levels are reproduced. No response to seasonal rainfall. Statistics: 10.1% SRMS and 8.4m RMS. Used 16 hydrographs, large number (155) of target water levels. No mine inflow targets until mining starts.
5.4	Are calibrated parameter distributions and ranges plausible?		Missing	No	Maybe	[✓ Yes]			Rain recharge rates consistent with Namoi Valley modelling; range from 0.5% to 1.9% - plausible. Permeability values are consistent with measurements and other studies. Values in fractured zones are informed by subsidence modelling and experience elsewhere – uncertainty here. Comprehensive reporting of property values and distributions in Appendix.
5.5	Does the calibration statistic satisfy agreed performance criteria?		Missing	Deficient	[✓ Adequate]	Very Good			10% SRMS is reasonable and meets the MDBC guideline.
5.6	Are there good reasons for not meeting agreed performance criteria?	[✓ N/A]	Missing	Deficient	Adequate	Very Good			

6.0	VERIFICATION								
6.1	Is there sufficient evidence provided for model verification?	[✓ N/A]	Missing	Deficient	Adequate	Very Good			All data needed for calibration.
6.2	Does the reserved dataset include stresses consistent with the prediction scenarios?	[✓ N/A]	Unknown	No	Maybe	Yes			
6.3	Are there good reasons for an unsatisfactory verification?	[✓ N/A]	Missing	Deficient	Adequate	Very Good			
7.0	PREDICTION								
7.1	Have multiple scenarios been run for climate variability?		[✓ Missing]	Deficient	Adequate	Very Good			No climate variability is simulated, as this will have a minor effect on deeper groundwater levels compared to mining depressurisation.
7.2	Have multiple scenarios been run for operational /management alternatives?		Missing	Deficient	[✓ Adequate]	Very Good			Injection of saline water into fractured zone or goaf.
7.3	Is the time horizon for prediction comparable with the length of the calibration / verification period?		Missing	[✓ No]	Maybe	Yes			29 years prediction compared to 1 year calibration.
7.4	Are the model predictions plausible?			No	Maybe	[✓ Yes]			Based on best estimates of fractured zone permeabilities, but considerable uncertainty and sensitivity.
8.0	SENSITIVITY ANALYSIS								
8.1	Is the sensitivity analysis sufficiently intensive for key parameters?		Missing	Deficient	Adequate	[✓ Very Good]			Done for steady state for all Kh, Kz and rain recharge. Sensible perturbations. Performance indicator based on heads only.
8.2	Are sensitivity results used to qualify the reliability of model calibration?		Missing	Deficient	[✓ Adequate]	Very Good			SRMS reported for each steady state perturbed run. Compared to calibrated parameter set run 9.94%, best runs give 9.79% (Kh), 9.54% (Kz), 9.65% (rain) - not much change.
8.3	Are sensitivity results used to qualify the accuracy of model prediction?		Missing	Deficient	[✓ Adequate]	Very Good			Alternative models are used in prediction uncertainty analysis.
9.0	UNCERTAINTY ANALYSIS								

9.1	If required by the project brief, is uncertainty quantified in any way?		Missing	No	Maybe	[✓ Yes]			Uncertainty is explored in part by sensitivity analysis. Alternative models are used in prediction to illustrate uncertainty in baseflow impacts, mine inflow and mine water salinity.
	TOTAL SCORE								PERFORMANCE: