NAMOI CATCHMENT WATER STUDY

INDEPENDENT EXPERT

FINAL STUDY REPORT

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50371/P4-R2 FINAL

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REPORT REVIEW SHEET

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EXECUTIVE SUMMARY

Study context and purpose

The Namoi catchment is located in north-eastern New South Wales (NSW) and is recognised as an agricultural area of significance within Australia that includes one of the most intensively developed groundwater resources in NSW.

Coal and potentially economic coal seam gas (CSG) resources exist within the Namoi catchment. Coal is currently extracted from both open-cut and underground operations. Current CSG activity ranges from initial investigations of potential to production from seven small-scale pilot CSG sites. Substantial additional mining and gas projects are planned or being investigated and their development could impact catchment water resources.

In response to rising levels of concern within the community, in August 2010 the NSW Government commissioned a study, The Namoi Catchment Water Study (the Study), into the potential effects of coal resource development activities on catchment water resources. The purpose of the Study is "to undertake a strategic assessment of the likelihood of potential impacts posed by coal and gas development in the catchment on the quantity and quality of surface and ground water resources in the catchment".

The Study includes the construction of a three-dimensional numerical model that can be used to develop scenarios of different mining and gas developments and predict their effects on water resources. Since its commencement in 2010, the Study has progressed in four phases with each resulting in the publication of separate reports and presentations to the community. This document provides the report of the final phase of the Study.

General assessment

Water resources

The principal water resources of the catchment comprise the surface water system of the Namoi River, its tributaries, and the alluvial groundwater systems associated with the water courses. The Namoi surface water catchment drains west towards the Darling River and flows are regulated by three storages: the Keepit, Chaffey and Split Rock dams. The Upper Namoi and Lower Namoi Alluvium form the principal aquifers and are heavily utilised for irrigation.

The Namoi alluvium is characterised by high permeability and storage capacity and water quality is good, although it varies within different layers. Recharge rates are generally high due to direct association with the river and stream systems. Smaller scale pumping also occurs from the consolidated or 'hard' rocks that comprise the groundwater system surrounding the alluvium. The hard rocks are less utilised due to lower permeability, storage and recharge rates and characterisation data is sparse.

Groundwater resources have historically been managed by areas: the Lower Namoi Alluvium is treated as a single area; the Upper Namoi Alluvium is subdivided into 12 separate management zones; and the recognised hard rock units and lesser alluvial aquifers are managed as separate areas. These management areas are shown on Figure E1 and listed in Table E2. The Study has assessed the potential impacts and risks to water resources from coal and gas development in the Namoi catchment using these same management areas.

Impact pathways

Mining and CSG activities can impact water resources through pathways that are both broad-scale and highly localised. Local-scale pathways cannot be determined by a catchment-wide study. Since coal resources are hosted in below-ground, hard rock units, the main impacts are likely to be on subsurface water (groundwater). Open pit mines also have a significant footprint on the surface which results in some rainfall and surface water capture. Underground mines and CSG extraction also requires some surface infrastructure development which can impact surface water flows.

The primary broad-scale pathways by which coal mining (open-cut and underground) and CSG extraction can impact surface and groundwater quantity and quality are:

- Interception or disruption of rainfall and run-off from mine pits, surface infrastructure and subsidence. This can result in; i) reduced recharge to the groundwater system and lowering of levels and quality changes, and ii) reduced runoff and surface water flow and quality changes.
- Flow of groundwater to mine voids, mine dewatering facilities or to CSG production wells. This can result in; i) leakage from utilised aquifers, ii) mixing of different quality groundwater, iii) reduced flow from groundwater to rivers, and iv) increased leakage from rivers to groundwater.

Coal resource investigation and development activities such as drilling or hydraulic fracturing, and accidental releases or emergency releases during operations, can also pose shorter-term risks to water quality.

Proximity of water resources and coal and gas resources

A catchment-wide assessment of the location of potential coal bearing formations and their proximity to near-surface water resources is shown by Figure E2. Although the presence of coal bearing formations does not mean that either CSG development or coal mining is economically viable, the proximity assessment indicates that:

- Coal resources exist only in the western 60% (by area) of the Namoi catchment and water resources in the upstream eastern sector of the catchment are not at risk from coal development activities.
- The prospective area for coal mining extends a maximum of 50 kilometres to the west of the Upper Namoi Alluvium and beyond this the depth to coal bearing formations is likely to be excessive for mine development.
- The prospective areas for CSG extraction overlap with the prospective coal mining areas but also extend into a much greater area of the catchment where the coal seams are deeper.
- Most of the Upper Namoi Alluvium Zones are in very close proximity to coal bearing formations.
- Less than half of the area of Upper Namoi Alluvium Zone 3 is underlain by coal bearing formations indicating lower direct risk to this area.
- Upper Namoi Alluvium Zones 6, 9 and 10 and the Lower Namoi Alluvium are separated by more than 100 metres from coal bearing formations and will be at lower risk from direct impacts than other management zones.

Numerical model and scenario development

A key output of Phase 3 of the Study has been the development of numerical models (the Model) to facilitate assessment of the long-term and cumulative impacts on catchment water resources that could result from coal resource development. The Model provides a tool for future use and management that also allows the uncertainties associated with these predictions to be investigated. The Model has two main components:

I. a rainfall / runoff model - the Hydrologic Model;

II. a groundwater flow and groundwater / surface water interaction model - the Groundwater Model.

In order to assess the effect of coal resource development activities on water resources, seven future coal mining and CSG development scenarios were developed for testing (predictive simulation) by the Model. Each scenario was simulated until the year 2100 (90 year period of prediction) and the main elements of these scenarios are detailed in Table E1. The spatial distribution of coal and gas developments is illustrated in Figure E3 for Scenario 3. This scenario is the most intense future resource development option that has been simulated and reflects extensive CSG production and the annual extraction of around 60 million tonnes of coal for 90 years.

Table E1 Scenario configuration

Scenario No.	Description	Mines (number)		CSG fields (No.)
		Open-cut	Underground	
0	No current or future mining or CSG	0	0	0
1	Approved mines & CSG production	6	1	Pilot holes only
2	Approved & planned mines & CSG	10	2	2
3	Extensive & widespread mining & CSG	24	7	8
4	Extensive & widespread mining only	24	7	Pilot holes only
5	Extensive & widespread CSG only	6	1	8
6	Half underground mines beneath alluvium	24	7	8

Scenario 0 simulates no current or future coal resource development and provides a set of baseline results where the effects of climate variation and agricultural development are present. The results of all other scenarios can then be compared with Scenario 0 at any future time and location to isolate the change resulting from the particular coal resource development scenario.

Strategic assessment of likely effects of coal and gas developments

This assessment considers the conceptual and geological models developed during the Study in addition to the Model simulation results. The location, timing, type and size of the future mining and CSG developments are currently unknown and these factors will have a major effect on Model results, as does the very long predictive simulation period. The assessment needs to be viewed in this context.

At current levels of development, extensive regional scale impacts on water resources are unlikely. More local scale impacts are likely and the cumulative effects of numerous developments in close proximity will increase the risk to the water resources in those areas. This is evident in Upper Namoi Alluvium Zones 7 and 11 where numerous developments are approved or possible. However, the impacts will mainly be on groundwater levels in the hard rock units and in the vicinity of the mines or CSG fields. The Model predictions of groundwater level decline ('drawdown') from approved (Scenario 1) and possible future developments (Scenario 2) are shown in Figures E4 and E5 (respectively).

With long-term and more extensive development, especially within the Gunnedah Basin Management Area where the likelihood of further development of coal and gas resources is highest, the cumulative effect of impacts on groundwater levels in the hard rock units and alluvium will be more significant. Declines in groundwater levels predicted by the Model for extensive long-term development of coal resources (Scenario 3) are shown in Figure E6.

Mining and CSG development will impact groundwater levels in the hard rock units with much greater magnitude, spatial extent and speed of onset compared to their effect on groundwater levels in the alluvium. Impacts that propagate to the alluvium will be of a lesser magnitude and extent and will take much longer to reach a maximum.

The main impacts to surface water flows are derived from open cut mining, with little impact predicted from CSG or underground mine developments. For Scenario 3 the long-term average flow in the Namoi River near Narrabri is predicted to reduce by up to 1.8%. As a percentage of average flow this impact is low, however, in volume terms, this is equivalent to about half the current surface water abstraction from the regulated Namoi River below Keepit Dam. Simulation of the same coal resource development scenario but using a drier future climate pattern increases the predicted reduction to 3.3%. No impacts upon the water captured by the three main storage dams are predicted.

Measurement errors inherent in data collection at surface water gauging stations are approximately 5% and the potential changes may not be distinguishable in the observed data.

Groundwater discharge to rivers ('baseflow') occurs along several reaches of the Upper Namoi and contributes to measured surface water flow. For all coal development scenarios the baseflow contribution to stream flow declines and the maximum change is usually at the end of the prediction period (year 2100). The source of these impacts is either predominantly mining or a mix between mining and CSG developments. In comparison to the 'no mining and CSG' case (Scenario 0), the maximum baseflow reduction is 5% and occurs when underground mines are placed directly beneath the alluvium (Scenario 6).

To describe the risk to groundwater resources an assessment has been undertaken using the impact trigger levels defined in the Queensland Water Act 2000 since the equivalent guidelines for NSW aquifers are in draft form and currently being re-written. The trigger levels define at what point impacts are considered acceptable and at what point mitigation measures need to be commenced. The impact trigger levels are expressed as drawdown of groundwater levels and are:

- 0.2 metres for springs;
- 2 metres for unconsolidated aquifers (such as alluvial aquifers);
- 5 metres for consolidated aquifers (such as hard rock aquifers).

Using these trigger levels, the predictive modelling results (excluding Scenario 6), and an understanding of the sensitivity of the results to model input uncertainty, the risk to groundwater in each of the Management Areas and Zones has been classified as low, moderate or high. In the Oxley Basin and Great Artesian Basin Management Areas, risks to groundwater levels are dependent on the specific location within these large zones and multiple classifications are possible. The confidence in the assessment of risk for each zone has also been classified based on the type, quantity and quality of data available. The primary cause or source of the impact is also identified and the results of the classification are summarised by Table E2 and by Figure E7 (risk) and Figure E8 (confidence).

Table E2 Risk of impacts to groundwater levels and confidence in predictions

Management Area / Zone	Risk	Confidence	Source
Upper Namoi Alluvium Zone 1	Low	Low	Mining
Upper Namoi Alluvium Zone 2	Low	High	Mining and CSG
Upper Namoi Alluvium Zone 3	Low	High	Mining
Upper Namoi Alluvium Zone 4	Moderate	High	Mining
Upper Namoi Alluvium Zone 5	Moderate	Moderate	Mining and CSG
Upper Namoi Alluvium Zone 6	Low	Low	Mining and CSG
Upper Namoi Alluvium Zone 7	High	Low	Mining
Upper Namoi Alluvium Zone 8	Moderate	Moderate	Mining
Upper Namoi Alluvium Zone 9	Moderate	Low	Mining and CSG
Upper Namoi Alluvium Zone 10	Low	Low	Mining and CSG
Upper Namoi Alluvium Zone 11	High	Moderate	Mining
Upper Namoi Alluvium Zone 12	Low	High	N/A
Lower Namoi Alluvium	Low	High	CSG
Gunnedah Basin	High	Moderate	Mining and CSG
Oxley Basin	Moderate High	Low	CSG
Liverpool Ranges Basalt	Low	Moderate	Mining and CSG
Great Artesian Basin	Low Moderate	Moderate	CSG
GAB Alluvial	Low	Moderate	CSG
New England Fold Belt	Low	High	N/A
Peel Valley Alluvium	Low	High	N/A
Peel Valley Fractured Rock	Low	High	N/A
Misc. Alluvium of Barwon Region	Low	High	N/A
Galarganbone Tertiary Basalt	Low	High	N/A

Note - highlight colours reversed for Risk & Confidence

Groundwater levels in four locations are determined to be at high risk from coal and gas developments: Upper Namoi Alluvium Zones 7 and 11, the Gunnedah Basin and parts of the Oxley Basin Management Areas. Confidence in the predictions for the most heavily utilised areas can be considered high (Upper Namoi Alluvium Zones 2, 3 and 4 and the Lower Namoi Alluvium) or moderate (Upper Namoi Alluvium Zones 5 and 8). In some of the lesser utilised areas, where available data is sparse, the confidence is low.

For Scenario 6, where half the underground mines (of Scenario 3) are moved to locations immediately below the Upper Namoi Alluvium, the risk to alluvial water resources is considered high, as shown by Figure E9.

For the most part, the Groundwater Dependent Ecosystems (GDEs) identified in the most recent 'State of the Catchment' report fall within low risk areas.

Analysis of the Model water balance for Scenario 3 shows that both the Lower and Upper Namoi Alluvium will experience a relatively low impact when compared to existing anthropogenic water use impacts. However, the hard rock groundwater system, particularly within the Gunnedah Basin Management Area, is likely to experience a high impact. The Model water balance also indicates that the impact on surface water flow, although likely to be a small percentage of the average flow, may peak at about half the current surface water usage level. These results are illustrated by Figure E10.

The configuration of the predictive scenarios enables assessment of the relative contribution to potential impacts from different types of coal resource development. In the Upper Namoi Alluvium, impacts to groundwater are more likely to be due to coal mining than due to CSG development. For the Lower Namoi Alluvium, the very small predicted impacts are derived mostly from CSG extraction. In the hard rock areas, the source of impacts is more mixed. To the east (Gunnedah Basin Management Area), where coal seams are shallow, it is likely that impacts would be derived mostly from mining. In the west, where coal seams become deeper, impacts would be derived mostly from CSG development.

Open cut and underground mining will impact the water resources in different ways. Open cut mines are likely to have the greatest direct impact on surface water runoff, groundwater recharge and groundwater levels, depending on pre-existing conditions and the pit configuration. Underground mines will primarily impact groundwater levels due to their depth and limited surface infrastructure and footprint. The primary impact of CSG extraction will be similar to underground mines although more diffuse and over a larger area. Re-injection to alluvial aquifers of groundwater abstracted during CSG operations has the potential to alleviate impacts, whether they are derived from CSG, mining or both.

Model simulations of different future rainfall conditions indicate the magnitude of predicted impacts on groundwater levels and on surface water flows may increase under a drier climate. The magnitude may decrease with a wetter climate, but the degree of change is less than for the drier climate simulation.

At a regional and sub-regional scale, the modelling has confirmed that mining and CSG activities have the potential to both negatively and positively impact the groundwater quality of the hard rock and alluvial aquifer systems. This would occur by the migration of water between different levels in the alluvial aquifer and between the alluvial aquifer and the bordering hard rock formations. Significantly more extensive and detailed water quality data would be required to quantify potential changes. At a regional scale, any impacts to surface water quality are likely to be too small to identify.

At a project scale, mining and CSG activities both have the potential to negatively impact groundwater and surface water resources via localised pathways. These local scale pathways, conditions and effects cannot be determined with any degree of accuracy by a catchment-scale study or predicted by a model designed to assess catchment-wide, long-term and cumulative impacts. This highlights the importance of project-specific detailed investigations, supplemented by comprehensive monitoring and appropriate operational management.

Data gaps and impact management

Data gaps

During the course of the Study and model construction, a number of data gaps were identified. Those of greatest importance can be summarised as:

- The low density of relevant data away from the Upper and Lower Namoi Alluvial systems;
- The absence of test data on the hydraulic connection between rock layers and aquifers within the catchment.

To reflect the uncertainty associated with many of the input datasets to the Model, the variability of predictive results was tested by using a range of input values. This process identifies important controls on results and indicates where higher value will be derived from the collection of new data. The data gaps identified form the basis of recommended future investigations and monitoring.

Investigation and monitoring

A practical investigation and monitoring program has been outlined to: i) provide data for future maintenance, updating and improvement of the Model, and; ii) reduce the uncertainty in predictive results and enhance the Study. The higher priority elements of the recommended investigation and monitoring program are summarised in Table E3.

Table E3 Higher priority investigation and monitoring recommendations

Investigation / monitoring element	Rationale
Continued monitoring of existing sites. To include sites currently used for Model calibration and those for future calibration.	To ensure Model datasets can be updated efficiently. Comprising climate, groundwater and surface water. Sites with short monitoring records not used in current calibration will be suitable for longer-term enhancement.
Drilling and construction of new investigation and monitoring holes, primarily in:	For definition of geological and groundwater conditions and parameters in at-risk areas with sparse available data. To form new monitoring sites.
- Upper Namoi Zones 4, 6 & 10;	Alluvial zones that currently have sparse groundwater level data.
- the hard rock units across the full geological sequence;	Drill and complete as multi-level monitoring sites to determine pressures and characteristics of the hard rock units.
- areas where coal seams are at or very close to the alluvium.	To assess the hydraulic connection between the alluvium and hard rocks in areas most likely to be near new coal developments.
Groundwater quality monitoring of the alluvium and hard rock units.	There is no systematic collection of water quality samples across the catchment and insufficient data to characterise the system.
Surface water quality sampling, particularly near coal resource developments.	A more rigorous sampling regime is required to characterise the baseline hydrochemistry of the receiving waters and of any discharges.

Mitigation

The severity or seriousness of an impact can be reduced by mitigation. Prevention of an impact is generally preferable to mitigation and many prevention measures exist to minimise local-scale impacts (spills, discharges etc.). These should be included in the approvals and environmental management plan for each particular development project. On a sub-regional scale, impact prevention options are more limited, potentially placing greater reliance on mitigation.

Effective impact mitigation is reliant on establishing the impact source and having a comprehensive baseline dataset for both water quantity and quality so that impacts can be defined, tracked and mitigation implemented in time. Trigger levels for both water quantity and quality components should be set which define at what magnitude of impact the mitigation measures are activated.

For future coal resource development aligned with Scenario 3, the Model results suggest that mitigation will be required in several of the Groundwater Management Areas if NSW trigger levels are set at similar levels to those in QLD. Three of the Upper Namoi Alluvium zones include small areas where the maximum predicted impact is greater than 2 metres, and hard rock areas of the Gunnedah and Oxley Basins indicate water level declines greater than 5 metres. In addition to this there are several springs classified as high priority GDEs which are located in areas where impacts could be greater than 0.2 metres (Figure E6). A number of potential mitigation options are outlined within this report but the most appropriate choice will depend on specific local conditions.

Study value and utility

The Namoi Catchment Water Study has resulted in:

- collation, review and assessment of all relevant data and including information provided by the coal resource development industries that is confidential to those participating companies;
- compilation of digital information within a relational database that contains over 30 million records, facilitating simultaneous interrogation of multiple datasets and the production of integrated diagrams and plans;
- the integration of geological data for the entire Namoi catchment to establish the spatial (three-dimensional) extent of all unconsolidated and consolidated rock formations and the location of potential coal-bearing units.

These activities have enabled the spatial relationship between the catchment water resources and the potential coal bearing units to be identified. It allows the general location and type (open cut mining, underground mining or CSG production) of possible future coal resource development to be inferred. Plausible future mining and CSG production scenarios can then be designed.

The integrated assessment of all data has resulted in a whole of catchment conceptualisation and qualitative evaluation of the ways that the potential effects from coal resource development activities can propagate away from the source and affect water resources. The assessment also identified the general locations (at a sub-regional scale) of zones which may be most at risk from these activities.

The numerical Model constructed for the Study is based on this conceptualisation and is able to incorporate and assess a wide-range of potential future coal resource development activities. The Model provides a robust tool that can be updated with new data, recalibrated as necessary and used to assess alternative scenarios and the effects of changing other inputs and assumptions such as a change in climate.

The Model provides predictions of the long-term, cumulative effects of mining and CSG developments on water resources at a catchment-scale and identifies those areas (sub-regionally) that are most at risk from developments and quantifies the potential magnitude of impacts for different coal resource development options. Assessment of the sensitivity of the results to different inputs, and the level of confidence in these predictions, has also been undertaken.

The Model predictions must be viewed in the context of the significant uncertainty associated with the location, type, scale and timing of potential future coal resource developments and take into account the very long predictive period (90 years). The Model is not designed to predict local-scale effects and does not replace the requirement for project-specific detailed investigations, supplemented by comprehensive monitoring and appropriate operational management.

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1 INTRODUCTION

1.1 Background

Project synopsis

In 2008, in response to community concerns regarding the potential impacts of coal and gas development in the Namoi catchment, the then NSW Minister for Mineral and Forest Resources commissioned a study (the Study) to undertake a strategic assessment of the likelihood of potential impacts posed by coal and gas development on the quantity and quality of surface and ground water resources in the catchment. The Study was to consider the whole of the Namoi catchment and was to include the construction of a suite of numerical models to aid in the investigation.

A Ministerial Oversight Committee (MOC) was established to appoint an Independent Expert, tendering of the project and ongoing administrative oversight of the Study. The MOC consisted of an independent chair (appointed by the Minister), and one representative from each of the following; NSW Farmers Association, NSW Minerals Council, NSW Irrigators Council, Australian Petroleum Production & Exploration Association and Regional Development Australia – Northern Inland Committee.

A Stakeholder Advisory Group (SAG) was also formed, with the purpose of keeping the local community informed on the progress of the Study, and community information sessions were programmed for the end of each phase. The SAG was comprised of an independent chair (appointed by the Minister) and representatives from the agricultural industry, resources industry and local government.

Schlumberger Water Services (Australia) Pty Ltd (SWS) were appointed as the Independent Expert for the Study in August 2010.

Setting and context

The Namoi catchment covers an area of approximately 42,000 km^2 and is located in northeast New South Wales. The catchment location is depicted in Figure 1.1

The catchment is a part of the Murray Darling Basin (MDB) covering approximately 3.8% of the total basin area (CSIRO, 2007). Agriculture is an important industry in the catchment and irrigation is a key component of that. In addition to large areas of cropped land, major land use comprises areas of natural vegetation, grazed land, forestry, nature conservation, water, urban development and irrigated pastures in the catchment.

From its headwaters on the western flank of the Great Dividing Range, the Namoi River flows in a westerly direction over a distance of 659 km to its confluence with the Barwon River near Walgett. The river plain merges with the Gwydir, Castlereagh, and Barwon River flood plains near Walgett. A number of wetlands are situated throughout the catchment, the largest being Lake Goran. There are smaller lagoons and billabongs on the river flood plains.

A significant portion of the flow in the Namoi River originates in the tributaries of the Macdonald, Peel, Cockburn and Manilla Rivers. Flows in the Namoi are regulated by three major dams; the Split Rock Dam on the Manilla River, the Keepit Dam on the Namoi River and the Chaffey Dam on the Peel River, as shown on Figure 1.2.

Extensive alluvial floodplain deposits are found in the central and northern areas of the catchment, with smaller alluvial areas along the Peel Valley in the east (Figure 1.3). The main alluvial body upstream (south) of Narrabri is known as the Upper Namoi Alluvium, with anything downstream of Narrabri becoming part of the Lower Namoi Alluvium. Deposits of the Upper Namoi are relatively restricted in extent, occurring mainly in the river valleys but the Lower Namoi alluvium is much more extensive and forms large outwash sequences.

Groundwater is a significant resource in the Namoi catchment and has been extensively developed. According to the NSW Government (2010) the highest rate of groundwater extraction in NSW occurs in the Namoi catchment. Groundwater abstractions are primarily located in the alluvial aquifers associated with the main rivers and their major tributaries, although a large number of smaller scale abstractions are located in the fractured rock aquifers, especially within the Peel catchment.

A large part of the catchment is underlain by the Sydney-Gunnedah Basin containing significant coal resources and a potentially viable Coal Seam Gas (CSG) resource. Coal is currently extracted from a number of mines throughout the region, both open-cut and underground operations, and substantial developments are currently being planned or investigated. The Gunnedah Basin is also subject to a number of CSG developments in various stages of exploration and appraisal.

1.2 Study requirements

Strategic Terms of Reference

The Strategic Terms of Reference for the Study state that the Study should:

- Provide a spatial understanding of underground and surface water flows in the catchment through the most appropriate methodology (potentially a three dimensional understanding).
- Undertake a strategic assessment of the likelihood of potential impacts posed by coal and gas development in the Catchment on the quantity and quality of surface and ground water resources in the catchment
- Within this strategic context, advance the understanding of the nature, extent and condition of water resources in the catchment having regard in particular to:
    - The different sub-catchments characterised within the Catchment area;
    - The spatial distribution of water resources in relation to the spatial distribution of coal and gas resources in their geological context;
    - Surface and groundwater as a connected resource, aquifer architecture (confined or unconfined aquifers), drainage, recharge zones and discharge;
    - Interaction between shallow and deep aquifers in a multi-layered system;
    - Data on water usage by agriculture, coal and gas activities, and town, domestic and stock are considered as factors in modelling;
    - Identifying the likelihood of potential impacts posed by coal and gas development.

- Enhance the technical foundation for government and government agencies' actions, decisions and policies in relation to coal and gas resource development within the Catchment;
- Advance community understanding and awareness of the scientific and technical issues concerning the potential impact of coal and gas resource development on water resources in the Catchment;
- Make recommendations as to practical measures which could be considered in mitigating or managing potential impacts of coal and gas development.

Further to this, the specification states that an integrated suite of models (the Model) should be developed that allow investigation of the nature and extent of the potential effects of the catchment water resources from coal and gas development.

To achieve the Study aims, the work was organised into four phases, with reports produced and MOC / SAG review and community consultation sessions at the end of each. The phases were:

1. Phase 1: Scoping and literature review;
2. Phase 2: Data collation, analysis, and conceptualisation;
3. Phase 3: Modelling and
4. Phase 4: Final reporting.

Phase 1 – Scoping and literature review

Phase 1 of the scope of work was completed in November 2010 with the release of the "Namoi Catchment Water Study: Independent Expert, Phase 1 Report". The Phase 1 report presented a detailed scope of work, project schedule and flow chart for the remainder of the study program, as well as a comprehensive Literature Review.

Phase 2 – Data collation, analysis, and conceptualisation

Phase 2 of the project was completed in August 2011 with the release of the "Namoi Catchment Water Study: Independent Expert, Phase 2 Report" (also known as Phase 2.5). The report presented a detailed description of the data collation process and subsequent analysis. A discussion of an initial conceptual model, an outline of the numerical modelling plan, and issues relating to the calibration and validation of the model were also included in the report. These three items had originally been assigned to Phase 3 of the Study.

The Request for Tender defined a set of wide-ranging aims for the model(s):

- To be a three dimensional model capable of simulating surface water and groundwater flow and quality characteristics in time;
- To have the capability to represent past, current and future water use scenarios at spatial and temporal scales that realistically represent those processes;
- To have the capability to account for coal and gas developments, their spatial relationship to water resources and the potential effects of those developments;
- To be a whole of catchment model in order to account for all water users including agriculture, industry, resources, and the broader community;

- To produce outputs that will enable the quantification of current and potential future effects on surface water and groundwater flow and quality;
- Designed to be readily transferred to and useable by a third party at the conclusion of the Study;
- Capable of taking no more than one day to execute a model run;
- Designed to allow ongoing operation and maintenance in a reliable and efficient manner;
- Suitable for incorporation of future data (post-Study); and
- Capable of the management and display of spatial data.

There were no detailed requirements on the detail or the configuration of the model or models, nor the assumptions, limitations and compromises that might be required. It was recognised that prior to completion of conceptual model development it was not appropriate or possible to specify this.

Phase 3 – Modelling

Phase 3, the numerical modelling component of the Study, was carried out between June and December 2011. The modelling component included:

- Model construction,
- Model calibration,
- Development and running of predictive scenarios (Model testing) and
- Sensitivity and uncertainty analysis.

Originally the Phase 3 outputs were to comprise a Model Reference Manual and a separate Phase 3 report. However, these were combined into one document that described the entire modelling process, from conceptualisation to sensitivity analysis, thus avoiding unnecessary duplication. It provides a detailed description of the Model including model architecture, the justification and background for all physical processes and the basis for selection of parameter values. A description of the predictive scenarios is provided and the results of predictive simulations are presented. No interpretation of the results was provided however, as this was intended for Phase 4.

In addition to the above, further documentation associated with Phase 3 will be submitted when the model is formally handed over to the client. This will comprise a User Manual which will document the process of Model set up, parameterisation, operation and update procedures. The User Manual will allow a third party operator to maintain, update, and expand the Model in the future.

Phase 4 – Final reporting

This document presents the Phase 4 Final Study Report. The four main aims of this document as follows:

- Provide a plain English overview of the Study outcomes (the Executive Summary)
- To present an overview of the conceptualisation of the study area;
- To present an overview of the numerical models
- To provide a summary of the predicted impacts of coal and CSG developments;

- To recommend additional monitoring activities and further work and investigations that may help to reduce uncertainty in many aspects of the Study; and

- To discuss potential mitigation and management options for the predicted impacts.

1.3 Scenario 7

Six coal and gas development scenarios were run with the Model. The scenarios were designed to investigate the impacts of increasing levels of development in the catchment, to provide an indication of the proportion of impacts from either mining or CSG developments and to consider the effects of mining under the alluvium. Of the 6 scenarios, the greatest level of development is simulated in Scenario 3. Following a request from the SAG an additional scenario has been run (Scenario 7). This scenario considers a more rapid development of CSG and a more rapid and extensive development of mines than the original scenarios. The scenario was developed based on requirements defined by the SAG. Compared to Scenario 3, this scenario has the same CSG field and open cut mine configuration but brings them on-line earlier and has an additional 8 underground mines. In terms of coal output this scenario reaches a maximum of about 160 million tonnes per annum (Mtpa) compared to the estimated 60 Mtpa in Scenario 3. As well as resulting in more rapid build-up of mining activity, Scenario 7 also results in earlier mine closure than in Scenario 3.

The set-up and results of Scenario 7 will be described in an addendum to this report.

1.4 Summary

The Study has involved the collation of a wide set of background information, development of conceptual, geological and numerical models, for analysis of surface water and groundwater effects of mining and CSG extraction. The Study provides a series of simulations of future mining and CSG developments to enable prediction of the impacts from these on water resources over time.

Sensitivity and uncertainty studies were carried out to assess the reliability of the model in relation to particular aspects of its predictive capacity. The Model is now available as a tool to support planning and policy development within the Namoi catchment. Recommendations for monitoring and further studies are made to develop the modelling tools to improve their effectiveness and recommendations are developed to mitigate potential adverse impacts on water resources arising from future coal mining and coal seam gas development.

The Study deliverables have been subject to periodic review from both the MOC and SAG and the outcomes of each of four phases of work have been communicated directly to the community via public presentations and the provision of reports to catchment libraries and online.

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2 CONCEPTUALISATION

2.1 Introduction

Prior to the development of an integrated suite of models a conceptual understanding of the catchment was required. A conceptual model is a high-level representation of the system to be modelled; it represents the best ideas of how the groundwater and surface water systems function. It is a representation of a complex natural system that can more easily be adjusted prior to dedicating the effort in developing the numerical model. Conceptual models include the characteristics of the hydraulic parameters of each unit, the positions of the phreatic and piezometric surfaces and also groundwater and surface water flow characteristics. Recharge areas and processes must be identified and reserves must be evaluated. The purpose of creating a conceptual model is to simplify the issue being examined and organise the data so the system can be analysed effectively.

For the Study, the conceptual model also included the interaction between water systems and coal and CSG resources. This initial conceptual model was then refined and updated in Phase 3 of the Study to form the basis on which the numerical models would be constructed.

In order to complete the conceptualisation, the most reliable, accurate and detailed information possible was collected through liaison with government departments, Industry Partners, the MOC, the SAG and other relevant stakeholders. This data was then compiled into a validated relational database capable of interfacing with a Geographical Information System (GIS). From the geological data, a comprehensive 3D geological model covering the whole of the catchment was constructed. It was then possible to combine the outputs from all these tools to create three-dimensional visual representations of the study area detailing the spatial relationships between coal mines and coal resources, potential CSG resources, geology, hydrogeology, water resources, abstraction, land use, geography and topography.

A summary of the conceptualisation of the geology, hydrology and hydrogeology of the Namoi catchment, developed during Phases 1, 2 and 3 of the Study is presented in the following sections.

2.2 Geology

2.2.1 *Regional geology*

The regional geology of the Namoi catchment can be subdivided into three distinctive structural units, the New England Fold Belt in the east, the Gunnedah Basin centrally in the catchment and the Surat Basin in the west as shown in Figure 2.1.

An overview of the regional geology is provided below:

- The Devonian to Carboniferous strata of the New England Fold Belt are located in the eastern and southeastern areas of the catchment. They are separated from Gunnedah Basin by the Hunter-Mooki Thrust Fault. These rocks have been subject to large scale folding and faulting and as a result comprise a complex mixture of sedimentary and igneous rocks that have been subject to metamorphism.

- The Gunnedah Basin is the central section of the north-south oriented Sydney-Gunnedah-Bowen Basin system. Tadros (1993) describes the Gunnedah Basin as containing up to 1,200 metres of marine and non-marine Permian and Triassic sediments within which the coal bearing strata of the Black Jack Formation and the Maules Creek Formation occur.

- The Jurassic age Surat Basin unconformably overlies the Permian to Triassic sediments of the Gunnedah Basin. They consist of a series of volcanic rocks, overlain by fluvial and lacustrine sedimentary rocks that are part of the Great Artesian Basin. The Surat Basin is separated from the Gunnedah Basin by the Rocky Glen Ridge basement high.

- Underlying these sedimentary basins are the basement bounding rocks of the Boggabri Volcanics and the Lachlan Fold Belt.

- Extrusive volcanic rocks, Tertiary in age, occur in the northeast, south and southwest of the study area (Tadros, 1993). The rocks are formed from basaltic lava flows which were extruded over the older Gunnedah and Surat Basin sediments. They form the elevated areas of the Liverpool, Warrumbungle and Nandewar Ranges.

- Alluvial deposits of Neogene to Quaternary age are found associated with the stream systems overlying the consolidated Gunnedah and Surat Basin sediments. In the Upper Namoi area the alluvium is subdivided into two formations, the shallow Narrabri Formation and the deeper Gunnedah Formation. In the Lower Namoi the Gunnedah Formation is underlain by a third layer, known as the Cubbaroo Formation. The alluvium can be over 100 m thick.

A more detailed breakdown of the Gunnedah and Surat Basin stratigraphic units and a description of the alluvial deposits are provided in Table 2.1.

Table 2.1 Summary stratigraphic table

Period	Formations and groups	Main lithologies	Reference
Quaternary	Narrabri Formation	Clays with minor sand and gravel	Williams, 1986
Quaternary	Gunnedah (and Cubbaroo) Formations	Gravel and sand with minor clays	McNeilage, 2006
Jurassic and Cretaceous	Surat Basin GAB sediments	Sandstone, siltstone, mudstone, minor thin coal seams	GA, 2011
Jurassic	Pilliga Sandstone	Sandstone and conglomerate with minor mudstone, siltstone and coal	GA, 2011
Jurassic	Purlawaugh Formation	Sandstone thinly interbedded with siltstone, mudstone and thin coal seams	GA, 2011
Jurassic	Garrawilla Volcanics	Flows and intrusions of dolerite, basalt, trachyte, tuff and breccia	GA, 2011
Triassic	Deriah Formation	Sandstone with volcanic fragments and mudclasts	Tadros, 1993

Table 2.1 Summary stratigraphic table (continued)

Period	Formations and groups	Main lithologies	Reference
Triassic	Napperby Formation	Claystone, interbedded siltstone and sandstone	Tadros, 1993
Triassic	Digby Formation	Sandstone and conglomerate	GA, 2011
Permian	Black Jack Group	Conglomerate, sandstone, claystone, tuff and numerous coal seams	Tadros, 1993
Permian	Watermark Formation	Siltstone, claystone, sandstone	GA, 2011
Permian	Porcupine Formations	Basal conglomerate passing upwards into bioturbated silty sandstones and minor siltstones with dropped pebbles	GA, 2011
Permian	Maules Creek Formation	Conglomerate, sandstone, siltstone, claystone and numerous coal seams	Tadros, 1993
Permian	Goonbri and Leard Formations	Claystone and sandstones	GA, 2011
Permian	Boggabri Volcanics	Rhyolitic to dacitic lavas and ashflow tuffs with interbedded shale	GA, 2011

An illustrative cross section is provided in Figure 2.2. This shows how the thickness and depth of both the Gunnedah and Surat Basin sediments varies in an east to west direction across the Study area. This pattern is in part controlled by major structural features of the deep basin bounding rocks that include two north to south trending structures or 'basin highs', known as the Boggabri Ridge and the Rocky Glen Ridge. These deep basin structures are illustrated on the 'SeeBase' (SRK, 2011) Digital Surface in Figure 2.3 which represents the base of the Permian/top of the Boggabri Volcanics.

The Gunnedah Basin is split into a number of smaller sub-basins. The Boggabri Ridge separates the Maules Creek sub-basin from the main basin. The main Gunnedah Basin is further subdivided into three smaller basins (Bellata, Mullaley and Bando) by three minor east to west trending 'basin highs'. Much of the current coal mining is located in the Maules Creek and Mullaley sub-basins. CSG activity is currently focused in the Mullaley sub-basin.

There is a thin strip of Permian and Carboniferous outcropping strata which lie immediately to the east of the Hunter-Mooki Fault from Carroll to the southern boundary of the catchment. The area is known as the Werrie Basin and includes a small coal outlier (hosted by the Willow Tree Formation) which is being extracted by Werris Creek Coal. Investigations by Rio Tinto (Rio Tinto, 1997) concluded that although extensive coaly units were present across a large portion of the Werrie Basin they were not of any economic significance.

2.2.2 *Geological model*

A digital 3D geological model of the catchment was constructed using Petrel v2010.2 software (Schlumberger, 2011). The geological model represents the geology of the entire Namoi catchment from ground surface down to a lowest elevation of -2,000 mAHD. It was constructed to fulfil two key requirements:

- To develop an understanding of the spatial relationship between the occurrence of coal measures (suitable for mining and gas extraction) and the key aquifers;
- To provide a platform for numerical modelling of the aquifer systems – identify layer thicknesses, vertical and horizontal relationships and overall geological structure.

Data for model construction was sourced from a number of sources including:

- Surface topography from government digital datasets.
- Published geological maps and reports.
- The NSW Office of Water Pinneena 3.2 dataset (NSW Office of Water, 2010).
- Open access and Industry Partner information describing the interpreted top and base of formations intersected in coal and gas wells.
- Interpolated geological surfaces obtained from studies completed by Industry Partners.
- The SeeBase project (top surface of the Boggabri Volcanics) (SRK, 2011). SeeBase™ is a depth-to-basement model.

As previously highlighted, detailed geological information is only present where there are resources to exploit (water, coal or gas). Elsewhere, required geological information is frequently absent. Due to the varied spatial distribution of data it was not feasible to delineate all the hard rock units present within the catchment and, therefore, the following approach was taken:

- It was not possible to construct a detailed geological model of the New England Fold Belt rocks due to their complexity and the lack of deep geological exploration in the area. They were represented as one layer in the geological model designated as the 'fractured rock layer'. Since there is no known coal bearing formations to the east of the Hunter-Mooki fault, further sub-division of the strata in this area was unnecessary and has no bearing on the outcome of the Study.
- The Gunnedah Basin has been subject to the greatest amount of geological investigations and is therefore understood in the most detail. Where sufficient data is available, coal seams have been modelled as a single layer. It was possible to delineate the Hoskissons and the Melville seams within the Black Jack Group but none of the individual seams in Maules Creek Formation could be defined separately therefore the whole formation was modelled as a single layer.
- In the western part of the Study area the data density is much sparser therefore the understanding of the geology in the Surat Basin is not as certain. The current understanding is that the strata dip towards the northwest, into the centre of the Surat Basin. There is sufficient data to represent and model the bottom two layers of the Surat Basin. The remaining layers were grouped together in one single layer.

The resulting Petrel geological mode comprises 19 layers; these are listed in Table 2.2. Where possible, surfaces were interpreted according to the geological information. Where data was scarce the interpolation was controlled mathematically by extrapolating relationships with other surfaces for which more data was available. For example, the top of Boggabri Volcanics and top of Purlawaugh Formation were used as trend surfaces.

There is a high degree of confidence in the definition of the base of the alluvium (base of the Gunnedah Formation) as there are a large number of boreholes which can be used to map its distribution.

Confidence in the model in the central part of the catchment is high as this corresponds to the area of greatest data density. Confidence to the west is limited however, as this is an area of low data coverage, and many assumptions are required to extend known geological surfaces to this region.

Table 2.2 Geological model layers

Petrel model layer	Geological units
1	Narrabri Formation
2a	Gunnedah Formation
2b	Weathered zone
3	Fractured rock aquifer
4	Great Artesian Basin
5	Pilliga Sandstone
6	Purlawaugh Formation
7	Garrawilla Volcanics
8	Napperby and Deriah Formation
9	Digby Formation
10	Upper Black Jack Formation
11	Hoskissons Seam
12	Middle Black Jack Formation
13	Melville Seam
14	Lower Black Jack Formation
15	Watermark and Porcupine Formations
16	Maules Creek Formation
17	Goonbri and Leard Formation
18	Willow Tree Formation and Boggabri Volcanics

The model formed a precursor to any numerical flow modelling of the sub-surface, as it provided model geometry and layers.

2.3 Hydrology

2.3.1 *Introduction*

Information regarding the geographical setting of the catchment and the characteristics of the surface water system was necessary to complete the development of the Hydrologic Model.

Data required to provide inputs to the model includes topography, soil type, land use, rainfall, evaporation, surface water storage and drainage (natural and artificial) and surface water flow measurements. A comprehensive review of the data collated is reported in Sections 3 and 8 of the Phase 2 Report and a summary is provided in the following sections.

2.3.2 *Catchment setting and surface water features*

As shown on Figure 2.4, the Namoi catchment is a north westerly draining system with headwaters on the western flank of the Great Dividing Range. It is bounded to the northeast by the elevated and rugged topography of the Nandewar Ranges and the New England Plateau, and to the south and west by the Liverpool and Warrumbungle Ranges.

Extensive soils mapping has been undertaken within the catchment and has been used by the Namoi Catchment Management Authority (Namoi CMA, 2011) to create 22 different land management units based on the soil mapping, topography, and hydrogeological properties.

The main drainage channel is the Namoi River with flow contributed by the major tributaries of the Macdonald River, Manilla River, Peel River, Mooki River, Cox's Creek, Maules Creek, Bohena Creek, Bundock Creek and Baradine Creek. Figure 2.5 illustrates the river systems and shows the five key sub-catchments of the Macdonald/Manilla, Peel, Mooki, Middle Namoi and Lower Namoi. The largest natural lake in the catchment is Lake Goran on the Liverpool Plains. It is ephemeral and is intermittently filled by streams that flow into it. When full the lake area can reach approximately 80 km^2, when dry the lakebed is used for cropping.

Flows in the Namoi catchment are regulated by three head water storages: Keepit Dam on the Namoi River upstream of the Peel River confluence (427,000 ML); Split Rock Dam on the Manilla River (397,000 ML); and Chaffey Dam on the Peel River upstream of Tamworth (62,000 ML) (Thoms et al., 1999) (Figure 2.5). The dams are primarily used to provide water supplies to irrigators on the alluvial plains. Additional benefits include flood mitigation and releases for environmental flows throughout drier periods. Chaffey Dam is also used to augment the Tamworth town water supply.

In addition to the main dams there are a series of regulating weirs within the catchment. They are designed to regulate flows, improve the precision of supply, and provide storage for downstream irrigators. An extensive network of semi-natural and artificially constructed surface water channels and drains distribute the water throughout the catchment. There are also a large number of private farm dams and ponds throughout the catchment that are likely to be a mixture of surface water and pumped groundwater storages.

2.3.3 *Surface water levels and flow*

The amount of rain falling on the catchment varies as a function of climate and topography. The catchment average is approximately 690 mm/yr with the upland areas in the east receiving on average 1,300 mm/yr and the alluvial plains in the west receiving on average 480 mm/yr (Figure 2.6). Average evaporation varies from around 1,000 mm/yr in the southeast, to over 2,100 mm/yr in the northwest of the catchment.

Only a small percentage of the rain falling on a catchment becomes surface water runoff. The long term annual average runoff at Gunnedah is 734,000 ML/yr, which represents 6% of the average annual catchment rainfall (Ivkovic, 2006). Processes including interception (by vegetation), transpiration (taken up by plants), evaporation (from soil and plants) and infiltration (into aquifers via the soil and unsaturated zone) intercept most rainfall before it can become surface water runoff.

There are 81 stream gauging stations which have, at some time, recorded surface water flow rates within the catchment; they are plotted on Figure 2.7. There are a large number of smaller streams that have had no regular flow gauging undertaken. Measured flows in the Namoi River at the Gunnedah gauging station are shown in Figure 2.8.

Flows in the Namoi River are extremely variable and many of the streams on the higher ground are ephemeral and only flow for a short period after significant rainfall events. The presence of significant flows outside rainfall events is therefore highly dependent on baseflow (groundwater discharge). Generally, annual flows increase with increasing catchment area, but downstream of Gunnedah annual flows decrease due to increasing evaporation, transmission losses and water use (Thoms et al., 1999).

Major flooding has occurred approximately every 10 years on average. However, the maximum period between flooding events on the regulated river sections has increased by around 50% as a result of water resource development (CSIRO, 2007). The size of events has decreased and the average annual flood volume is now lower.

2.3.4 *Surface water abstraction*

Records of surface water abstractions were provided by the NSW Office of Water and the locations are shown in Figure 2.9. A total of 379,000 ML/yr is allocated from the surface water systems of the Namoi catchment. The majority of this is extracted from the Lower Namoi, with an allocation of 253,500 ML/yr. The Upper Namoi accounts for 9,700 ML/yr while the Peel catchment has 48,300 ML/yr of water allocation. Currently 115,000 ML/yr is allocated as supplementary water allowances. These supplementary allowances however will be reduced to zero over the next 10 years.

Figure 2.10 summarises the annual abstraction rates for each area of the catchment. Abstractions within each year are highly seasonal, ranging from <700 ML/month to over 30,000 ML/month in most years. Peak abstractions normally occur at the start of each calendar year.

2.4 Hydrogeology

2.4.1 *Introduction*

Information regarding recharge, groundwater levels and flow, groundwater and surface water interactions, hydraulic properties of the aquifers and groundwater abstractions are critical inputs to the model. A summary of these systems is provided in below.

2.4.2 *Recharge*

The groundwater systems are replenished (recharged) by both natural processes (rainfall) and anthropogenic processes (irrigation). The majority of rainfall is removed from the system before it can reach the groundwater by a variety of processes including interception, transpiration, evaporation and runoff to surface water. It is important to quantify recharge to groundwater as this constitutes the main source of water to the Groundwater Model.

Recharge is thought to occur by several different processes within the Namoi catchment, these are summarised below and the schematic processes are illustrated in Figure 2.11.

Diffuse recharge

Diffuse recharge occurs over large areas through infiltration of rainfall. The amount of rainfall that becomes recharge varies depending on local conditions such as previous climatic events, vegetation, soil type and underlying geology. An estimate for diffuse recharge has been made using the lumped parameter Hydrologic Model.

Alluvial margin recharge

Due to the low permeability of the rock beneath the ridge systems, there is limited potential for water to percolate vertically downwards. Therefore, water that does not become surface water runoff, or is not intercepted by the plant canopy or removed by evapotranspiration travels laterally down slope away from the ridge. This process effectively removes water from the ridge system and delivers it to the edge of the alluvial plains. Once it reaches a more permeable material it is likely to infiltrate into the ground. This creates a zone of enhanced recharge along the alluvial margins.

Flood recharge

Overbank flooding of surface water during high flow events has the potential to create short term localised recharge pulses. The areas where this can occur are restricted to the flood plains as shown on Figure 2.12. Short term recharge events are also likely to occur through the beds of ephemeral streams after rainfall events. More permanent recharge events occur along perennial losing streams, such as those in the Lower Namoi, creating recharge corridors within the catchment.

A CSIRO study (CSIRO, 2008) predicted that flood recharge supplied 4.5% of inflow to the Upper Namoi alluvial aquifer, with river leakage supplying an additional 18.5%. It was also estimated that 56% of inflow to the Lower Namoi alluvial aquifer is derived from river leakage, with this 'predominantly a result of flooding inundation' (CSIRO, 2008).

Irrigation recharge

Ashton and Oliver (2011) estimate that average irrigation rates within the Namoi catchment are 4 ML/ha/yr. This equates to approximately 400 mm/yr of applied irrigation water. However, a large proportion of this is taken up by plants or evaporated and does not contribute to groundwater recharge. The Office of Water Upper Namoi Groundwater Model (McNeilage, 2006) uses values of 30 and 72 mm/yr for groundwater recharge over the Murray Darling Basin irrigated areas. The irrigated area within the model equates to approximately 380 km^2.

Recharge estimates

Recharge is often difficult to measure accurately and must be derived by calibration to streamflows, groundwater levels etc. Estimates of recharge have been made in several different studies. These are discussed in the Phase 2 report. A summary of those recharge estimates is provided in Table 2.3.

Table 2.3 Recharge summary table

Area of study	Findings	Reference
Office of Water Upper Namoi Groundwater Model	Rainfall recharge (includes recharge from ridge runoff and flooding) - spatially variable but an average of 3% (20 mm/yr). Irrigation - 30 and 72 mm/yr over localised areas.	McNeilage, 2006
Office of Water Lower Namoi Groundwater Model	Recharge equivalent to 0.5% of rainfall in the southern half of the model and 0.1% in the northern half. Previously used a value of 0.6% (4 mm/yr)	Merrick, 2001
Liverpool Plains	Diffuse recharge of 20 mm/yr a reasonable assumption for the alluvial plains. Estimates from other models evaluated range from 157 mm/yr in the Liverpool Ranges to c. 70 mm/yr on the sedimentary hills, and from <20 to 32 mm/yr on the alluvial plains	Zhang et al., 1997
Liverpool Plains	Groundwater recharge estimated as between zero and 75 mm/yr, with recharge only occurring in wet years. Over 50% of the predicted recharge occurred in two particular years. Average recharge is estimated at approximately 5.3 mm/yr.	Sun and Cornish, 2005
Lake Goran	When wet the lake is estimated to provide 6 mm/yr recharge	Zhang et al., 1997

Table 2.3 Recharge summary table (continued)

Area of study	Findings	Reference
GAB intake beds	Recharge rates of 0.5 to 10 mm/yr estimated using chloride mass balance techniques.	GAB sustainability initiative, 2010
GAB Southern Recharge Zone	Long term average annual recharge to the Southern Recharge Zone is 42,400 ML/yr. SWS Note: Given the area is 30,766 km^2 this equates to an average of 1.3 mm/yr recharge.	NSW DWE, 2009
Boggabri coal mine continuation - groundwater assessment	Calibrated model values: Alluvial aquifer – 18 mm/yr Slope wash zone – 90 mm/yr Ephemeral creeks – 90 mm/yr Bollol Creek headwaters – 150 mm/yr Outcrop hill zones – 1 mm/yr	AGE, 2010
Maules Creek coal mine	Calibrated model values: Alluvial aquifer – 7.2 mm/yr Permian outcrop – 0.66 mm/yr Volcanics outcrop – 2.7 mm/yr Slope wash zone – 116.3 mm/yr	AGE, 2011
Narrabri North coal mine	Calibrated model values: Variable from 0.5% (~3 mm/yr) to 5% (~30 mm/yr) of rainfall	Aquaterra, 2009

2.4.3 *Groundwater levels and flow*

Monitoring for groundwater levels is undertaken within the Namoi catchment by the New South Wales Office of Water. Several of the coal and gas companies operating within the Namoi catchment also undertake baseline and operational monitoring programs for water resource management.

The most widespread dataset available comes from the Pinneena 3.2 GW database (NSW Office of Water, 2010). Figure 2.13 shows the locations of all the groundwater level monitoring boreholes in that dataset. It can be seen that the bores are almost completely limited to either the alluvial areas of the catchment or the artesian areas of the GAB. There are very few monitoring bores and associated time variant water level data, located in the remaining hard rock units.

There is currently very little monitoring of bores by the CSG companies other than those used for production. Santos has one site (Kahlua) that has recently been test pumped. In addition to three bores that monitor the coal seam being dewatered the site also includes two monitoring bores with multi-level sensors. These bores have only been active for a few months and the data is still being compiled and reviewed by Santos.

All of the groundwater monitoring undertaken by coal mining and CSG companies is currently highly localised and concentrated only in the area of active development. As a result, there are large areas of the catchment with no groundwater monitoring data.

In the alluvial areas there is sufficient information to gain an overview of the groundwater level fluctuations over time due to seasonal and climatic conditions. These variations are recorded in the hydrographs for each monitoring point. A selection of locations was taken to represent the larger scale characteristics of the alluvial aquifers and were analysed in detail. A summary of the findings is provided below and illustrated in Figure 2.14:

- Static groundwater levels across the much of the catchment have been falling steadily. This most likely reflects the effects of the extended dry spell on the catchment combined with a continuation of groundwater abstraction during this time;
- Monitoring points in the zone of influence of groundwater abstractions show a marked reduction in groundwater levels due to abstraction with the deeper alluvium showing the greatest range in levels;
- Monitoring points further away from the groundwater abstractions do not show a response to abstraction but they do in general show the same reduction in static groundwater levels over time;
- The shallowest installations tend to be largely unaffected by groundwater abstraction but often appear to show a response to changes in stream flow, with a number of sharp rises followed by recession curves that most likely represents groundwater recharge associated with a flooding event.

The only hard rock area that has time variant groundwater level monitoring points is the GAB. The GAB hydrographs in Figure 2.15 demonstrate that artesian groundwater levels in the GAB have fallen over time but have been relatively stable since the 1970s. It is likely that this is due to a legacy of uncapped artesian bores that have allowed water to freely leave the system and cause a decrease in pressure. According to the Queensland Government (DERM, 2007) in many areas of the GAB an intensive program to find and cap these bores has led to pressures within the GAB aquifers stabilising or even increasing.

A catchment-wide water level contour map (Figure 2.16) has been produced using average water levels for any non-GAB site that had a groundwater level recorded after 1950. It shows that groundwater levels follow a similar pattern to topography, with projected flow paths mirroring the surface water systems, although locally these flows may be influenced by natural features such as fracturing or artificial influences such as groundwater abstraction.

For the purposes of this study it was necessary to construct specific groundwater contour maps for single aquifers or grouped aquifers to define starting heads for the groundwater flow model. Groundwater levels across the catchment were therefore classified into five stratigraphic groups for analysis. The groupings were chosen based on an assessment of the likely degree of connection between units, the availability of data for each unit, and the importance of each unit in transmitting potential effects of coal and gas developments. The selected groupings were:

- Upper Namoi Alluvium – Narrabri Formation and Gunnedah Formation.
- Lower Namoi Alluvium – Single unit.
- GAB – GAB, Pilliga Sandstone and Purlawaugh Formation.
- Hard Rock – Units below the Pilliga to the east of GAB extent.
- Fractured rock – Anything within the conceptual fractured rock unit defined and interpreted in the geological model.

Based on the above, the following 3 contour maps were produced:

1. The non-alluvial system (Figure 2.17a). This is derived from a combination of groundwater levels that have been assigned to the GAB, hard rock and fractured rock systems.
2. The Narrabri Formation (Figure 2.17b). This is comprised of groundwater observations from within the Narrabri Formation only.
3. The Gunnedah Formation and Lower Namoi Alluvium (Figure 2.17c). Based on groundwater observations from within the Gunnedah Formation and Lower Namoi Alluvium only.

An understanding of the groundwater flow directions is also important for defining flow conditions around the edges of the catchment, in order to construct a model which replicates the prevailing flow conditions adequately. Boundary conditions can be flow divides (where there is minimal groundwater flow, or flow parallel to the boundary) or represent movement of groundwater in or out of the catchment. If cross boundary flows are present they must be included in any water balance modelling.

It has been assumed that in the upland areas of the catchment, groundwater divides are coincident with surface water divides. The hydrogeological units typical of the upland areas are characterised by fairly low yielding groundwater bores (compared to bores in the Upper and Lower Namoi Alluvium or the GAB). Groundwater flow in these units is dominated by flow through fractures in the rock matrix. Only minimal groundwater flow across the Hunter-Mooki Fault is anticipated given the geological units present on the eastern side of the fault.

The volcanic basement has been assumed to form an impermeable barrier to flow at depth. Where the basement comes close to surface, e.g. around the Boggabri Ridge, there is the potential for flow through the material where it has become weathered or fractured.

There is no groundwater divide present in the north west of the catchment. This area forms the edges of the Surat Basin, and the geological units dip towards the north. Water recharges into the GAB units where they outcrop or are near surface in the Pilliga area. Some of the recharged water diffuses upwards into the overlying systems, such as the Lower Namoi Alluvium, the rest leaves the system in deeper groundwater systems that support the main Surat Basin. The rate at which this water moves through the system is low, with estimates of between 1 and 4 m/yr (Herczeg, 2008).

2.4.4 *Groundwater surface water interactions*

A thorough introduction to the principles of groundwater-surface water interaction is provided in Winter et al. (1998).

The two water systems can be either ‘connected’ or ‘disconnected’ and this depends on relative elevations of the base of the streambed and the level of the groundwater. If the base of the streambed is above the level of the groundwater (i.e. there is an unsaturated zone beneath the streambed) the water systems are disconnected and surface water can be lost to groundwater through downward unsaturated flow. If the base of the streambed is below the level of the groundwater the water systems are connected and water can flow either way depending on the relative difference between the two water levels. For example, during a flood event the water level in the stream would be high causing water to flow from the stream to the groundwater, but this could be reversed during low flow conditions. Where rivers and aquifers have a direct connection there is the highest probability of groundwater extraction having an impact on river flows and levels.

Potential interaction can occur in one of three ways:

- Streams gain water from inflow of groundwater through the streambed (a gaining stream).
- Streams lose water to groundwater by outflow through the streambed (a losing stream).
- They do both (a variably gaining / losing stream), depending on conditions.

There are several studies that have been carried out on surface water – groundwater interactions in the Namoi catchment, notably Ivkovic (2006) and CSIRO (2007). Whilst there are some differences, most studies in the catchment agree that there is a general pattern of gaining streams in the upland incised valleys with losing (connected or disconnected) stretches in the flatter alluvial systems (Figure 2.18).

During the modelling, a more detailed understanding of the local variations between losing and gaining streams in the Upper Namoi was required. In order to achieve this, the relative positions of the stream water levels and groundwater levels were mapped. Analysis of stream bed elevations measured at gauging stations shows that the stream beds can typically be up to 4 m below the floodplain. Where groundwater levels, as illustrated in Figure 2.19, are contoured as being close to surface there is high potential for groundwater and surface water interaction if the streams are deeply incised. In areas with a large difference between the ground surface elevation at the streams and the elevation of the groundwater table, there is likely to be a lower degree of interaction between surface water and groundwater, and any potential interaction is likely to take the form of losses from stream flow into the groundwater system.

2.4.5 *Aquifer properties*

Aquifer units

Groundwater resources in the Namoi catchment are highly developed. Abstraction occurs primarily from the alluvial aquifers associated with the main rivers and their major tributaries. A large number of smaller scale abstractions also occur from the fractured rock aquifers, especially within the Peel catchment.

The Namoi catchment can broadly be split into five hydrogeological classes:

- Alluvial material along the low lying river valleys, especially the lower lying areas of the Namoi. These are the Narrabri, Gunnedah, and Cubbaroo Formations.
- Fractured fold belt material to the east of the Hunter-Mooki Fault, overlain in several locations by upland alluvium.
- Jurassic sandstones and Permian Gunnedah Basin sediments underlying and surrounding the alluvial deposits within the centre of the catchment but west of the Hunter-Mooki Fault.
- Great Artesian Basement (GAB) units in the northwest of the catchment.
- Volcanic basement underlying the Gunnedah Basin and GAB deposits.

A thorough introduction to the hydrogeological properties of different rock types and alluvial deposits is provided in Price (1996) and a brief overview is provided below:

- Coarse grained alluvial deposits and sedimentary rocks tend to have a high porosity and permeability and water is able to flow through them quite readily. These are defined as aquifers;
- Fine grained alluvial deposits and sedimentary rocks, and volcanic, igneous and metamorphic rocks tend to have lower porosity and permeability and the flow of water through them is usually several orders of magnitude less than in aquifers. These are defined as aquitards.

Hydraulic gradient is also an important factor with groundwater flowing from areas of high to low groundwater pressure. Depending on the gradient, groundwater can flow laterally (sideways) or vertically (both downwards or upwards).

Hydraulic parameters

The hydraulic parameters (hydraulic conductivity and storage) of the different geological units reflect how easy it is for water to move through them and how quickly any impacts caused by stresses propagate from the source. A combination of high hydraulic conductivities and low storage means that influences can spread quickly, lower hydraulic conductivity and higher storages reduces the spread of any stresses.

Information regarding the hydraulic properties of the rocks and alluvial deposits in the Study area has been collated from as many different sources as possible but there is limited data available. The main source of tested, assumed or calibrated hydraulic parameters is from previous groundwater studies associated with resource management of the Upper and Lower Namoi, or localised studies associated with coal and CSG assessments.

Table 2.4 provides a summary of the hydrogeological understanding of the different geological units based on the studies carried out on behalf of NSW Office of Water and Industry Partners, with any gaps filled using data from published literature. The values shown in the table were used as a starting point in the parameterisation of the numerical models, although were subject to change once calibration is started. The hydrogeological significance of each unit has been included to reflect their contribution to water resources on a catchment scale. It is also recognised that the less significant units may provide important water resources on a local scale.

Table 2.4 Hydraulic parameters

Geological units	Hydrogeological significance	Horizontal hydraulic conductivity, K_H (m/d)	Vertical hydraulic conductivity, K_V (m/d)	Specific yield, S_Y (-)	Specific storage, S_S (1/m)
Narrabri Formation	Significant Aquifer	0.1– 30[a] (6.3[a])	0.000001.7 – 0.037 [a] (0.0003 [a])	0.005 – 0.1[a]	0.000005[b]
Gunnedah Formation	Significant Aquifer	0.05– 30[a] (7.1 [a])	3.5 to 7.2[d]	0.15[d]	0.000001 – 0.0005[a]
Lower Namoi / Weathered Horizon	Significant Aquifer	0.0009 – 8.6[f]	0.009 – 0.9[f]	0.15[d]	0.000001 – 0.0005[a]
Fractured rock horizon	Aquifer	0.01 – 10[f]	0.001 – 0.1[f]	0.01[f]	0.00001[f]
Great Artesian Basin	Aquifer	0.004 – 0.265[b]	0.000015 – 0.0002[b]	0.1[e]	0.0001 – 0.00001[e]
Pilliga Sandstone	Aquifer	0.004 – 0.265[b]	0.000015 – 0.0002[b]	0.1[b]	0.000005[b]
Purlawaugh Formation	Aquifer	0.004 – 0.02[b]	0.000015 – 0.001[b]	0.001[b]	0.000005[b]
Garrawilla Volcanics	Minor Aquifer	0.001 – 0.04[b]	0.000006- 0.001[b]	0.002[b]	0.000005[b]
Napperby and Deriah Formation	Minor Aquifer	0.001 to 0.04[b]	0.000006[b] to 0.71[d]	0.1[d]	0.0001[d]
Digby Formation	Minor Aquifer	0.9 to 1.5[d]	0.62 to 0.71[d]	0.1[d]	0.0001[d]
Upper Black Jack	Aquitard	0.0003 – 1.1[d]	0.19 – 0.59[d]	0.1[c]	0.00001[d]
Hoskissons seam	Aquifer	0.13 to 3.3[c]	0.00022 to 0.002[c]	0.2[c]	0.0001[c]
Middle Black Jack	Aquitard	0.0015 to 0.047[d]	0.005 to 0.4[d]	0.1[d]	0.0001[d]
Melvilles seam	Aquifer	0.02[g]	0.005 to 0.4[g]	0.1[g]	0.0001[g]
Lower Black Jack	Aquitard	0.0015 to 0.047[d]	0.005 to 0.4[d]	0.1[d]	0.0001[d]
Watermark and Porcupine Formations	Aquitard	0.0009 – 0.00014[f]	0.00009 – 0.0014[f]	0.01	0.00001[d]
Maules Creek Formation	Aquifer	0.13 to 3.3[c]	0.00022 to 0.002[c]	0.1[c]	0.0001[c]
Leard Formation	Aquitard	0.009 – 0.25[f]	0.0009 – 0.025[f]	0.01[f]	0.00001[f]

Refs: a = NSW Office of Water (2010), b = Aquaterra (2009), c = Golder Associates (2008), d = Golder Associates (2010), e = GABCC (2010), f = Freeze and Cherry (1979), g = GeoTerra (2008).

2.4.6 *Groundwater quality*

There are no long-term groundwater quality monitoring points in the Namoi catchment. Groundwater quality has been sampled intermittently from NSW Office of Water boreholes and the results are available in the Pinneena 3.2 database. A larger amount of data has been collected for various industry studies, and this provides some detailed information but the temporal and spatial distribution of this type of data is very limited. A summary of the groundwater quality data available is provided below:

- Salinity - this is a prominent issue in several areas of the catchment because of shallow water tables and an increase in the salinity of the irrigation water in some areas (Timms et al., 2010, Mawhinney, 2011 and Kelly et al., 2007). Figure 2.20 shows the range of salinity recorded in the groundwater from the Pinneena database;
- Major ions:
    - a number of studies have looked at major ions as these provide information regarding groundwater flow paths, groundwater provenance and interaction between surface and groundwater;
    - CSG studies have also reported major ion chemistry of coal seam water and Gunnedah Basin sediment water as part of their investigations. Table 2.5 shows the data obtained during the Santos drilling program (Golder Associates, 2010). From the data it can be seen that coal seam water is very different from Gunnedah Basin sediment water, the former being predominantly of sodium-bicarbonate type with higher Total Dissolved Solids (TDS).

Table 2.5 Mean groundwater quality values for the Gunnedah Basin (Santos)

Parameter	Unit	Hoskissons seam	Gunnedah Basin sediments (excluding coal seams)
pH	---	8.0	7.3
EC	µS/cm	5,337	2,463
TDS	mg/L	3,240	1,712
Calcium	mg/L	6.8	55.1
Magnesium	mg/L	8.1	84.1
Sodium	mg/L	1,337	313
Potassium	mg/L	11.0	9.5
Bicarbonate	mg/L	3,166	698
Chloride	mg/L	297	349
Sulphate	mg/L	2.6	126
Carbonate	mg/L	102	N/A

(Golder Associates, 2010)

2.4.7 *Groundwater management and abstraction*

Historical groundwater abstraction data is held by the NSW Office of Water in both electronic and paper format. The datasets used in the Office of Water Upper Namoi Alluvium (McNeilage, 2006) and Lower Namoi Alluvium (Merrick, 2001) groundwater models are considered to be the most complete set of abstractions records as early paper records were added by NSW Office of Water staff to the electronic dataset. These datasets were therefore taken forward and used in the Phase 3 modelling in the areas which they covered.

Locations of abstractions in the catchment are shown on Figure 2.21 and the volumes abstracted are shown in Table 2.6.

Table 2.6 Groundwater abstractions

Groundwater area	Abstraction shares*, 2009-2010 water year	Abstraction in 2009	
		ML/yr	m^3/d (approx)
Upper Namoi Zone 1	3,405	1,237	3,390
Upper Namoi Zone 2	10,772	11,468	31,420
Upper Namoi Zone 3	22,139	14,137	38,730
Upper Namoi Zone 4	33,875	19,950	54,660
Upper Namoi Zone 5	18,708	12,868	35,250
Upper Namoi Zone 6	11,448	563	1,540
Upper Namoi Zone 7	3,704	676	1,850
Upper Namoi Zone 8	18,935	6,647	18,210
Upper Namoi Zone 9	11,342	1,471	4,030
Upper Namoi Zone 10	1,420	3	8
Upper Namoi Zone 11	2,218	622	1,700
Upper Namoi Zone 12	2,774	506	1,390
Upper Namoi total	140,739	70,149	192,190
Lower Namoi	98,525	63,800	174,800
Hard rock	---	14,355	39,330

* Abstraction shares (or share components) entitle the holder to take a volume share of the water available in a particular area or zone. The volume will change depending on the amount of water available.

As expected, there is significantly less abstraction in the area of the hard rock system compared to the alluvial units. A comparison of abstractions from the two groundwater systems is shown in Figure 2.22. Abstraction from the basement was an average of around 33,000 m^3/d between January 2002 and December 2009. Abstraction from the alluvium over the same period averaged about 573,000 m^3/d. Peak abstraction from the alluvium in the dataset reached approximately 1,510,000 m^3/d in October 2002. The highest abstraction rate in the Upper and Lower Namoi models was 2,255,000 m^3/d.

The level of uncertainty in the groundwater usage figures is not well defined. Unlicensed bores exist in the catchment but these are likely to account for a relatively small proportion of the total groundwater abstracted. If future investigations should identify any significant errors in the abstraction datasets used as inputs to the current Study, it will be possible to test the sensitivity of the Groundwater Model to the abstraction volumes by increasing or decreasing the abstracted volumes in a sensitivity run.

3 COAL AND COAL SEAM GAS RESOURCES

3.1 Introduction

The purpose of the Namoi Catchment Water Study is to assess the nature and extent of potential effects from coal and gas developments on the water resources of the Namoi catchment. Both types of development interact with the water resources in the catchment, although the scales of the areas affected are likely to be significantly different.

When considered in isolation the effects of individual mines or CSG wells will be localised and these effects are evaluated during the permitting process for each individual development. Each coal mining or CSG operation is required to submit an Environmental Impact Assessment (EIA) and Site Water Management Plan. An assessment of the potential impacts on surface and groundwater resources during and after the life of the operation and details of how these impacts will be minimised and mitigated is included in each EIA. Predictions of how the operations may affect the local groundwater environment are often undertaken by creating a groundwater model of the area around the proposed development.

In catchments such as the Namoi however, which contain extensive coal seams, it is not uncommon to have clusters of mines or CSG tenements in a particular area. These combined developments have the potential to create greater impacts than when the developments are considered individually. No existing groundwater or surface water models cover the whole of the Namoi catchment and none include both CSG and coal mining developments.

The goal of the Namoi Catchment Water Study is to provide this level of understanding. In order to do this it is first necessary to develop a thorough understanding of historical, current and likely future mining and CSG developments, focusing on aspects such as extraction methodologies, target seams, locations, water production, etc. This knowledge will advise the conceptualisation of groundwater and surface water quality and quantity impact pathways and the development of mining and CSG scenarios for use in the Model.

3.2 Coal mining

Coal was first discovered in the catchment in the 1870s and coal mining has been occurring in the catchment for the last 130 years (NSW Minerals Council, 2011), although the number and size of mines has increased in recent years. Coal mining occurs along a narrow band within the catchment where the coal lies sufficiently close to surface to be economically mined. Figure 3.1 shows the locations of both active and closed coal mines in the catchment along with those in the exploration phase.

There are currently 6 active mines, 3 closed mines and 8 operations in varying stages of exploration or planning in the catchment. Their locations are plotted in more detail in Figure 3.2 which places the mines in the context of the position of the alluvium. The Black Jack Group and the Maules Creek Formation are the key formations targeted by coal mining operators.

The Black Jack Group contains a number of coal seams. They comprise at least the following named seams although there may also be others present: Doona, Springfield, Clift, Breeza, Howes Hill, Caroona, Hoskissons and Melvilles. The principal seams of interest are the Hoskissons and Melvilles seams, the two seams appear to be laterally continuous over a wide area. The Hoskissons seam is known to be up to 16 m thick in the southeast of the basin (NSW DPI, 2011). The Hoskissons seam is being targeted in all of the coal mines which extract from the Black Jack Group (i.e. from Narrabri in the north to Caroona in the south).

Coal seams within the Maules Creek Formation are shown in Table 3.1 and in most coal mines multiple seams are extracted.

Table 3.1 Coal seams within the Maules Creek Formation

Seam name	Mines targeting this seam		
Herndale	Maules Creek		
Onavale	Maules Creek		
Teston	Maules Creek		
Thornfield	Maules Creek		
Braymont	Maules Creek	Boggabri	Tarrawonga
Bollol Creek		Boggabri	Tarrawonga
Jeralong	Maules Creek	Boggabri	Tarrawonga
Merriown	Maules Creek	Boggabri	Tarrawonga
Velyama	Maules Creek		Tarrawonga
Nagero	Maules Creek		Tarrawonga
Upper Northam	Maules Creek		
Therribri	Maules Creek		
Flixton	Maules Creek		
Tarrawonga	Maules Creek		
Templemore	Maules Creek		

Canyon – not correlated - WAA to WAG seams.
Rocglen – not correlated – Upper Glenroc, Lower Glenroc, Belmont seams
Vickery – not correlated – Tralee, Gundawarra, Kurrumbede, Shannon Harbour, Stratford, Bluevale, Cranleigh
Eastern Star Gas – not correlated – 4 seams identified including Namoi and Bohena

Mining methods in the catchment include open-cut and underground mining both of which currently target coal at up to about 300 m below ground level.

Open-cut mines are generally developed when deposits of commercial minerals or rock are found relatively close to the surface. Open-cut mining usually involves blasting and removing surface layers of soil and rock (overburden) to reach the deposit. Once the economic resource has been removed from that area the void is often backfilled with the overburden being removed from the next area being mined. Backfilling is undertaken for a number of reasons including economical (it minimises the distance that waste rock has to be moved) and environmental (it minimises the area to be rehabilitated and buries any material that could otherwise oxidise and require ongoing maintenance after site closure).

Surface facilities will be required for both open-cut and underground mines to hold the initial material removed, coal washing and processing areas, stockpiles and loading areas etc. In most cases any surface water collected from these areas will require testing to ensure it is of suitable water quality before it can be discharged from the site. The areas taken up by the open-cut and surface infrastructure will vary from site to site and also through time for a single site. Rehabilitation of the site is carried out in stages as each area reaches its final approved state.

Historically underground mining used the 'bord and pillar' method in which coal was extracted in a regular grid pattern whilst leaving behind pillars of coal to support the roof of the workings and prevent the overburden from collapsing into the void. This method was used at the Gunnedah and Preston collieries which are now closed.

The bord and pillar method of underground mining leaves economic coal behind in the supporting pillars. Most of the newer underground mines in Australia use a technique known as longwall mining. This involves the mining of an extended wall (normally about 250-400 m long) of coal in a single slice (generally at least 1 - 2 m thick) (Greatmining, 2011). The roof is temporarily supported while the extraction process proceeds (Kentucky Geological Survey, 2011) but as the cavity behind the longwall increases, eventually the roof collapses under the weight of the overlying strata (Smith, 2009). This technique is being used at the Narrabri North underground mine which has just started operations. At the Narrabri mine the target seam is a thickness of 9.4 m although the approved mining plan only allows for the lower 4.2 m to be extracted at the present time (Whitehaven, 2011).

During their operation, coal mines require water for various activities including coal washing, dust suppression, drilling and human consumption. The mining process may directly intercept surface water and groundwater which can then be stored on-site for use; however some mine sites have to import water to supplement their usage. Excess water may have to be discharged to either surface or groundwater and may have to be stored and treated prior to release. Depending on the technique used underground mining can also cause subsidence of the ground surface. Subsidence is most common with longwall mining as the cavity behind the longwall collapses. Potential impacts associated with water management and subsidence are discussed in more detail in Section 3.4.

In 2010 the Gunnedah Basin exported around 6 million tonnes per annum (Mtpa) coal (ARTC, 2011). Predictions are for this to increase to approximately 50 Mtpa by 2020 (ARTC, 2011).

3.3 Coal seam gas

The Coal Seam Gas (CSG) industry has only been present within the catchment for around the last 10 years and the industry is still very much in an exploration phase of development compared to other regions within Australia. As CSG developments are generally focused on deeper (up to 1km depth) laterally extensive coal seams there is the potential for CSG developments to occur over a larger area of the catchment than coal mining. The existing CSG tenements cover a much larger area than those issued for coal mining.

The Gunnedah Basin is currently subject to a number of CSG developments in various stages of exploration, pre-development and extraction that are licensed under the Petroleum Act. There are three types of licence issued under the act including the Petroleum Exploration Licence (PEL), the Petroleum Assessment Lease (PAL) and the Petroleum Production Lease (PPL). Figure 3.3 shows the areas of the catchment covered by these different types of Licences. Coal seams in both the Black Jack Group (Hoskissons) and the Maules Creek Formation (Namoi and Bohena) are being targeted by the CSG companies for exploration and appraisal.

Santos and Eastern Star Gas (recently acquired by Santos) operate the majority of the petroleum exploration licenses in the Gunnedah Basin, with the remaining leases held by Dart Energy (Figure 3.3). The history of CSG in the catchment is much shorter than for the coal mines and there is consequently less historical data available.

There is only one PPL in the area of Namoi catchment; PPL 3 has been granted to Eastern Star Gas (ESG) for the development of the Coonarah conventional gas field, located about 20 km west of Narrabri. Current production is from the Maules Creek sandstone reservoir and the gas is piped to the Wilga Park Power Station (Eastern Star Gas, 2011).

Except for one pilot scheme operated by Santos at Kahlua, near Gunnedah in PEL 1, the main focus of activity is currently located in PEL 238 and PAL 2 where Eastern Star Gas operate six pilot or pilot production plants (Figure 3.4). The different sites target different coal seams and trial different well configurations (Table 3.2). Gas from the sites is piped to the Wilga Park power station.

Table 3.2 Eastern Star Gas pilot sites

Site	Target seam	Start date	Configuration
Bohena	Bohena seam, Maules Creek Frm	Since Nov 2006 in present configuration	Three vertical wells in a straight line
Bibblewindi 9-spot	Bohena seam, Maules Creek Frm	Early 2007	Nine vertical fracture stimulated wells
Bibblewindi multi-lateral	Bohena seam, Maules Creek Frm	Main pilot March-May 2009; shield wells online Sept 2009; electric submersible pumps installed 2011	Two adjacent bi-lateral wells plus two lateral shield wells
Bibblewindi West	Namoi seam, Maules Creek Frm	Nov 2009	Tri-lateral pilot with four vertical production wells
Tintsfield	Hoskissons seam, Black Jack Group	Apr 2011	Three parallel lateral wells with three vertical production wells
Dewhurst	Bohena seam, Maules Creek Frm	Preliminary testing	Three parallel lateral wells with three vertical production wells

CSG comprises mostly methane gas formed within coal seams that are usually saturated with water. The water pressure serves to hold the methane within the coal. When the water is pumped out of the coal, the fluid pressures in the seam are reduced and the gas is desorbed and released from the coal. Groundwater abstraction is a necessary by-product of CSG production and is known as ‘produced’ water or ‘associated’ water. When the coal seams are initially dewatered, large volumes of water are produced, but as extraction continues the volumes of water decreases. This is illustrated in Figure 3.5 which shows the projected water production curves for two potential wellfields within the Namoi catchment. CSG companies are required to develop a water management strategy and this will likely include produced water being stored and treated on-site before being reused or discharged.

CSG project development involves the drilling of a large number of wells to extract gas over wide areas. Gas can often be extracted from multiple coal seams via a single multilateral well. Companies have experimented with various drilling techniques and both horizontal and vertical drilling is now being trialled in the Namoi catchment (Gas Today, 2009). Hydraulic fracturing of the coal seam may be required in order to increase the gas recovery (QLD Government, 2011). This process involves pumping fluid and sand, under pressure, into a coal seam. The pumping action fractures the coal seam, which provides a pathway that increases the ability of gas to flow through the coal (QLD Government, 2011).

In addition to the underground infrastructure required to reach and extract the gas from the coal seams surface works are also required. These are detailed in Section 7 of the Phase 3 report. In summary each site requires a wellhead area, an access road, and pipelines to remove the produced gas and water. The gas pipelines run to centralised locations where the gas is compressed before it is moved away from the area and into the distribution network. The water pipelines run to centralised storages where the water is held before it is disposed of. Depending on the final destination of the water there may be a water treatment facility located near to the storage site.

3.4 Potential impacts of coal and CSG development on water resources

3.4.1 *Spatial relationship to water resources*

Figure 3.2 shows the location of the both the open-cut and underground coal mining operations and licensed areas. Figure 3.3 shows the CSG PEL areas which clearly have a much greater extent than the coal mining areas.

A much more detailed assessment of the spatial relationship between water resources and formations hosting coal seams was carried out using the digital geological model. The result of that analysis is displayed in Figure 3.6 and illustrates the extent of the Black Jack Group and Maules Creek Formations, and the location of those areas where either of these units come within 400 m of the ground surface. This provides an approximation of the areas prospective for open pit and underground coal mining (i.e. anything within 400 m of the surface). The actual potential of prospective coal resources is based on numerous factors, including grade, geological constraints, global economics, etc., none of which were taken into account in the purely spatial analysis.

Within the catchment, the areas with the highest potential for coal mining lie beneath and adjacent to the Upper Namoi Alluvium, stretching from Narrabri in the north to Quirindi in the south. The prospective area extends a maximum of 50 km to the west of the western boundary of the alluvium, but beyond this point the coal is generally at greater depths than could be economically mined.

The areas prospective for coal seam gas extraction may overlap significantly with the coal mining areas but also extend into a much greater area of the catchment where the coal seams are deeper. CSG extraction can also be considered possible at fairly shallow depths (potentially 200 m or less).

3.4.2 *Potential impacts of coal mining*

Both open-cut and underground coal mining have the potential to impact the quantity and quality of surface and groundwater resources. The potential impact mechanisms are illustrated on Figures 3.7 and 3.8 and are summarised below:

- Interception of rainfall and run-off. There is a greater potential for open-cut mines to intercept rainfall and run-off due to their larger surface footprint than underground mines. Where possible operators tend to divert existing surface water drainage around the perimeter of the site to minimise drainage into the open-cut. Water intercepted is removed from the surface/groundwater systems and stored on-site for use in operations or treated and discharged;

- Lowering of groundwater levels. Mining below the water table in either open-cut or underground mines can have an impact on groundwater resources. Dewatering of pits and mines can potentially induce local changes in groundwater gradients and flow directions;

- Pit runoff water and pumped groundwater can be contaminated with suspended solids and/or dissolved minerals and metals, and would need to be treated before discharge into the local drainage system;

- Surface subsidence, a possible consequence of underground mining, has the potential to change surface water drainage patterns;

- Connective cracking can potentially occur in strata overlying collapsed underground mine workings. This can possibly induce vertical connections between different aquifer systems and between aquifer and surface water systems (Smith, 2009). This creates a flow path that did not previously exist. If subsidence and cracking occurs under surface water bodies it can result in a significant increase in water entering the mine workings, and loss of water at the surface (Smith, 2009).

3.4.3 *Potential impacts of CSG extraction*

CSG extraction has the potential to impact the quantity and quality of surface and groundwater resources. The magnitude and extent of impacts depends on the extent of the drawdown in the groundwater system and the proximity and connectivity of the resources to the CSG extraction (Parsons Brinckerhoff, 2004). The potential impacts are illustrated on Figure 3.9 and described below.

The extraction of CSG involves pumping water from the coal seam in order to reduce the groundwater pressure that holds the gas in the coal. This will have an effect on the groundwater system surrounding it, as groundwater will then flow towards the zone of dewatering.

Potentially large quantities of groundwater are a by-product of CSG production. The water can be of a composition that makes it unsuitable for direct re-use in the environment, and as such it must be contained and dealt with. The amount of water that must be pumped varies from basin to basin, but also temporally during the history of individual producing wells. Management of this water can be undertaken using evaporation ponds, by re-injection to suitable strata at depth, or by treating it to a standard suitable for beneficial reuse (the standard will vary depending on the use). The most common treatment is to remove salinity by reverse osmosis (RO). RO involves pushing water through membranes with pores small enough to filter out most dissolved ions, resulting in a product that is suitable for operational use such as drilling and dust suppression, and which can be directly released to surface water courses or used for irrigation through water blending or nutrient supplementation. This water treatment process is currently in use for the Narrabri CSG pilot projects (Eastern Star Gas, 2006).

Release of treated CSG water into the catchment therefore carries a minimal risk of negatively impacting water quality if proper checks are in place. It is even possible for the treated water to be of a better quality than that which already exists, leading to an overall improvement in quality.

Between the time that it is pumped out of the ground and the time it is released or disposed of, CSG water must be stored. This is usually done in above ground ponds. The ponds are lined to prevent mixing of the produced water with the surrounding environment. However, breaches of containment systems have occurred in the past. The impact that any unauthorised discharge may have on the local area depends on the volume, composition and length of time that the breach occurs. If the discharge is due to overtopping after heavy rain there may be minimal harm as there will be significant additional surface runoff to dilute any discharge. If there is long term leakage from a punctured liner or leaky pipework then the impacts could be greater. These are localised issues that should be addressed in the Environmental Impact Statement. Simulation of this pathway in the regional scale model is not possible.

If hydraulic fracturing of the coal seams is required to increase productivity it may result in fracturing beyond the target coal seams resulting in increased connection between the seams and the surrounding groundwater systems. All reasonable measures are taken to prevent this occurring as it is of no economic benefit to enhance the permeability of material other than the coal seams. If other material is fractured it will lead to increased water production which will have to be disposed of with no gain in gas yield. The chemical make-up of the fracturing fluid may also have an impact (QLD Government, 2011) although this is only likely to be noticeable on a local rather than regional scale and once the wells are pumping a significant proportion of the injected fluid will be drawn towards the well and removed with the produced water.

The surface infrastructure associated with the CSG extraction wells is also likely to affect water resources on a localised scale. Areas of land have to be prepared for the borehole drilling equipment. Depending on existing use this may involve removal of existing land cover and installation of a roadway in order to access the site. These changes in land use have the potential to change surface runoff characteristics in the immediate area. A gas production well also requires pipelines to remove gas and water. These are usually buried to reduce their long term impacts. Compressor stations and water treatment plants will have relatively small footprint areas which will limit their impacts on the surrounding landscape.

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4 NUMERICAL MODELLING

4.1 Introduction

Numerical models are used to create representations of natural systems using mathematical formulae. Models try to recreate the changes in behaviour of the natural system as different stresses are placed on it. The physical controls on water movement through a system are very complex and varied and must be simplified for inclusion in a model. Numerical models can require many input files and produce many output files and require high performance computers to undertake millions of calculations.

The process of creating a model involves a number of steps:

1. Data collection and conceptualisation. This step is fundamental in creating a robust numerical model. The available data is translated into a 2D or 3D understanding of the system. It is not possible to measure every single parameter at all points in the system and the conceptualisation stage is commonly subject to a number of assumptions and simplifications.

2. Model construction. A model framework is constructed and populated with real or synthetic datasets based on the conceptual understanding. This is the first pass model and is often significantly different to the final product.

3. Historical calibration. The model is tested to see how well it replicates the system as it has been observed at some time in the past. The conceptual model may have to be revised and the setup of the model changed if the numerical model results are significantly different to those observed. This process is known as model calibration and is repeated until there is a good match between modelled and observed datasets.

4. Sensitivity analysis. The calibrated model is then tested to see how important the various inputs are in determining the simulated behaviour of the system. In this way future investigations can be designed to increase the accuracy in the values assigned to the inputs that have the greatest control over the system behaviour.

5. Future predictions. Changes are made to model inputs that reflect potential changes in the future (additional coal mines for example). As the future is the biggest unknown in the whole process a number of alternate configurations can be considered. These are known as model scenarios.

6. Uncertainty analysis. The model is used to provide an understanding of what range of predictions are possible given the knowledge of the system at that time. This is based on the premise that there is often significant uncertainty associated with most aspects of the model and that many different model configurations can provide a good calibration but different predictions.

As more data is collected from continued monitoring or further investigations it is customary to revisit the model and update it. In this way the model, and its associated predictive results, become more certain over time. In the Namoi catchment this process has been occurring for over 20 years in those areas covered by existing groundwater models.

The aim of this section is to provide a summary of the numerical modelling undertaken in the course of the Study, from construction and calibration to predictive, sensitivity and uncertainty analysis. A detailed assessment of the results is provided in the following section.

4.2 Model requirements

The requirements of the Namoi Catchment Water Study dictate that the modelling tools should be able to simulate the salient features of the groundwater, surface water and rainfall / runoff systems where they may be affected by mining and CSG development.

According to the Request for Tender (Section G "Specification") the modelling tool produced as part of Phase 3 of the Namoi Catchment Water Study should:

"Allow investigation of the nature and extent of potential effects on the catchment's water resources from coal and gas developments" and, specifically should:

- Be a 3D physically based continuous simulation model that includes all important physical processes relating to surface water and groundwater aquifers and the interaction between flow and water quality.
- Account for the activities of the agricultural industry, resources sector and broader community.
- Generate outputs that enable quantification of the likelihood of potential effects.
- Take no more than one day to execute.
- Model the potential effect of coal and gas development.
- Provide for the management and display of spatial data.
- Generate outputs that enable consideration of ongoing economic, environmental and social sustainability.
- Be acknowledged by the MOC as the most appropriate methodology.
- Be capable of being readily transferred to a third party.
- Be designed for reliable and efficient ongoing operation and maintenance beyond conclusion of the Study.
- Be suitable for incorporation of future data (post-Study).

4.3 Model rationale

During refinement of the modelling methodology, a consideration which was equally important to the objectives outlined in the Terms of Reference was to define the limitations and scope of the Model. These considerations have gained importance as the understanding of the extent and spatial availability of critical data has been improved, as the understanding of the processes key to the interaction between the water resources and coal and gas activities has been refined, and as the expectations of the Study by the wider community have become more evident. The following elements have been identified as key data and conceptualisation limitations and were critical to prioritising the development of the Model:

- The scale of the "area of interest" (very large). Data and understanding in large study areas is often inconsistent.
- The unprecedented nature and complexity of the modelling requirements. The conceptualisation and modelling of complex abstractions over such a large hydrogeological system is unusual in regional water resources studies.
- Groundwater and surface water data available for input to the model are almost exclusively focussed within the alluvial areas.
- Significant uncertainty exists in how, where and to what extent the coal resources will be developed in the future (most of these factors are outside the scope of the Study).

In addition, the scope and development of the Model should not be compared to specific site models such as:

- Localised and detailed groundwater, surface water and geotechnical models developed for existing, approved and proposed mines as required by the approval process.
- Localised models which will still be required for any future proposed mining or gas activities, regardless of the outcome of this Study.
- Alluvial systems models which have been developed over a 20 year period.

The local scale models are developed only with site specific data and with a site specific focus. They do not allow any consideration of the regional and cumulative impacts of mining and gas developments and how these might develop in the future.

The focus of the Model produced for the Namoi Catchment Water Study was therefore to produce a robust set of tools capable of providing an indication of what magnitude and where the cumulative impacts might be within the entire catchment and allow for the uncertainties in these predictions to be investigated.

An initial numerical modelling plan was developed in Phase 2 of the Study. This outlined a methodology for development of the modelling tools and was based on the understanding at that time. It included discussion of the following:

- The model objectives.
- Available numerical modelling codes for:
  - Groundwater flow simulation.
  - Surface water flow simulation.
  - Rainfall / runoff simulation.
  - Groundwater / surface water interaction simulation.

- The benefits of a single model or of several models to cover rainfall, recharge, surface water and groundwater flow processes.
- The likely configuration (domain, cell size etc) of models.
- The likely external and internal boundary conditions.
- The simulation time.
- The types of output that could be expected.

The plan proposed an approach involving the production of separate rainfall / runoff and groundwater flow models. Two groundwater flow models were anticipated to be required. One for the simulation of CSG related impacts and one for mining related impacts.

During the Phase 3 model construction tasks, understanding of the systems developed and it was found that it was possible to combine the Coal Seam Gas groundwater model with the Coal Mine groundwater model, without compromising the Study objectives in terms of detail of coverage and model run times. As a result, the modelling plan proposed in the Phase 2 report was modified, and the scope for the Phase 3 modelling works was determined to be as follows:

- A lumped parameter Hydrologic Model was constructed as planned. Based on further research and discussions with peer reviewers LASCAM was chosen as the modelling code.
- A single groundwater flow model (the Groundwater Model) was constructed to simulate both the effects of coal mine operation and the development of CSG operations. The MODFLOW modelling code was used in this case.

4.4 Modelling extent and scale

The data collection and conceptualisation undertaken as part of Phase 2 of the Study outlined the likely area for groundwater flow model development as that part of the catchment west of the Hunter-Mooki Fault. However, this still encompasses an area of about 30,380 km^2. The Hydrologic Model includes all of the eastern and central surface water catchments to a point approximately 6 km upstream of Narrabri, which comprises an area of approximately 25,000 km^2. Within these areas, two constraints necessarily apply:

- There are large areas of the model domain where data coverage is low / absent.
- It is not possible to provide fine detail representation (and therefore output) anywhere within the model domain due to the size.

The models are therefore regional in extent and will provide predictions at this scale. Table 4.1 illustrates the differences between regional and local scale models.

Table 4.1 Local vs. regional models

Prediction	Local model	Regional model
Model size	10's km^2	100's to 1,000's km^2
Data density	High	Low
Output scale	Local	Regional
Accuracy	Locally high, regionally low	Locally low, regionally high

These elements have an effect on the scale and accuracy of prediction. The models constructed as part of this Study do not provide small scale, highly certain predictions. They do however provide regional scale and regionally accurate predictions.

In summary, a model of this scale attempting to incorporate this many physical systems (and the interaction between them) cannot be expected to produce highly accurate and local scale predictions, such as:

- The behaviour of a spring.
- The exact water level at a groundwater bore.
- The flow at any one point along a river.
- Groundwater flow characteristics within discrete layers that make up an aquifer.
- Estimates of point scale recharge.

A regional scale model can however be expected to produce the following estimates:

- Regional changes in water level.
- Water balance of a stream reach.
- Groundwater transfer between hydrogeological formations.
- Catchment scale rainfall / runoff processes.

Modelling efforts were focused on the processes and inputs deemed to have the greatest control on the potential impacts. Therefore, the priority was to accurately simulate the interactions of mine voids and CSG abstraction with the groundwater system as these were conceptualised as having the greatest impact on the water resources. The impact of these development activities on other systems (i.e. recharge and surface water) were not ignored however, and provision in the models was made to attempt to quantify the impacts on these elements.

In terms of the spatial concentration of the modelling efforts, the following applies:

- All of the existing coal mine lease boundaries are within 6 km of the Upper Namoi Alluvium in the Gunnedah Basin.
- The majority of potential CSG abstractions are in the groundwater sub-catchments which drain towards the Upper Namoi Alluvium.
- There are no coal mines located adjacent to the Lower Namoi Alluvium. However, there may be future CSG abstraction from deep coal seams in the vicinity.
- There is no direct impact to the rivers in the Lower Namoi Alluvium from CSG activities as in this area the rivers are above the water table (disconnected/losing rivers) and any decrease in groundwater level will not create a change in flow within the rivers.

Accordingly, in the Groundwater Model, the Upper Namoi Alluvium is simulated in some detail and incorporates groundwater abstraction, rivers and a complex recharge input and the Lower Namoi Alluvium is simulated to a simplified level, with no groundwater abstraction or rivers. Simulating the Lower Namoi Alluvium to the same level of detail as the Upper Namoi Alluvium would not add to the Study outcome or the predictive capability of the Model.

The calibrated model should not be thought of as providing a definitive prediction of potential impacts. There are likely to be significant uncertainties in predictive scenario outputs as they move beyond the model calibration period and even within it. Prediction model results may therefore have to be considered along with a sensitivity analysis of key parameters to give a range of potential impacts.

Once the regional scale output is available from the model, it is then possible to use further assumptions to make judgements on how the results might translate to the local scale influences, but these are much more uncertain than if they were produced with a small scale local model.

4.5 Simulation of water quality

4.5.1 *Groundwater quality*

One of the requirements of the Study is that impacts on the chemical quality of water resources should be considered. This can be done in many ways, the most elaborate of which is to include the transport of solutes in the numerical flow models (groundwater and surface water). However, given the scale of the Model, the diverse impact pathways, the data availability and the many other competing requirements of the Model, this approach is not feasible. The rationale behind the simulation of water quality is considered in more detail in Section 3.4 of the Phase 3 Report and summarised in the following paragraphs.

The ways in which mining and CSG development may impact groundwater quality must first be identified before any decisions can be made about how the mechanisms should be simulated or if their inclusion in the Model is even viable. The most significant mechanisms by which groundwater quality could be impacted are described below:

- An increased flow of water from the alluvium towards, into and through the hard rock system following depressurisation of coal seams and overburden (CSG, underground mining and open-cut mining) possibly resulting in:
    - increased flow of lower quality water from the shallow parts of the alluvium into the deeper parts
    - increased downwards flow of water through the hard rock system
    - increased leakage of water from rivers into the shallow alluvial groundwater system and
    - potentially induced increased recharge into the alluvium.
- Introduction of non-native quality water into coal seams (and potentially other formations) during the process of hydraulic fracturing. Note that the subsequent process of well development and pumping should remove much of this introduced water from the system.
- Introduction of treated CSG produced water into the shallow alluvial aquifers. It is to be expected that permits will limit discharge water quality to something that is equal or better to that in-situ in the aquifer. Water quality is therefore only likely to be impacted in a positive way.
- Introduction of non-treated CSG produced water into deep hard rock formations. As these locations will be located in deep formations that are not utilised due to their depth and/or poor quality it is unlikely that addition of this water will negatively impact groundwater within the catchment.

- Connective cracking associated with underground mines resulting in a greater connection to surrounding units. Hydraulic fracturing may have the same effect, although this is not the desired result and would be counter-productive. Both phenomena would produce more flow towards either the mine void or CSG well during operations. Both would also ultimately result in increased leakage from the base of the alluvial aquifer into the hard rock units below.

Groundwater quality data in the catchment is limited in both the hard rock and alluvial systems. This was highlighted in the Phase 2 Report and has been noted by other authors (for example Kelly et al, 2007). Key data gaps include:

- There are no bores with long term records of Total Dissolved Solids (TDS) (time variant data).
- There are only a few areas where government held time variant data is available and these are Electrical Conductivity (EC) measurements rather than TDS. Even then these are limited to two small areas of the catchment; one area in the Lower Namoi and one area in Zone 3 of the Upper Namoi GMU.
- In locations with multiple monitoring points in one borehole (nested piezometers) there is sometimes no indication of which pipe, and therefore depth and formation, from which a sample was collected.
- Records are often grouped into qualitative descriptions (fresh, brackish, salty, etc) rather than quantitative values.

Therefore it appears that whilst the pathways for mining and CSG development to directly impact groundwater quality are fairly easy to define, the data required to accurately simulate them at a regional scale is entirely absent. This presents so much uncertainty that the numerical simulation of the movement of solutes with groundwater cannot be achieved with any accuracy. The initial conditions cannot be set, the transport settings cannot be calibrated and the model cannot incorporate what may be the controlling level of detail (thin layers within the Gunnedah and Narrabri Formations) and at the same time provide regional scale predictions.

Therefore qualitative measures were used to assess the likelihood of impacts on water quality (salinity) in the alluvium. The qualitative approach includes:

- The predicted changes in flows from the alluvium to the hard rock.
- The variation in groundwater levels in the Gunnedah and Narrabri Formations.

The first approach indicates to what extent the alluvium is being impacted in terms of flow volumes and the second indicates if this is being translated into an increased gradient between the shallow (lower quality) Narrabri Formation and the deeper (better quality) Gunnedah Formation.

Whist data limitations severely restrict the implementation of numerical simulation of solute transport; the code chosen for groundwater flow simulation does have this functionality. Therefore, if at some time in the future there are sufficient data, the model can be used to directly investigate water quality.

4.5.2 *Surface water quality*

In contrast to groundwater quality data, there is a reasonable amount of surface water quality data in terms of sampling frequency and spatial distribution. The data show that:

- Early studies, including Nancarrow (1998), concluded that prior to 2000, the water quality of the Namoi River system was generally moderate to poor, with high levels of nutrients, areas contaminated by agricultural chemicals, and areas with on-going salinity problems. While trends for parameters such as salinity, turbidity and nutrients varied in the short term, longer term trends showed little signs of a decline through time.

- A more recent study analysed data collected between 2002 and 2007 (Mawhinney, 2011) and identified that median values for many of the parameters of interest were similar to earlier data sets. This was partly attributed to low flows and drought reducing the amount of surface runoff into the waterways.

- A review of the latest data for the catchment was undertaken as part of Phase 2 of the Study and showed that although there were some exceedances of trigger and guidance levels, there were no obvious significant rising or falling trends in surface water quality compared to those seen in the past.

The authorised discharge of mine and CSG related water is assumed to only occur if the discharged water is of a similar of better quality than the receiving water. If this is undertaken in accordance with the authorisation there is no obvious potential for a reduction in water quality from this activity. However, a number of pathways by which mining and CSG activities may adversely impact surface water quality do exist and the most significant are outlined below:

- Major rainfall events and flooding may result in emergency discharges of untreated water from mines to the environment and the discharged water may be of a lower quality than the receiving water.

- Mine pits or subsidence induced by underground mines could intercept and alter surface water flows and this may lead to a reduction in groundwater recharge or runoff to streams. Depending on the local circumstances this could potentially have negative or positive impacts in terms of water quality.

The most significant mechanism by which mining and CSG have the potential to impact surface water quality is the release of poor quality untreated water either directly to streams or via flooding to a wider area. This mechanism cannot be included in the simulations because of the major uncertainties associated with these events. This uncertainty relates to fundamental inputs such as release locations, volumes, timing, duration and chemical composition. As little monitoring is available to characterise the impact of historical emergency discharges on surface water quality there is also no opportunity to calibrate this aspect of the Model.

The regional scale of the Study Model is therefore not the tool with which the impact of these events should be assessed as the uncertainties in the settings and therefore predictions would be large. However, the numerical code selected for simulation of rainfall / runoff and surface water flow does have the functionality to simulate water quality at a sub-catchment level. Therefore if at some time in the future this is deemed appropriate it can be undertaken.

4.6 Simulation of hydraulic fracturing (fracking)

The purpose of hydraulic fracturing in CSG development is to increase the fracture frequency, aperture and fracture extent within a particular coal seam. The resulting fractures typically extend 200 to 300 m from the well (CSIRO, 2012). Hydraulic fracturing can therefore locally increase the magnitude of hydraulic parameters in the immediate vicinity of the well that has been subject to the fracking process, but it does not result in significant change to the regional hydraulic characteristics of the geological units within the catchment. If undertaken, hydraulic fracturing is done on a well by well basis following well completion (casing, cementation, perforation, etc.). The process will also introduce water of different chemical composition into the target formation. However, a proportion of this will be removed as soon as the well starts to produce water and gas.

It is not possible to explicitly simulate the localised (well scale) hydraulic fracturing process in a numerical model with a cell dimension of 1 km x 1 km (plan view) that is primarily designed for long-term regional-scale prediction. Furthermore, in view of the uncertainty that is involved with synthesising future CSG fields for the Test Plan and the uncertainty associated with the main inputs required (location and volume of abstraction, target coal seam, timing etc.), any attempt to explicitly simulate the effects of hydraulic fracturing in the Groundwater Model would introduce even greater uncertainty into model outputs.

Due to the major uncertainties associated with all aspects of the process as described above, hydraulic fracturing is not explicitly simulated in the Groundwater Model. However, variations to the hydraulic conductivity of the Model layers and variations in the CSG abstraction volume were undertaken as part of the sensitivity analysis. The results of these, “what if”, scenarios were to assess the potential effect of very widespread and extensive hydraulic fracturing.

4.7 Model development

4.7.1 *Hydrologic model*

A lumped parameter hydrologic model, LASCAM (Sivapalan et al, 2002) was chosen to simulate the hydrologic processes which control surface water runoff and recharge to groundwater. The Hydrologic Model can be used to run a number of different simulations with differing land uses and compare the results.

The Hydrologic Model domain covers all of the eastern and central surface water catchments to a point approximately 6 km upstream of Narrabri, which comprises an area of approximately 25,000 km^2. This area was chosen as it includes all of the areas which could potentially be affected by coal mining and that also have the greatest potential for influencing the surface water system (as identified in the Phase 2 Report). The model domain also includes several areas of potential CSG development, and changes in recharge as a result of CSG infrastructure have been analysed as part of predictive simulations.

The Hydrologic Model is constructed as a series of 99 linked sub-catchments as illustrated in Figure 4.1. Each sub-catchment was characterised in terms of land use and vegetation characteristics, and stream channel geometry, so that the fate of incident rainfall could be determined in each model timestep. Sub-catchment characteristics that were required (rainfall, evaporation, vegetation cover, land-use and soil type) were determined from analyses of remote sensing, topographic and imagery datasets, stored within the Study GIS. Rainfall was allocated into canopy interception, runoff in the stream channel, storage in the subsurface materials, losses to evaporation and evapotranspiration, and recharge from shallow storage into the underlying groundwater system as shown in Figure 4.2.

Each of the sub-catchments forms the basis of the water balance. At each model time-step, infiltration, percolation, baseflow, evaporation and runoff were calculated according to the hillslope idealisation shown in Figure 4.3. Each sub-catchment was able to receive runoff at the upslope stream boundary, generate new runoff, and then discharge the combined runoff at a discrete sub-catchment outlet.

The model operates at a daily time-step. For the calibration and testing period of the model, output simulations from 1990 to 2010 were run, however the model was given 5 years to equilibrate and ensure that the initial values applied to each sub-catchment did not influence the subsequent model results. Therefore the period used for calibration and testing was the 15 years from 1995 to 2010.

A range of gauged surface water flow data was available for model calibration and assessment of performance. Based on the availability of data over the period 1995 to 2010 and the position of each station in relation to the LASCAM stream network a selection of data was used to assess the model performance (Figure 4.4).

Due to limitations with the LASCAM code, surface water abstractions were not simulated in the Hydrologic Model. This may have some impact on the calibration of the model but is not considered to directly affect the objectives of the rainfall / runoff modelling which are focussed on assessing the changes to groundwater recharge and stream flow from mining and CSG related activities.

Simulated lakes and surface storages act to mediate the flow between adjacent sub-catchments. The locations for these surface storages, in the stream network defined for the Hydrologic Model, are shown in Figure 4.4. Limited information was available for many of the storages, in particular their height-storage relationship and the relationship between storage level and the discharge rate. Since these are an important control on the hydrograph, uncertainty associated with these parameters limits the ability of the model to accurately predict the downstream hydrographs in relation to extreme floods or prolonged droughts. However since the purpose of this model is not for flow forecasting, but rather to assess of impacts of coal and CSG developments on the general water balance and potential changes in recharge rates, a focus on reducing the inaccuracies in flow forecasting at the extremes was not given a high priority.

The types of output that were used to compare the predicted and observed results at selected gauging stations include:

- Daily surface water hydrographs;
- Monthly flows;
- Annual flows;
- Long-term monthly average flows and
- Flow duration curves;

As expected, all of these model outputs tend to over-predict the small flows and under-predict the larger flood events, an example being the comparison of predicted versus observed annual flows at selected stations shown in Figures 4.5a and 4.5b. This could simply relate to an under-estimation of the stream velocity or also may be related to a lack of detail regarding the abstraction regimes and river operational practices within the model.

The surface water model was used to estimate recharge rates which were then input into the main MODFLOW groundwater model. Each sub-catchment produces a unique net-recharge which was input into MODFLOW. The recharge rates for selected catchments are presented in Figure 4.6 to demonstrate the nature of water table variation. The plots illustrate the downward (recharge) and upward (evapotranspiration) fluxes affecting the water table, together representing the net recharge flux for the sub-catchment area. The balance of the net recharge is highly dependent on the configured soil properties, the extent of deep-rooted vegetation and the vegetation LAI (leaf area index).

4.7.2 *Groundwater model*

The MODFLOW 2000 numerical code (Harbaugh et al, 2000) along with the user interface Groundwater Vistas, Version 6 (ESI, 2011) was used to simulate groundwater flow. MODFLOW is a widely adopted groundwater flow code. Through its flexibility and rapid set-up and run times, it provides an appropriate basis for the simulation of the flow of groundwater in the alluvial aquifers and the hard rock stratigraphy and the interaction between groundwater and surface water.

The Groundwater Model covers an area of approximately 30,380 km^2. The model domain comprises a rectangular model grid, rotated by 30 degrees anticlockwise from north, as shown in Figure 4.7. This aligns the model cells with the basin morphology, as the general dip direction of the hard rock units and orientation of the Upper Namoi Alluvium is along this axis.

The specific Groundwater Model structure includes:

1. The model origin is at 745,000E, 6,410,000N (MGA Zone 55, GDA94).
2. From the origin it extends 310 km to the NW and 180 km to the NE.
3. Cell size (plan view) is 1,000 m by 1,000 m (310 rows and 180 columns).
4. The model contains 20 vertical layers, with thicknesses provided by the geological model described in Section 2. Figure 4.8 provides an example cross section.
5. Each model layer is composed of 55,800 cells, resulting in a total number of cells for the model of 1,116,000.
6. The modelling has been undertaken assuming saturated, single phase, temperature independent and single density groundwater flow.

A number of parameter values, initial conditions and boundary conditions describing the physical systems were required to complete the model development and are summarised in the following paragraphs.

Recharge

Recharge inputs to much of the Upper Namoi Alluvium in the Groundwater Model were taken from the outputs of the Hydrologic Model. Where these data were not available, calibrated values from the Office of Water Upper Namoi Alluvium Groundwater Model (McNeilage, 2006) were used. Over the hard rock and Lower Namoi Alluvium areas an average literature value was used (a uniform value of 1.5 mm/yr). Rates assigned to simulate irrigation recharge were also based on the Office of Water model.

Hydraulic parameters

The MODFLOW code requires the definition of horizontal and vertical hydraulic conductivity and storage parameters (specific yield and specific storage depending on the MODFLOW layer type) for each active cell in the Groundwater Model domain.

Where calibrated hydraulic parameters were available from existing models (Office of Water Upper Namoi Alluvium (McNeilage, 2006) and the Lower Namoi Alluvium groundwater models (Merrick, 2001)) these were used. Given the long history of groundwater model development for both of these alluvial systems there was high confidence in the parameter values assigned to the Lower Namoi Alluvium and GMU Zones 2, 3, 4, 5, 11 and 12 in the Upper Namoi Alluvium, and values were not altered during model calibration.

The initial parameter values assigned to all other model layers (including Zones 1, 6, 7, 8, 9 and 10 of the Upper Namoi Groundwater Management Units) were based on those listed in Table 2.4 of this report. These values were treated as variable during model calibration.

Simulation period and initial conditions

Groundwater models are typically run commencing with steady state conditions. In the case of the Namoi catchment this would require the model to run from a time prior to European settlement of the catchment, or pre-1900, when the land started to be cleared for agriculture and the GAB was first drilled. Given the major changes in groundwater conditions that are known to have occurred during this period, and the lack of datasets for several major parameters until the 1980's it was not possible to start the Groundwater Model at steady state.

Instead the model was started as a time variant simulation from January 1985 using groundwater levels from that time period as the initial heads, and abstraction conditions from that time. A simulation of the systems from January 1985 to July 2010 produced a time variant historical model. This historical model was then taken forward to the calibration stages to produce a calibrated base-case model against which future coal and CSG development scenarios could be compared against to determine the differences resulting from the simulated developments.

External model boundaries

The active model domain is delineated by the Namoi catchment boundary to the west and the Hunter-Mooki Fault to the east (Figure 4.9). It was assumed that there is no flow either out of, or into, the groundwater system from adjacent groundwater systems.

Background groundwater abstractions

Background groundwater abstraction refers to any abstraction other than that associated with CSG activities. It therefore includes abstraction for irrigation, stock and domestic and public supply.

The abstraction rates applied to the wells were derived from the data described in Section 2 of the Phase 3 report. These rates were simplified however into monthly averages as part of the modelling process. The historical abstraction simulated includes:

- Abstraction from the Gunnedah and Narrabri Formations (938 wells);
- Abstraction from the hard rock formations and fractured rock (50 wells).

The locations of the groundwater abstractions represented in the groundwater model are shown on Figure 4.10.

Rivers

The rivers represented in the MODFLOW model are shown in Figure 4.11. The river network was split into 14 separate reaches, covering the main river channels within the Upper Namoi catchment. These rivers were included as they are in areas known to have stream-aquifer interaction or represent areas where river cells are required as a discharge zone to control groundwater levels.

The MODFLOW river package allows the flux between the river and model cell to be simulated. The flux varies depending on the difference in water level between the two cells. If the water level in the model cell falls below the base of the river (i.e. the river becomes disconnected from the groundwater) the flux from the river to the model cell becomes limited to a constant rate.

CSG extraction / injection wells

Simulation of the abstraction or re-injection of groundwater associated with CSG activities was achieved using the MODFLOW well package. For the historical model, the package was used to simulate the abstractions associated with the Eastern Star Gas pilot well sites. The package simulated a total of 26 wells abstracting from Layer 12 (Hoskissons Seam) or Layer 18 (Maules Creek Formation). The 3 wells involved with the Tintsfield pilot became active after the end of the historical model and are therefore not included in it.

Future production of groundwater from CSG related activities was simulated in the same way.

Mines

The flow of groundwater towards mine voids, both open-cut and underground, was simulated in the Groundwater Model with the MODFLOW drain package. The drain package removes water from the model cell in which it is defined if the water level in that cell is above a reference elevation assigned to the drain. If the head is below the reference elevation then no water is removed or added.

Drain cells for underground mines were assigned to model cells within the mine footprint but only within the model layer from which coal is being extracted. Drain cells for open-cut mines were assigned to all model cells within the mine footprint and in all model layers that the open-cut intersected.

4.8 Model operation

4.8.1 *Introduction*

Both the Hydrologic and Groundwater Models were subject to rigorous testing during the calibration process to determine whether they were appropriately constructed and calibrated. Once this process was completed the models were used in conjunction to investigate the potential cumulative impacts of coal and gas development. Finally the models were subject to a sensitivity and uncertainty analysis. This analysis aimed to investigate aspects of modelling methodology, potentially significant modelling assumptions and key (uncertain) parameter settings and ascertain whether the results of the predicative scenarios were sensitive to these variables.

4.8.2 *Calibration*

Model calibration is the process by which the initial parameter and boundary condition settings used in the numerical models are varied in order to produce a better match between model output (predictions) and the observed conditions for an historical period. Inputs that are varied are known as adjustable parameters and inputs that are not are known as fixed.

The aim of calibration is to improve the accuracy of the model set-up, reduce uncertainty and improve the (future) predictive capability of the models. However, parameters cannot be changed without justification based on the conceptual model or published guidelines.

The Hydrologic Model was calibrated by comparing the predicted rates of stream flow generated by the model against gauging data available for selected streams. Actual rainfall records were used as inputs to the calibration model, and the model was calibrated against stream gauging data collected over a 15 year period from 1995 to 2010. Calibration was achieved using an automated optimiser within the LASCAM package which continually adjusts the adjustable parameters assigned to the model to achieve the best fit to the observed data. At the conclusion of this process the Hydrologic Model was concluded to be appropriately constructed and calibrated, taking account of the quality and availability of the calibration data.

In the Groundwater Model the adjustable parameters were:

- Hydraulic conductivity (horizontal and vertical) of model layers and zones representing formations other than the Upper and Lower Namoi Alluvium covered by existing NSW Office of Water numerical models.
- Specific storage of model layers and zones representing formations other than the Upper and Lower Namoi Alluvium covered by existing NSW Office of Water numerical models.
- Specific yield of model layers and zones representing formations other than the Upper and Lower Namoi Alluvium covered by existing NSW Office of Water numerical models.
- Recharge.
- Drain conductance (mine boundary conditions).
- River conductance.

In terms of improving the Groundwater Model match to observed data, the focus was on:

- Time variant groundwater levels in the alluvium (time variant hydrographs).
- Time variant groundwater levels outside the alluvium.
- Reported (either observed or simulated) groundwater inflows to mine voids.
- River / stream reach water balances.

Given the spatial distribution of data within the catchment, there was no justification for applying heterogeneous parameter distributions within each formation (model layer) in the Groundwater Model, other than in the Upper Namoi Alluvium. Although the adoption of heterogeneous parameters within a layer may improve the model calibration in local zones, it would have no effect regionally (where future mines and CSG wells might be located) and would provide a false sense of accuracy to the predictive capability of the Model.

A detailed discussion of the results of the calibration testing is presented in Section 6 of the Phase 3 report and a summary is provided in the following paragraphs.

- Statistical analysis of the historical Groundwater Model indicates a good overall calibration, although analysis of the time variant hydrographs reveals that the calibration quality varies spatially.
- The hard rock units, especially at depth and in a regional context, are not calibrated. There is no data sufficient or suitable for this task. However, the adopted hydraulic values, especially of storage, are towards the low end of the scale when compared to expected values. These values are therefore conservative when thought of in terms of predicting impacts from coal and gas developments, as the impacts will be more significant under low storage conditions than high storage conditions.

- A comparison of observed / expected and simulated inflows to mine voids shows a good agreement, but the Model tends to overestimate inflows, especially for the small scale mines. Again, in terms of predicting impacts from coal and gas developments, this positions the Model at the conservative end of the scale, where inflows may be slightly greater than those seen in reality, and the Model is therefore more likely to overestimate than underestimate impacts.
- The Upper Namoi Alluvium has been shown to be variably calibrated to the time variant data.
    - Hydrographs in Groundwater Management Zones 3, 4 (apart from the area of Gin's Leap) and 5 are replicated well by the Model. In terms of the objectives of the Study these are in critical areas that have a high density of mine and CSG development in the predictive scenarios. This is therefore a very good outcome for the Model.
    - Hydrographs in Groundwater Management Zones 2, 6, 8 and 9 are replicated variably by the Model. Zones 2 and 8 are in the most critical areas in terms of the objectives of the Study and an improvement of the calibration here would therefore be of most benefit to the Study objectives.
    - Hydrographs in Groundwater Management Zones 1, 7, 10 and 11 are replicated quite poorly by the Model. Of these, Zones 7 and 11 are the most important to the objectives of the Study as they are in the vicinity of high density mine and CSG development in the predictive scenarios.

The calibration has therefore indicated where high or low confidence can be placed on model performance and therefore model predictions. This also indicates where further investigative effort would be most efficiently directed to improve confidence in model output.

In general this regional scale, exploratory numerical model can be considered fit for purpose. However, the lack of calibration opportunity in the hard rock areas means that the future predictions gained from this model cannot be considered as definitive and should be looked at in combination with the sensitivity analysis of hydraulic parameters.

In summary, the calibration of the Groundwater Model was assessed using published guidelines for groundwater modelling studies, and taking account of the specific objectives for The Model and the spatial and temporal availability of calibration data. This assessment concluded that the Groundwater Model is suitably calibrated for application to meet the objectives defined for the Study.

4.8.3 *Predictive scenarios*

The Hydrologic and Groundwater Models were used together to investigate the potential cumulative impacts of development. The set of potential future CSG and coal mine development scenarios is referred to as the Test Plan. The scenarios use set model configurations (parameters etc) defined at the completion of model calibration.

The Test Plan comprises seven scenarios which simulate progressively greater development of the coal resources. The specifics of the scenarios are defined in Table 4.2.

As per requirement G.3.7.1f.ii of the Study Terms of Reference the scenarios were run until the year 2100. It should be noted that based on the relatively small duration of calibration data available for the models this extended prediction period increases the uncertainty associated with the results.

Table 4.2 Scenario configuration

Scenario number	Project status	Mines	Coal seam gas
0	No mining	None	None
1	Approved	Werris Creek and extension Boggabri Tarrawonga Sunnyside Rocglen and extension Canyon Narrabri North	Eastern Star Gas pilot holes only
2	Approved and possible	As Scenario 1 plus Boggabri Extension Tarrawonga Extension Maules Creek Shenhua Watermark BHPB Caroona	As Scenario 1 and ESG Narrabri, Santos Bando
3	Exploratory long term	As Scenario 2 plus 21 hypothetical mines	As Scenario 2 and 6 additional hypothetical CSG fields
4	Exploratory long term (mining only)	As Scenario 2 plus 21 hypothetical mines	As Scenario 1
5	Exploratory long term (CSG only)	As Scenario 1	As Scenario 2 and 6 additional hypothetical gas fields
6	Exploratory long term (50% of underground mining repositioned to beneath alluvium)	As Scenario 3 but with 50% of hypothetical underground mines repositioned	As Scenario 2 and 6 additional hypothetical gas fields

In order to provide an appropriate framework within which to compare the potential impacts on water resources of mining and CSG development, the first predictive scenario (Scenario 0) was based on there being no development of coal mines or CSG projects in the Namoi catchment in the past or in the future. Although this model does not match reality it provides a baseline result within which the effects of climate variation and agricultural development are present, and can be used as a direct comparison against the other six scenarios which describe increasing levels of coal and gas development.

Scenario 1 includes only those projects that have been approved i.e. those mining developments that are currently active or will be commencing in the near future, and no major coal seam gas development (Figure 4.12).

Scenario 2 includes approved projects and those that have some level of planning or investigation associated with them at the present time (for these purposes termed “possible”) (Figure 4.13). This includes a number of additional mining projects and two coal seam gas developments. The developments simulated in Scenario 2 are ongoing until about 2040. After this time no new developments are simulated.

Scenario 3 includes the approved and possible developments but also additional hypothetical development of both coal and gas resources that continues until 2100 (Figure 4.14). The arrangement of the hypothetical resource development sites is based on the digital geological model (position and target coal seam) and existing mining practices (size and timing). These inputs are very uncertain. However this scenario provides a basis by which the impacts from catchment development on this scale can be judged.

The coal and gas development simulated in Scenario 3 equates to about 60 Mtpa of coal output for a duration of about 85 years. This figure is based on the maximum annual tonnage estimates for the coal mines which could be operating in the catchment in 2014. It has been assumed that each mine is operating at full capacity from the time it is approved. In reality there will be a start-up period and full production may not commence at a new mine for several years. In comparison the 2010 output and the industry prediction for 2020 are 6 and 50 Mtpa respectively (ARTC, 2011).

The level of development of the CSG resource is harder to quantify due to the very early stage of resource investigation.

Scenarios 4 and 5 consider the impacts of mining or coal seam gas separately; in other words mining without coal seam gas and coal seam gas without mining (Figures 4.15 and 4.16). These scenarios are identical to Scenario 3, but with one of these inputs removed. These scenarios are intended to try to quantify the proportion of impacts that each of these practices contributes to the predicted total.

Scenario 6 considers the impact when a number of hypothetical underground mines simulated in Scenario 3 are moved to positions directly beneath the Upper Namoi Alluvium (Figure 4.17).

The models are very complex with a high number of inputs and outputs. They therefore have the ability to produce a substantial amount of data for analysis. To allow for a robust consideration of the likelihood and magnitude of potential impacts, a selection of model outputs were assessed in Section 7.6 of the Phase 3 report. A description of the types of results presented in the Phase 3 report is provided below together with an example for each different type.

The outputs chosen and analysed from the Hydrologic Model included the following, with all of the presented results showing the difference between Scenarios 1 to 6 and Scenario 0:

- Graphs showing the change in 'whole of catchment' recharge on an annual timescale (Figure 4.18). These provided a check on the LASCAM output files to ensure that they were producing 'reasonable' datasets, and also show the cumulative changes to catchment recharge from mining and CSG developments.
- Maps of the average change in recharge for each sub-catchment (Figure 4.19). As the recharge signatures are stable through time these indicate which sub-catchments are predicted to be most affected (or not affected) by coal mining and CSG developments.
- Graphs showing the change in modelled stream flow at selected gauging sites (Figure 4.20). These show how surface water flows are influenced by each level of development.

The output chosen and analysed from the Groundwater Model included the following, with all of the presented results showing the difference between Scenarios 1 to 6 and Scenario 0:

- Contour maps showing the difference in predicted groundwater levels in 2030, 2060 and 2100 (Figure 4.21). This is provided for the Gunnedah Formation (i.e. the most productive hydrostratigraphic layer in the Upper Namoi Alluvium) and the Lower Namoi Alluvium for all scenarios. These provide the means by which the impact on groundwater levels can be assessed at the regional scale.
- For Scenario 3 the contour maps were also provided (at the same output times) for the Narrabri Formation (shallow Upper Namoi Alluvium), Pilliga Sandstone (Figure 4.22), Garrawilla Volcanics, Hoskinssons Seam (within the Black Jack Group) and Maules Creek Formation. These allow for an understanding of the regional impact on groundwater levels in these deeper hard rock formations.

- Hydrographs showing the difference in predicted groundwater level through time at several hypothetical locations within the Gunnedah Formation of the Upper Namoi Alluvium (Figure 4.23). These allow an appreciation of how the impact (in these locations at least) develops through time. This information is not captured by the contour maps which show only snapshots in time.

- Hydrographs showing the difference in predicted groundwater level through time at several hypothetical locations within the hard rock formations (Figure 4.24). Eight locations are used, each central to one of the simulated coal seam gas wellfields. Again, this output allows for an understanding of the time variant development of impacts in these locations.

- Time variant graphs showing the difference in modelled groundwater contribution to river flow (baseflow) and the loss of river water to the groundwater system (Figure 4.25). These provide a regional overview of the impacts on the interaction between surface water and groundwater systems.

- Time variant graphs showing the difference in the amount of predicted groundwater flow from the Upper Namoi Alluvium to the hard rock formations and vice versa (Figure 4.26). This allows for an understanding of the impact of coal and gas development on the nature and quantity of the flows between these groundwater systems, which are significant for a number of reasons including groundwater quality.

- A summary of the difference in predicted groundwater contribution to river flow (baseflow) and the loss of river water to the groundwater system along the length of the main simulated river reaches (Figure 4.27). These are provided in 2030, 2060 and 2100 and therefore provide a snapshot in time of the differences. These provide an understanding of how simulated interaction between surface water and groundwater may vary along the rivers associated with the Upper Namoi Alluvium.

The Model results were analysed and presented in such a way as to facilitate a strategic assessment of the likelihood of potential effects of coal and gas development on the quantity and quality of surface water and groundwater resources in the catchment. This analysis is presented in Section 5 of this report.

4.8.4 *Sensitivity and uncertainty*

The Request for Tender required that the Model undergo:

- "a rigorous program of calibration, validation, sensitivity analysis and uncertainty analysis such as the requirements set out in the Murray-Darling Basin Commission's Groundwater Flow Modelling Guideline" and that;

- "the Model responds to known scenarios in the manner expected and includes sensitivity and uncertainty analysis of key parameters and assumptions and the effects of plausible climate change scenarios up to the year 2100".

The specifics of the Model have been compared with the recommendations of the Murray-Darling Basin Commission's Groundwater Flow Modelling Guideline. The comparison has shown that for the purposes of this study, sensitivity and uncertainty analyses can be undertaken at the same time since, for the majority of hydraulic parameters in the Groundwater Model, any variation has little or no effect on model calibration.

The analysis was designed to investigate aspects of modelling methodology, potentially significant modelling assumptions and uncertainty in key parameters. The analysis provides an understanding of the sensitivity of predictions to these variables and a range of outcomes to provide bounds to the strategic assessment of likely impacts.

The analysis was undertaken on three themes; model methodology, model assumptions and model hydraulic inputs. A summary of the themes is provided below and a full description of the set-up and some of the major assumptions associated with them is provided in the Phase 3 report. In summary, the themes comprised:

- The first was an opportunity to test the significance of two aspects of modelling methodology on predictive results. These are the representation of connective cracking and the contribution of predicted reductions in groundwater recharge to the predicted groundwater impacts.
- The second was focused on some of the assumptions that are integral to the scenarios. These were the estimates of production of coal seam gas associated water, the management of coal seam gas associated water (injection into the alluvium) and the influence of climatic changes on predicted impacts.
- The third group was based on model hydraulic parameters. This involved investigating the significance of the values of horizontal and vertical hydraulic conductivity and storage parameters (in the hard rock formations) on Groundwater Model predictions, and soil specific yield and soil depth on Hydrologic Model predictions.

For all of these sensitivity runs the Scenario 0 model had to be re-run with the same parameters so that a like for like comparison of results could be made. The output from all of these runs was provided in the same format as described for the scenario runs to facilitate the comparison of results.

4.9 Model assumptions

The main assumptions associated with the Groundwater and Hydrologic Models are listed below. The assumptions are grouped based on whether they are related to the numerical code itself or to the system conceptualisation. An indication as to what effect on model predictions these assumptions might have is also provided.

Numerical assumptions

- Groundwater flow is assumed to be within porous media (rock). Dual porosity / permeability flow (e.g. fracture controlled) and fracture controlled storage was not simulated implicitly, but is incorporated into the bulk model parameters. For the current model, this is likely to be more significant in the “hard rock” units rather than the alluvial units where the porous media assumption is more valid.
- Hydraulic parameters, model inputs (e.g. wells), model outputs (e.g. water levels) and stream physical characteristics are assumed to be homogeneous throughout model cells (horizontally and vertically). These assumptions are valid at a regional scale, especially if model cell size can be kept to a maximum of around 1 km^2. This assumption can become a more important model constraint when distinct features are in close proximity, i.e. a stream and an abstraction well.
- Dual phase conditions (the presence of both water and gas) are assumed to have a limited effect on the regional groundwater flow and surface water system. They do, however, play a significant role in the coal seams on a local scale, where gas and water co-exist. At the regional scale, however, not simulating the influence of the gas phase is unlikely to have a major bearing on groundwater flow and the model results are not expected to be particularly sensitive to this assumption.
- Groundwater within the modelled systems is assumed to be single density (i.e. salinity does not vary). This is valid in a regional context. If local large variations in density should occur however, this may potentially lead to erroneous model results.

- Only saturated groundwater flow is simulated. At a regional and sub-regional scale this is unlikely to cause any major issues. At a local scale, for instance directly above an underground void, this assumption may be inaccurate as unsaturated flow may occur here.

- The influence of the assumptions built into the "lumped parameters" of the Hydrologic Model varies depending on how well the LASCAM assumptions match the actual hydrologic conditions in each sub-region of the model. These influences have been investigated using sensitivity analyses during model construction.

- Internal boundary conditions (rivers, mine drains, abstraction and injection wells) are assumed to occupy the entire 1 km by 1 km grid cell. At the very local scale this is not the case and predictions associated with these boundaries will not be accurate at a scale less than this. At a regional to sub-regional scale however, the assumption will have no impact on predictions.

- Connectivity between aquifers and between aquifers and surface water features is defined by the assigned parameters and boundary condition settings (vertical hydraulic conductivity, river bed conductance, etc). These values and the underlying equations of flow are based on referenced examples and have been tested and benchmarked previously.

Conceptual assumptions

- For the most part, especially for the "hard rock" strata, hydraulic parameters have been assumed to be homogeneous throughout model layers. Even at a regional scale this is unlikely to be the case in reality, but the data coverage is such that introducing localised heterogeneity is not possible with any degree of certainty. This has an effect on model predictions, and this has been quantified to some degree by the sensitivity / predictive analyses undertaken with the model. This type of assumption is necessary and is indicative of an "impact assessment tool" (MDBC, 2000).

- A number of stream parameters have been assumed as little data is available to constrain them. They are:

    - There is a fixed relationship between ground surface and stream bed elevation and width values and these have not been varied over the model domain, whereas in reality they may vary significantly regionally and locally. This may have a significant effect on model outcomes, but only if the interaction between groundwater and surface water proves to be important in the focus areas.

    - Stream bed conductance, defined as the rate of transfer of water between the stream and the sub-surface materials, has been defined with an average value, but there are likely to be significant local variations to this. At a local level this may have a significant effect on model results, and this is most detrimental where the interaction between groundwater and surface water proves to be important.

    - The roughness coefficient (an input to equations defining flow through streams) assigned to the modelled streams has been assumed based on literature values, but the value has been adjusted during calibration. The significance of this value on model predictions has been assessed in the sensitivity analysis.

- No flow boundaries are assumed along the catchment boundary in the Groundwater Model. The assumption may cause an overestimate of drawdown in these boundary areas as in reality some flow of water into the catchment would occur. For the most part however this assumption will have no influence on the predictions as the boundaries are in areas where no impacts are predicted. Areas where the boundaries may influence predictions include in Upper Namoi Alluvium Management Zone 4 and the hard rock formations to the east (along the Hunter-Mooki Fault), southeast and northeast.

- The mining and CSG processes have been simplified. This includes the development rate of mines and the distribution of abstraction to CSG wells. These simplifications will have virtually no effect on regional and sub-regional predictions but would compromise predictions at the scale of an individual CSG well or coal mine. The significance of these assumptions is however much smaller than that associated with the location, size and timing of the developments.

- In each sub-catchment in the Hydrological Model all processes and parameters are averaged into a single value. This is a major assumption and may have a significant impact on model predictions. The significance of this has however been minimised by carefully selecting sub-catchments based on key parameters.

- It is assumed that produced water from CSG developments does not re-enter the catchment water system. This assumption may have an influence on predictions and for that reason it is tested in the model sensitivity analysis. The uncertainties associated with the management of this water, and the numerous options available for disposal were considered too great to justify its inclusion in the scenarios.

- Many aspects of the mining and CSG developments are assumed to occur from the start of the simulation through to the end, regardless of the timing of those developments in the schedule. This includes connective cracking in the Groundwater Model and all developments in the Hydrologic Model. These simplifications are necessary to reduce the complexity of model inputs. As they result in certain aspects being simulated for longer than they would exist in reality, they will lead to an overestimation of impacts.

- The groundwater and surface water extraction data used in the model have been assumed to represent the full extraction for the Namoi catchment. This is unlikely to be the case for two main reasons; 1) there are many unlicensed extractions of water, and 2) erroneous records are present in the dataset. Depending on the level of discrepancy the impact of this can be significant, especially to model calibration, i.e. final model parameters may be erroneous because they are calibrated to erroneous extraction data. The potential impact can be assessed with a sensitivity analysis, but it is difficult to quantify the level of error contained in this data or reduce it.

- The geological model has been assumed to present an accurate depiction of the sub-surface and the geometry of the numerical flow model layers has been based directly on it. It is likely that the Model predictions are highly sensitive to this and the confidence in the geological model (due to data availability) varies considerably over the catchment.

- The effect of the mining process on the hydraulic and physical properties of sediments overlying underground mines has been assumed based on literature examples (see Section 7.3.1 of the Phase 3 report for more details). Both the extent and magnitude of the affected area have been derived in this way, and are a significant uncertainty in model inputs.

- It is assumed that the lack of equilibrium in Model initial groundwater levels will not influence the predictions. There is no reason to suspect that it would, given the fact that the non-equilibrium is expressed in all predictive models with or without mining and CSG in exactly the same way and that the system is not in equilibrium anyway.

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5 ASSESSMENT OF POTENTIAL IMPACTS

5.1 Introduction

Once run the Model produces a massive amount of predictive data. The types of data produced and the ways in which they have been presented are described in Section 4 of this report and provided in full in the Study Phase 3 report. However, when considered in isolation, these results are of little value and can be hard to interpret in the appropriate context. The purpose of this section therefore, as described in the Study request for Tender, is to analyse the results in order to:

> "undertake a strategic assessment of the likelihood of potential impacts posed by coal and gas development in the Catchment on the quantity and quality of surface and ground water resources in the Catchment"

This is a very complex undertaking due to the size of the catchment, the complexity of groundwater and surface water systems, and the complexity of the anthropogenic impact pathways. In order to achieve this Model results (predicted impacts) must be considered against:

- The conceptual groundwater and surface water models. This allows the predictions, especially in terms of magnitude, to be put into context with other system stresses and resource pressure and size.
- The uncertainty in the Model predictions. These may vary from place to place, between prediction types, or temporally, i.e. at the start of the model compared to the end. The value of the Model for the various predictive requirements will be assessed.
- The sensitivity in Model predictions. The data available for calibration of the Model were limited spatially. The results of the sensitivity analysis undertaken as part of the modelling phase will provide information that can inform on the possible ranges of impact magnitudes and extent.

The accuracy of the location and scheduling of the hypothetical mines and the location, scheduling and volume of associated water produced from the hypothetical CSG fields will determine the accuracy of predictions at any time in the future. Therefore the analysis is focused primarily on deriving the likelihood of impacts occurring, what magnitude they will be and where they might occur. It does not extend to determination of when the impacts will occur.

5.2 Proximity

An analysis of the proximity of water resources to coal resources provides a useful background to the analysis of Model results, particularly groundwater impacts. This analysis is undertaken by considering the formation extents, thicknesses and elevations as interpreted and interpolated during construction of the Geological Model. The geometry and layer configuration of the Groundwater Model is based on the Geological Model.

The analysis provides a rapid indication as to which parts of the groundwater system are likely to be at highest risk of impacts from the development of the coal resources. The data used for this analysis is the vertical distance between the base of the Upper and Lower Namoi Alluvium or the surface of the fractured rock aquifer and the top of the closest coal bearing formation (either the Black Jack Group or the Maules Creek Formation). The data does not indicate the precise depth of coal seams, the thickness of those coal seams or their economic viability.

The proximity analysis is summarised in the following forms:

- Table 5.1 provides the summaries by Upper Namoi Alluvium Zones and for the Lower Namoi Alluvium Management Area.
- Figure 5.1 displays the regional relationship between the groundwater resources and the coal bearing formations.

Table 5.1 Proximity of coal bearing formations to Namoi catchment groundwater resource

Groundwater Management Area or Zone	**Depth to coal bearing formation**		**% vertically underlain by coal bearing formation**
	Minimum (m)	**Average (m)**	
Upper Namoi Alluvium Zone 1	2	31	100
Upper Namoi Alluvium Zone 2	0	176	100
Upper Namoi Alluvium Zone 3	0	129	50
Upper Namoi Alluvium Zone 4	0	25	80
Upper Namoi Alluvium Zone 5	0	135	70
Upper Namoi Alluvium Zone 6	54	347	100
Upper Namoi Alluvium Zone 7	0	132	100
Upper Namoi Alluvium Zone 8	0	210	100
Upper Namoi Alluvium Zone 9	195	364	85
Upper Namoi Alluvium Zone 10	40	223	100
Upper Namoi Alluvium Zone 11	0	36	90
Upper Namoi Alluvium Zone 12	N/A	N/A	0
Lower Namoi Alluvium	360	556	40
Gunnedah Basin	0	142	78
Oxley Basin	75	441	89
Liverpool Ranges Basalt	2	806	57
GAB Alluvial	194	526	44
GAB	99	344	81

The analysis shows that:

- Potential coal resources exist beneath all Groundwater Management Areas west of the Hunter-Mooki Fault, and in the area of Werris Creek to the east of the fault.
- The prospective area for coal mining extends a maximum of 50 km to the west of the Upper Namoi Alluvium and beyond this the depth to coal bearing formations are likely to be excessive for mine development.
- The prospective areas for CSG extraction overlap with the prospective coal mining areas but also extend into a much greater area of the catchment where the coal seams are deeper.
- Most of the Upper Namoi Alluvium Zones are in very close proximity to coal bearing formations.
- Upper Namoi Alluvium Zones 6, 9 and 10 and the Lower Namoi Alluvium are separated by more than 100 m from coal bearing formations and will be at lower risk from direct impacts than other management zones.
- Less than half of the area of Upper Namoi Zone 3 is underlain by coal bearing formations indicating lower direct risk to this area.
- Upper Namoi Alluvium Zone 12 is not expected to be underlain by any coal bearing formations.
- Out of all of the hard rock Management Areas, the fractured rock of the Gunnedah Basin is in the closest proximity to coal bearing formations.

The locations with the highest potential for future open cut mining are the Gunnedah Basin Management Area and the north eastern part of the Oxley Basin Management Area. Over the majority of these areas the depth to coal bearing formations is low, between 0 and 300 m, although this does not rule out underground mining and CSG in these areas. The presence of these formations does not mean that coal resources exist in economically exploitable quantities. However, these are also the areas where there is the greatest direct risk to surface water flows from coal and gas developments as open-cut pits require a greater level of surface water flow management, compared to underground mines and CSG infrastructure.

There is also potential for underground mines and CSG developments where the depth to coal bearing formations is greater than 300 m. The proximity analysis shows that the remainder of the Oxley Basin Management Area and the eastern side of the Great Artesian Basin Management Area contain coal bearing formations within about 300 to 1,000 m of the water resources. In these locations the impact on surface water flows is likely to be much less, as the disruption to rainfall / runoff from surface disturbances associated with these developments is likely to be smaller, or at least more diffuse.

Surface water flows originating from catchments east of the Hunter-Mooki Fault (i.e. the McDonald / Manilla and Peel sub-catchments on Figure 5.2) are not at risk from coal and gas developments.

5.3 Surface water

5.3.1 *Introduction*

Predictions of impacts to surface water flows come from the Hydrologic Model (disruptions to rainfall runoff) and the Groundwater Model (reductions in baseflow and increases in river leakage). As they are derived from different models they will be discussed separately, but the reduction in flow from both these sources needs to be summed to provide a complete estimate on the impacts to surface water flow.

5.3.2 *Rainfall runoff*

Impacts

Five gauging stations have been chosen for further analysis of the predicted impact of mining and CSG developments on surface water flows. These are all located along the main alluvial channel within the Gunnedah Basin (Figure 5.2). There will be no impacts to surface water flows to the east of the Hunter-Mooki Fault as the potential for coal or gas developments in this area is very limited. The predicted reduction in surface water flow at the five gauging stations is provided in Table 5.2 for each of the scenarios.

Table 5.2 Average flow change 2010 to 2100 (% change from Scenario 0)

Scenario	**419027** **Mooki River at Breeza**	**419084** **Mooki River at Ruvigne**	**419001** **Namoi River at Gunnedah**	**419012** **Namoi River at Boggabri**	**419023** **Namoi River at Turrawan**
1	0.0	-0.1	-0.2	-0.1	-0.6
2	0.0	-0.3	-0.3	-0.2	-0.7
3	0.0	-1.3	-1.1	-1.2	-1.7
4	0.0	-1.3	-1.1	-1.1	-1.7
5	0.0	-0.1	-0.1	-0.1	-0.4
6	0.0	-1.2	-1.1	-1.2	-1.7

Station 419027 is located on the Mooki River at Breeza. Approved, possible and hypothetical developments above this site are limited. The impacts predicted at this location are therefore negligible. Station 419023 is on the Namoi River close to Narrabri. The majority of approved, possible and hypothetical developments are upstream of this site and it is therefore here that the maximum impacts are predicted.

Approved and possible developments (Scenarios 1 and 2) result in a maximum of 0.7% reduction in the average flow at station 419023. Long term development (Scenario 3) results in a maximum of 1.7% reduction in the average flow at this station. Based on the average yearly flows at this point, this impact equates to a reduction of about 40,000 m^3/d.

The smallest changes in flow are seen for Scenarios 1 and 5. In terms of mining activity these scenarios only contain approved mines. Scenario 5 also contains eight hypothetical CSG fields. It is apparent from the very similar percentages that CSG infrastructure as simulated does not have a significant impact on surface flows. At a couple of the locations the reduction in flow is smaller than with no CSG present. This could either be from additional runoff generated by the additional impervious areas or may be a result of averaging the datasets. The model predicts that there will be less than a 0.5% change in flow at each of the sites due to CSG infrastructure and approved mines.

Scenarios 3, 4, and 6 show similar changes in flow, indicating that the greatest changes in catchment flows will be related to open-cut mining, as there is little, if any, change when CSG fields are removed or the underground mines are redistributed within the catchment.

The impacts to the surface water flows described above originate from the disruption of rainfall runoff by mine and CSG infrastructure. By far the most significant component is derived from the impact of open-cut mines. Surface infrastructure associated with underground mines and CSG wells has less of an impact on a regional scale because the spatial extent is smaller. The representation of the developments was simplified to the extent that all mines and CSG developments in any one scenario were assumed to be active throughout the entire simulation (from 2010 to 2100). The results are therefore conservative (at the high end of potential impacts) and represent the impact if all developments were active at the same time.

Subsidence caused by long wall underground mining will be extremely site specific and the amount of surface movement and the extent of connective cracking seen will depend on many factors including the depth of workings, width of each longwall, thickness of coal removed overlying geology etc. The only longwall underground mine in the Namoi catchment is the Narrabri North mine which has just started operations. Predicted subsidence is up to 2.4 m, with connective cracking expected in the geological units between the coal seam and the overlying Garrawilla Volcanics (Whitehaven, 2011).

Subsidence effects have been included in the Hydrologic Model, which assumes that 1% of the mine footprint area is subject to increased ponding. The results suggest that this does not have a significant impact on regional or sub-regional surface water flows. Subsidence may however have a significant impact on surface water flow processes on a much more local scale. These will depend highly on the location specifics, including the local geological regime, and as such have not been incorporated in any of the models. This detailed scale analysis must be undertaken to support Environmental Impact Statements conducted as part of any proposed underground mines.

Sensitivity

The sensitivity of these predictions to some key controlling parameters was tested and the results are summarised in Table 5.3.

Table 5.3 Flow changes from sensitivity analysis (as % of Scenario 0)

Model run	**419027** Mooki River at Breeza	**419084** Mooki River at Ruvigne	**419001** Namoi River at Gunnedah	**419012** Namoi River at Boggabri	**419023** Namoi River at Turrawan
Scenario 3	0.0	-1.3	-1.1	-1.2	-1.7
CSG infrastructure doubled	0.0	-1.2	-0.9	-1.1	-1.6
Soil thickness doubled	0.0	-1.3	-1.1	-1.2	-1.6
Soil thickness halved	0.0	-1.4	-1.3	-1.4	-2.0
Soil storage doubled	0.0	-1.2	-0.9	-1.1	-1.7
Soil storage halved	0.0	-1.2	-1.1	-1.1	-1.6
Wetter climate	0.0	-1.3	-1.1	-1.2	-1.5
Drier climate	0.0	-2.1	-2.1	-1.9	-3.3

The predictions from the sensitivity models are very similar to those seen in the calibrated Scenario 3 model. This indicates that the Hydrologic Model outputs are relatively insensitive to all of the parameters tested, i.e. any small inaccuracies in these parameters will not make a great deal of difference to the Model results presented. Only the drier climate results in a significant variation to the predicted impacts, which increase from 1.7% to 3.3% at station 419023.

Uncertainty

Uncertainty is inherent in any predictions. In this case, simplifications were made in order to limit the computing times and file sizes and have been applied to parameters as diverse as sub-catchment definition, soil thickness, and water storage fill/release equations. The Hydrologic Model area has been split into 99 sub-catchments for analysis, and the average sub-catchment size is 252 km^2. This immediately limits the detail at which processes can be simulated and also the scale at which results can be reported. For each parameter (i.e. soil depth) only a single value can be allocated per model sub-catchment whereas in reality there would be an ever changing continuum. Although the values used have been chosen based on observed data or best practice it is clear that a single value used over such a large area is unlikely to produce a good fit to all observed stream flows. It is therefore important to recognise these differences from observed, identify reasons for them occurring, and incorporate these uncertainties of results into any interpretation of model outcomes. The five gauging stations used for discussion of predictive results are analysed in Table 5.4 for predictive uncertainty.

Table 5.4 Surface water flow sites chosen for uncertainty analysis

Gauging station	Site name	Years of calibration data available	Total modelled flow as % of actual flow	On sub-catchment boundary	Confidence in flow calibration
419027	Mooki River at Breeza	1990 - 2009	7	Yes	Low
419084	Mooki River at Ruvigne	1994 - 2009	1790	No	Low
419001	Namoi River at Gunnedah	1990 - 2009	191	Yes	Moderate
419012	Namoi River at Boggabri	1990 - 2009	174	Yes	Moderate
419023	Namoi River at Turrawan	1996 - 2009	252	Yes	Moderate

The analysis shows that the modelled flows are highly variable, with flows in the main Namoi River an average of 174 – 252% of observed flows, and modelled flow on the smaller streams showing a much larger variation from observed. The sites along the Mooki generate modelled flows which are significantly higher (downstream) and lower (upstream) than those observed. Observed flows at these sites over the period 2001-2009 were approximately 10% of those on the main Namoi River and it is therefore more difficult to match these as small changes in model output will make larger percentage difference in flow. It is possible that there is a larger proportion of groundwater-surface water interaction along the Mooki compared to the main Namoi River channel, with a higher percentage of flow within the alluvium surrounding the stream channel rather than in the stream channel itself. This would partially explain the over-prediction of flows at Ruvigne (station 419084). This gauge is also not located at a sub-catchment boundary so the modelled catchment area will be slightly greater than observed.

Mainly due to the issues with scale and calibration over-prediction, the confidence in predicted flows along the Namoi River is classed as moderate and the flows along the Mooki as low.

Water quality

Potential water quality impacts from coal and CSG developments fall into two categories:

- Local scale impacts
- Sub-regional scale impacts
    - as a result of changes in the quantity of runoff to streams
    - as a result of large scale changes in the quality of the groundwater which becomes stream baseflow.

The potential for localised water quality impacts should be identified in the site Environmental Impact Statement. Examples are emergency or unauthorised discharges from tanks or ponds, and enhanced turbidity in runoff during construction of roads and pipeline trenches, etc. It would not be appropriate to use a regional model to predict the possible impacts of such discharges. Authorised releases of water from sites are monitored for key parameters and should not affect water quality.

A change in runoff volume from particular sub-catchments may change water quality either positively or negatively depending on the original water quality. There is not enough detail on the current water quality of minor streams to accurately model or quantify potential changes in water quality.

Changes in baseflow quality are essentially groundwater quality issues. They can be identified by looking at the degree of interaction between different systems, as has been analysed in the water balance.

5.3.3 *Surface water / groundwater interaction*

Impacts

The predicted impacts on groundwater and surface water interaction in the long term development scenario (Scenario 3) are summarised in Table 5.5. The configuration of river reaches in the model is displayed in Figure 5.3.

The analysis shows the following:

- The most significant reaches in terms of the proportion of flow impacted are 3 and 5, located on the Namoi River immediately upstream and downstream of Boggabri. Interaction flow is reduced by a maximum of 14% and 18% respectively. This result is likely to be more significant along Reach 5 where the interaction flows are greater (roughly 2,000 m^3/d). The reduction equates to about 350 m^3/d less water in the river along that reach.
- The maximum impact on interaction flow in all other reaches is less than 10%.
- The maximum impact on a high interaction flow reach is on Reach 1 and is 5%. As the interaction flow along this reach totals about 19,000 m^3/d this equates to a loss of 950 m^3/d from the river. Reach 1 is located along the Mooki River between Caroona and Gunnedah.
- The maximum impact on Reaches 8, 9, 10, 11 and 14 is less than 1%. These are all located in the far south of the catchment where there is little potential for development.

Table 5.5 Summary of surface water / groundwater interactions for Scenario 3

Reach	Based on previous model	Average interaction flow (m^3/d)	Dominant behaviour	Maximum reduction in interaction flow (%)	Maximum reduction in interaction flow (m^3/d)
1	Yes	19,000	Variable	5	950
2	Yes	200	River leakage	4	8
3	Yes	600	River leakage	14	84
4	Partially	48,000	Baseflow gain	2	960
5	Yes	2,500	Baseflow gain	18	450
6	Yes	2,000	Baseflow gain	2	40
7	Yes	3,700	River leakage	8	296
8	No	11,000	Baseflow gain	1	110
9	No	11,000	Baseflow gain	0	0
10	No	10,000	Baseflow gain	0	0
11	No	2,500	Variable	1	25
12	No	2,700	Baseflow gain	9	243
13	No	600	River leakage	6	36
14	No	2,400	Baseflow gain	0	0

Table 5.5 also shows the magnitude of predicted interaction flows and whether the interaction is one of baseflow gain, river leakage or a mixture of both. The data shows that in terms of the type of interaction, in all of the high flow reaches apart from Reach 1, the dominant contribution is from baseflow gain. In Reach 1 it is from both baseflow gain and river leakage. Most of the moderate flow reaches are also dominated by baseflow gain. All of the low interaction flow reaches are dominated by river leakage.

Therefore the main interaction between groundwater and surface water simulated by the Model (in terms both of the number of reaches dominated by this flow and the flow volume) is the flow from groundwater to surface water (baseflow gain).

The predominant impact is on the baseflow component of groundwater / surface water interaction. It is likely that these impacts will be most obvious under low river flow conditions, where the baseflow component of river flows is more evident, and in some areas may represent the only flow in the river.

In the majority of cases the maximum impact on groundwater / surface water interaction occurs at the end of the simulation. Along the reaches with the greatest reduction in interaction flow, the source of the impact is either predominantly from mining or roughly a 50:50 split between mining and CSG activities.

The combined maximum impact on interaction flows along all reaches is 3,200 m^3/d. As this impact is experienced upstream of the Namoi River at Turrawan (Station 419023) the impact will be focussed here. The flow at this point in the river, under median, mean, minimum and maximum conditions, is shown in Table 5.6 and compared to the predicted maximum impact.

The analysis shows that the predicted impacts will have little effect on the river under median, mean and maximum flow regimes (all less than 0.2% of the total flows). However, at minimum flows the river may be much more sensitive to the impacts, as the combined impacts (baseflow and river losses for all reaches) are just over 6% of the total flow.

Table 5.6 Flow statistics and Scenario 3 impacts for the Namoi River at Narrabri

Flow measure	Measured river flow ML/yr	Measured river flow m^3/d	Reduction in interaction flow m^3/d	Reduction in interaction flow % of measured flow
Median	403,500	1,104,723	3,200	0.3%
Mean	629,000	1,722,108	3,200	0.2%
Min	19,000	52,019	3,200	6.2%
Max	3,624,000	9,921,971	3,200	0.0%

(River flow rates after Thoms et al., 1999)

Sensitivity

The sensitivity of interaction impact predictions to changes in Groundwater Model settings is limited to less than 10% in most instances. The highest variations are in response to changes in hydraulic conductivity and storage, and for one reach a change in climate, but the increases in predicted impacts are all less than about 50% of the Scenario 3 case.

Uncertainty

As with all other predictions, the predictions of interaction flow and the impacts on them from coal and gas developments will be subject to uncertainties. No calibration of these model outputs has been undertaken. Some of the modelled reaches are however based very closely on reaches in pre-existing models, such as the Upper Namoi Groundwater Model (McNeilage, 2006). The settings in these models have been calibrated to a certain degree. Table 5.5 also identifies the reaches that are based on data from previous models.

Where river reaches were not, or are only partially, included in the Upper Namoi Groundwater Model the river bed conductance was based on values in close by reaches that were included and the values were varied during model calibration. In these cases river bed elevations and water level elevations were interpolated from observed data or fixed to a set distance below ground level. Therefore predictions of the interaction in the river reaches not based on existing model settings is more uncertain than those that are.

The data shows that over 80% of the predicted reduction in flow occurs along river reaches that are based on existing calibrated models.

Water quality

The results do not suggest that there is any significant potential for impacts on groundwater / surface water interaction to affect either groundwater or surface water quality. The changes in flow are very small relative to the total flows in the river system.

5.4 Groundwater

Trigger levels

Modelling has shown there to be groundwater level impacts from coal and CSG developments. These impacts need to be considered within the context of what levels of impact are acceptable. These levels are known as trigger levels. If these levels are exceeded then pre-determined actions must be implemented to mitigate the effects on impacted areas.

New South Wales is in the process of developing an 'Aquifer Interference Policy', the first draft was published in March 2012 (NSW Government, 2012). The document defines four different classes of risk management zone and sets different levels of permitted interference for six different types of water sources for each of the four zones. This leads to a complicated matrix of permitted impacts. Discussions with NSW Office of Water personnel (pers comm. C Barrett) have indicated that the final document may be significantly different to the draft and the matrix may be simplified.

For this reason it was decided to compare impacts to trigger levels developed in other areas. For example, in Queensland, the State Government has recently set water level trigger levels for impacts from CSG activities to bores and springs under the Water Act (QLD) 2000. These are defined as (QLD Government, 2012):

- *Bore trigger threshold.* A decline in the water level in the aquifer that is:
    - if a regulation prescribes the bore trigger threshold for an area in which the aquifer is situated the prescribed threshold for the area; otherwise
    - for a consolidated aquifer – 5 m; or
    - for an unconsolidated aquifer – 2 m.
- *Spring trigger threshold.* A decline in the water level of the aquifer that is:
    - if a regulation prescribes the threshold for a particular area the prescribed threshold for the area; otherwise
    - 0.2 m.

Surface water and groundwater quality trigger values are generally set from the relevant limits and standards set by a regulatory body for a particular water use e.g. stock, domestic, biodiversity. In Australia the applicable standards can be found in the ANZECC Guidelines (ANZECC, 2000). It is an accepted rule that impacts should not change the water use category of a source.

Impacts

The maximum predicted groundwater drawdown from coal and gas developments in each model cell at any time between 2010 and 2100 has been defined for Scenarios 1, 2, 3 and 6. For areas outside the alluvium the maximum drawdown in the shallow hard rock groundwater resource is shown. The exact formation varies over the catchment as the hard rock layers do not lie horizontally within the basin. The results are plotted in Figures 5.4 to 5.7. The key points are summarised below.

- *Lower Namoi Alluvium*. Predicted drawdown does not exceed 2 m in any of the scenarios.
- *Upper Namoi Alluvium (excluding Zone 12).* With increased development the area of alluvium affected by drawdown increases, but the magnitude generally remains below 2 m. There are significant areas where the maximum drawdown does not exceed 0.2 m and significant areas where drawdown is between 0.2 and 2 m. There are some localised areas in Management Zones 4, 7 and 11 where drawdown in excess of 2 m is predicted. Mining beneath the alluvium may cause drawdown in excess of 10 m in the vicinity of the underground voids.
- *Gunnedah Basin Management Area.* In the vicinity of mines maximum drawdown is predicted to exceed 5 m. As the number of mines and CSG developments increases the cumulative effect is that the majority of this Management Area is predicted to experience drawdown exceeding 10 m.

- *Oxley Basin Management Area.* With approved coal and gas development projects only, this area is predicted to experience no drawdown exceeding 0.2 m. As the development increases the magnitude and spatial extent of drawdown also increases. With long term coal and gas development some locations within this area experience drawdown exceeding 5 m but in others it does not exceed 0.2 m.

- *Liverpool Ranges Basalt Management Area*. There are no impacts greater than 5 m in any of the scenarios.

- *Great Artesian Basin Management Area*. Predicted drawdown in this area is generally less than 0.2 m, although drawdown in excess of 5 m is predicted towards the boundary with the Gunnedah Basin Management Area in the long term development scenario.

- *Great Artesian Basin Alluvial Management Area*. There are no impacts greater than 0.2 m in any of the scenarios.

- *New England Fold Belt Management Area.* Drawdown exceeding 5 m is predicted in the locality of the Werris Creek mine. Away from this area no drawdown exceeding 0.2 m is predicted in any of the scenarios.

- *The Peel Valley Fractured Rock and Peel Valley Alluvium Management Areas and the Upper Namoi Alluvium Zone 12*. No drawdown exceeding 0.2 m is predicted in these areas.

- *Groundwater Dependent Ecosystems (GDEs).* Under current and possible development scenarios (Scenarios 1 and 2) the impacts at these locations are generally less than 0.2 m. In the long term development scenario (Scenario 3) several locations fall in areas where drawdown may exceed 0.2 m. These locations are all within either the Gunnedah or Oxley Basin Management Areas.

Maximum impacts will occur at different times in different formations. Maximum drawdown in the hard rock formations will occur more quickly than in the alluvium and will be more dependent on the proximity and timing of coal and gas developments. Maximum drawdown will occur later in the alluvium and will present more of a cumulative response when compared to the hard rock formations.

The proportion of the predicted average drawdown in the alluvial aquifers in Scenario 3 that originates from either coal mining or CSG activities is summarised in Table 5.7. This data is calculated based on the predictions from Scenarios 4 and 5 which are identical to Scenario 3 but have either mining or CSG inputs removed. The analysis considers the average result from 2030, 2060 and 2100. If more than 70% of the impact in a zone can be attributed to a particular industry then the zonal impact is classified as being dominated by that industry.

This analysis assumes that there is a linear relationship between the amount of development and the impact, i.e. a 1 m impact in Scenario 4 and a 1 m impact in Scenario 5 combine to form a 2 m drawdown in Scenario 3. This is not always the case however, so whilst these results do provide an indication of the source of the impacts they should not be taken to be definitive.

Impact source analysis in the hard rock areas has been undertaken qualitatively as the results will be highly dependent on the location of mines and the specifics of the CSG gas fields (size, abstraction amount, target coal seam etc). As both are such great uncertainties, quantitative analysis using the results of Scenarios 3, 4 and 5 would be inappropriate.

The data shows that the predicted impacts in all Upper Namoi Alluvium Zones are either dominated by mining (Zones 1, 3, 4, 7, 8 and 11) or show a roughly equal proportion of impacts from mining and CSG activities (Zones 2, 5, 6, 9 and 10). Only the Lower Namoi Alluvium presents a case where the majority of predicted impacts are derived from CSG activities.

For the hard rock areas the qualitative analysis suggests that (for the specific scenarios run) there will either be a mixed source to the impacts (mining and CSG) or they will be dominated by CSG activities.

Open-cut mining, underground mining and CSG abstraction will impact the groundwater resources in different ways. Underground mines will primarily impact groundwater levels via direct flow to the underground void. This is due to their depth (i.e. beneath the water table) and limited surface infrastructure and footprint. The primary impact of CSG extraction will be similar although more diffuse and potentially spread over a larger area. Open-cut mines on the other hand have the potential to impact the groundwater system both via direct seepage flow to the open pit and by reducing groundwater recharge. However, in very shallow open-cut operations groundwater may only be intersected over a small proportion of the pit or not at all.

The results have shown that mining and CSG development will impact groundwater levels in the hard rock to a much greater magnitude, spatial extent and speed of onset compared to their effect on groundwater levels in the alluvium. Impacts that propagate to the alluvium will be of a lesser magnitude and extent and will take much longer to reach a maximum.

Table 5.7 Source of groundwater level impacts

Groundwater Management Area or Zone	Dominant source of impacts
Upper Namoi Alluvium Zone 1	Mining
Upper Namoi Alluvium Zone 2	Both
Upper Namoi Alluvium Zone 3	Mining
Upper Namoi Alluvium Zone 4	Mining
Upper Namoi Alluvium Zone 5	Both
Upper Namoi Alluvium Zone 6	Both
Upper Namoi Alluvium Zone 7	Mining
Upper Namoi Alluvium Zone 8	Mining
Upper Namoi Alluvium Zone 9	Both
Upper Namoi Alluvium Zone 10	Both
Upper Namoi Alluvium Zone 11	Mining
Lower Namoi Alluvium	CSG
Gunnedah Basin	Both
Oxley Basin	CSG
Liverpool Ranges Basalt	Both
Great Artesian Basin	CSG
GAB Alluvial	CSG

Sensitivity

The predicted impacts are based on a single model configuration and this presents two main issues. Firstly, there is little to no data with which to calibrate the model in the majority of the area that it covers and little hydraulic testing data to narrow down the adopted parameters. Secondly, there are many parameter combinations that are possible which will produce a similar calibration but will produce different predictions.

The model has been tested to see how much the predictions might vary given these uncertainties in model settings by running the same long term development scenario (Scenario 3) several times with different hydraulic parameters and settings. Ten sensitivity simulations were undertaken. They were:

- CSG abstraction doubled (Sensitivity A).
- CSG abstraction re-injected to the Gunnedah Formation of the Upper Namoi Alluvium (Sensitivity B).
- Groundwater recharge increased to simulate a wetter climate (Sensitivity C) or reduced to simulate a drier climate (Scenario D).
- Horizontal hydraulic conductivity of hard rock formations 1 order of magnitude higher (Sensitivity E) or lower (Sensitivity F).
- Vertical hydraulic conductivity of hard rock formations 1 order of magnitude higher (Sensitivity G) or lower (Sensitivity H).
- Storage parameters of hard rock formations doubled (Sensitivity I) or halved (Sensitivity J).

The results of the sensitivity analysis are summarised in Table 5.8. The analysis is based on the maximum average drawdown in Upper Namoi Alluvium Zones 1 to 11 and Lower Namoi Alluvium. This measure is the maximum prediction of average drawdown within each zone in 2030, 2060 or 2100.

Considering the potential increases in predictions of drawdown only (because the variations can also cause reductions in drawdown), the results indicate that:

- Upper Namoi Alluvium Zone 7 shows the greatest sensitivity to the tested inputs and on several occasions the maximum average drawdown exceeds 2 m.
- Upper Namoi Alluvium Zones 5 and 11 also show a high sensitivity to tested inputs. The drier climate case (Sensitivity D) produces a maximum average drawdown exceeding the trigger level of 2 m.
- In all other zones the sensitivities to tested inputs do not cause the maximum average drawdown to increase above the trigger level.
- Upper Namoi Alluvium Zones 5, 7, 8, and 9 show a moderate to high sensitivity to the tested model inputs.
- Upper Namoi Alluvium Zone 11 actually shows quite a high sensitivity to the tested inputs, but a significant increase in impacts is predicted only with the drier climate scenario (most of the other sensitivities produce lower predicted impacts).
- Upper Namoi Alluvium Zones 1, 2, 3, 4, 6 and 10 and the Lower Namoi Alluvium show a low sensitivity to the tested model inputs.
- The drier climate (Sensitivity D) appears to have a greater control on predictions than the wetter climate (Sensitivity C), although the most significant sensitivity is restricted to Upper Namoi Alluvium Zones 5 and 11.
- Of all of the parameters tested, the predictions are most sensitive to an increase in horizontal and vertical hydraulic conductivity (Sensitivities E and G) and a decrease in aquifer storage (Sensitivity J).

Table 5.8 Maximum average drawdown (m) predicted in the Upper and Lower Namoi Alluvium Management Zones in the sensitivity analysis

	Sensitivity run											
		A	B	C	D	E	F	G	H	I	J	Range (m)
Groundwater Management Area or Zone	**Scenario 3**	**CSG abstraction doubled**	**CSG water reinjection**	**Wetter climate**	**Drier climate**	**Kh x 10**	**Kh / 10**	**Kv x 10**	**Kv / 10**	**Storage x 2**	**Storage / 2**	
Upper Namoi Zone 1	0.2	0.4	0.2	0.0	1.0	0.4	0.4	0.3	0.0	0.0	0.4	1.0
Upper Namoi Zone 2	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.1	0.1	0.1	0.1
Upper Namoi Zone 3	0.1	0.2	0.1	0.1	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.2
Upper Namoi Zone 4	1.0	1.2	0.9	0.6	1.0	0.7	1.2	0.8	0.9	0.8	0.8	0.6
Upper Namoi Zone 5	0.8	1.3	0.5	0.8	2.6	1.2	0.5	0.7	0.8	0.3	0.3	2.4
Upper Namoi Zone 6	0.1	0.1	0.1	0.1	0.1	0.4	0.0	0.1	0.2	0.2	0.2	0.4
Upper Namoi Zone 7	1.1	2.2	0.7	1.1	1.2	1.9	1.1	4.6	0.9	1.4	2.5	3.9
Upper Namoi Zone 8	0.5	0.6	0.5	0.5	0.6	1.0	0.2	1.4	0.2	0.4	0.6	1.2
Upper Namoi Zone 9	0.5	0.8	0.5	0.5	0.5	1.1	0.3	1.4	0.1	0.3	1.4	1.3
Upper Namoi Zone 10	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.9	0.9
Upper Namoi Zone 11	1.6	1.7	1.6	1.2	2.6	1.9	0.3	1.5	0.6	0.7	0.1	2.5
Lower Namoi	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.1

Note: Blue highlights correspond to runs where the trigger level of 2 m was approached or exceeded on average within the zone / area. The grey highlights correspond to the zones / areas where the range in predicted average drawdown in all the sensitivities was greater than 1 m and can therefore be considered significant.

The analysis has only been undertaken on the predictions in the alluvial formations. In terms of the hard rock areas the sensitivity to these inputs will be more pronounced, a doubling of the CSG abstraction for example will produce roughly a doubling of drawdown in the local area. An increase in horizontal hydraulic conductivity will reduce the magnitude of impact but increase the spatial extent (and so on). The significance of these results will be incorporated into the assessment of risk to the water resources, which is discussed below.

The sensitivity test of re-injection of CSG produced water has shown that this can reduce (mitigate) groundwater level impacts to some extent. Far more detailed investigations are required however to determine the operational viability of re-injection. This includes consideration of water quality (injected and receiving water bodies), location, injection rate and timing.

Uncertainty

A qualitative assessment of prediction uncertainty in the Groundwater Management Areas covered by the numerical model has been undertaken based on several factors:

- Whether the inputs and parameters have been based on data from existing models.
- The calibration; how many observation locations were used and a qualitative assessment of the match between observed and simulated groundwater levels in these locations.
- The numerical performance of the model (whether any instability such as fluctuating groundwater levels were observed in the model).
- The proportion of predicted drawdown that was derived from the reductions in recharge from simulated open cut mines (bearing in mind that this is likely to be a conservative (i.e. worst case) representation of the impacts).

Each of these factors has then been considered in determining the overall uncertainty associated with predictions, which have been classified as high, moderate or low. The results are provided in Table 5.9.

The results show that:

- Uncertainty is high in Upper Namoi Alluvium Zones 1, 7, 10 and 11. Of these Zones 7 and 11 are the most significant to the Study outcomes as they are in areas where mining is currently active and / or where plans for future developments are most advanced. The impacts in Zones 1 and 10 are likely to be minimal given the distance of these areas from locations where mining is likely to be focused in the future and the significant depth of potential coal resources beneath them. The high uncertainty in these zones is therefore less significant.
- Uncertainty in the highly utilised Upper Namoi Zones 3, 4 and 5 is low and this is appropriate given that the calibration achieved a good level of agreement between observed and simulated groundwater levels and the inputs are based on an existing model.
- The high level of impacts derived from recharge reduction (i.e. over 75%) in Upper Namoi Alluvium Zones 1, 4, 5 and 11 is significant and means that these predictions should be considered with that in mind.
- Uncertainty in the predictions in the Gunnedah Basin is deemed moderate since additional calibration data associated with current or possible mining was utilised effectively in this area. It is not considered to be low uncertainty since it is a very large area with a relatively low density of data (spatially).

Table 5.9 Model predictive uncertainty

Groundwater Management Area or Zone	Based on existing model	Calibration: Number of calibration sites	Calibration: Calibration performance	Numerical performance	Proportion of predicted drawdown derived from recharge reduction	Qualitative assessment of predictive uncertainty
Upper Namoi Zone 1	No	1	Poor	Variable	>75%	High
Upper Namoi Zone 2	Yes	5	Variable	Variable	25 – 50%	Moderate
Upper Namoi Zone 3	Yes	14	Good	Variable	50 – 75%	Low
Upper Namoi Zone 4	Yes	16	Variable	Good	>75%	Low
Upper Namoi Zone 5	Yes	7	Good	Good	>75%	Low
Upper Namoi Zone 6	No	3	Variable	Variable	<25%	Moderate
Upper Namoi Zone 7	No	1	Poor	Poor	<25%	High
Upper Namoi Zone 8	No	3	Variable	Good	<25%	Moderate
Upper Namoi Zone 9	No	4	Variable	Variable	<25%	Moderate
Upper Namoi Zone 10	No	1	Poor	Variable	<25%	High
Upper Namoi Zone 11	Yes	1	Poor	Poor	>75%	High
Lower Namoi	Partially	0	-	Variable	<25%	Moderate
Gunnedah Basin	No	2*	Variable	Variable	-	Moderate*
Oxley Basin	No	2	Variable	Variable	-	High
Liverpool Ranges Basalt	No	0	-	Variable	-	Moderate
GAB and GAB Alluvial	No	0	-	Variable	-	Moderate

* Calibration of the model in the Gunnedah Basin was informed from other datasets (mine inflow and local groundwater observations)

Risk to groundwater

The model results have been combined with the discussion of sensitivity and uncertainty and the key findings from the conceptual and geological models to produce a conclusion of the risk to the quantity of the groundwater resource from coal and gas developments. The result is displayed in Table 5.10 and Figure 5.8.

Table 5.10 A qualitative assessment of predictive confidence

Groundwater Management Area or Zone	Potential risk to resource	Total GW abstraction 2009 (m^3/d)	Average saturated thickness (m) 2010	
			Gunnedah Formation	Narrabri Formation
Upper Namoi Zone 1	Low	3,387	1	1
Upper Namoi Zone 2	Low	31,398	23	9
Upper Namoi Zone 3	Low	38,705	28	22
Upper Namoi Zone 4	Moderate	54,620	25	13
Upper Namoi Zone 5	Moderate	35,231	26	16
Upper Namoi Zone 6	Low	1,541	2	16
Upper Namoi Zone 7	High	1,851	2	11
Upper Namoi Zone 8	Moderate	18,198	15	18
Upper Namoi Zone 9	Moderate	4,027	18	11
Upper Namoi Zone 10	Low	8	2	13
Upper Namoi Zone 11	High	1,703	10	2
Upper Namoi Zone 12	Low	2,738	-	-
Lower Namoi	Low	192,057	39	n/a
Gunnedah Basin	High	39,302 (all non-alluvial)	-	-
Oxley Basin	Moderate / High		-	-
Liverpool Ranges Basalt	Low		-	-
GAB and GAB Alluvial	Low / Moderate		-	-

The key conclusions are:

- The main risk to the groundwater resources is in the hard rock aquifers in the central area of the catchment. The risk to groundwater resources in the Oxley Basin and Gunnedah Basin Management Areas can be considered high.
- The risk to groundwater resources in Upper Namoi Alluvium Zones 7 and 11 is also high. This conclusion is derived from a number of factors including the high sensitivity and uncertainty associated with the predictions in these zones, as well as the high impacts predicted.
- The Lower Namoi Alluvium, Zones 1, 2, 3, 6, 10, 12 of the Upper Namoi Alluvium, the Great Artesian Basin, Liverpool Ranges Basalt, New England Fold Belt, Peel Valley Alluvium and Fractured Rock Management Areas are considered to be at low risk. This is either because they are a significant distance either vertically or horizontally from coal and gas resources or because the modelling has shown that the impacts are likely to be less than the trigger levels used in Queensland.

- Upper Namoi Alluvium Zones 4, 5, 8 and 9 and the most south-westerly portion of the New England Fold Belt Management Area are considered to be at moderate risk from coal and gas developments. This is because they are predicted to experience fairly high impacts (although less than the trigger levels) and the predictions have been shown to be highly / moderately sensitive and / or uncertain in these locations. The groundwater resource in the eastern portion of the Great Artesian Basin (along the border with the Gunnedah Basin) can also be considered at moderate risk.

The risk analysis is put into context in Table 5.10 where it is compared against groundwater utilisation and average estimated saturated thickness of the aquifers.

The context analysis shows that:

- Those resources considered at highest risk account for a very small proportion of the total groundwater abstraction.
- Although the estimate of saturated thickness is relatively coarse, the high risk areas of the Upper Namoi Alluvium Zones 7 and 11 appear to have a limited saturated thickness of aquifer which could make the results even more significant.
- The majority of the abstraction from the hard rock formations comes from the Gunnedah and Oxley Basin Management Areas, which are considered to be at moderate to high risk.
- Resources classified as low risk account for about 60% of the total groundwater resource west of the Hunter-Mooki Fault as measured by volume extracted.

If the source of risk is considered, the Model identifies the predominant cause of predicted impacts in the Upper Namoi Alluvium as being from mining related activities (see Table 5.7). This is especially true in high risk Zones 7 and 11. The source of impacts in the high / moderate risk Gunnedah and Oxley Basin Management Areas is harder to define with confidence given the sensitivity of the results to the specific mine or CSG development plans. If both mining and CSG developments are occurring concurrently in these areas then the impacts will be generated from both industries.

Predictive confidence

The assessment of uncertainty and sensitivity of model predictions has been combined to provide an assessment of predictive confidence (Table 5.11). This measure is important in understanding the relevance of the results. For example, in general terms, if a model prediction has been shown to be insensitive to changes in key inputs but the inputs are highly uncertain, the confidence in the prediction can still be relatively high. Furthermore, if the impacts have been shown to be highly sensitive to changes in key inputs but the uncertainty in the inputs is low, the confidence in predictions may be moderate or even high (and so on).

Table 5.11 A qualitative assessment of predictive confidence

Groundwater Management Area or Zone	Sensitivity	Uncertainty	Confidence
Upper Namoi Zone 1	Moderate	High	Low
Upper Namoi Zone 2	Low	Moderate	High
Upper Namoi Zone 3	Low	Low	High
Upper Namoi Zone 4	Low	Low	High
Upper Namoi Zone 5	High	Low	Moderate
Upper Namoi Zone 6	Low	Moderate	Low
Upper Namoi Zone 7	High	High	Low
Upper Namoi Zone 8	Moderate	Moderate	Moderate
Upper Namoi Zone 9	Moderate	Moderate	Low
Upper Namoi Zone 10	Low	High	Low
Upper Namoi Zone 11	High	High	Moderate
Lower Namoi	Low	Moderate	High
Gunnedah Basin	-	Moderate	Moderate
Oxley Basin	-	High	Low
Liverpool Ranges Basalt	-	Moderate	Moderate
GAB and GAB Alluvial	-	Moderate	Moderate

The analysis shows that confidence in predictions in most of the zones is either high or moderate. The only locations considered to provide low confidence predictions are:

- Upper Namoi Alluvium Zone 7 and 11. This is because predictions in these zones show both a high sensitivity to variations in hard rock parameters and a high uncertainty.
- The Oxley Basin Management Area. This is because the uncertainty in this zone is high resulting from the paucity of data available to calibrate the model response in this area.

Water quality

In terms of groundwater quality, the conceptualisation phase of the Study has identified a number of pathways through which coal mining and CSG development could have negative or positive impacts. Some of these pathways are localised or impossible to define in space or time and cannot be simulated with any accuracy. These include mechanisms such as emergency / unlicensed releases of poor quality water, mixing of drilling fluids and aquifer water during drilling. Some of the mechanisms however are more regional in scale and do lend themselves to simulation in numerical models. This includes the impacts that regional declines in water levels might have on water quality by enhanced mixing between low and high quality water bodies. However, the conceptualisation phase of the Study also identified that the groundwater quality observational data is very limited, preventing the inclusion of water quality modelling even at this regional scale.

The data do however show that (generally) the hard rock aquifers are more saline than the alluvium. The results from previous studies, reported in Kelly et al. (2007) and Timms et al. (2010), appear to indicate that the alluvial aquifers are often fresher at depth, i.e. the Narrabri Formation may contain lower quality water than the Gunnedah Formation. The potential for coal and gas developments to impact regional groundwater quality has therefore been investigated via indirect methods. This is achieved by examining the following two key Groundwater Model outputs; the change in the predicted groundwater gradient (i.e. the difference) between the Gunnedah and Narrabri Formations in the Upper Namoi Alluvium and the predicted groundwater flows between the alluvium and the hard rock formations.

The analysis has shown that the predicted groundwater level gradient between the Gunnedah and Narrabri Formations in the Upper Namoi Alluvium remains relatively unchanged throughout the simulations. The changes that do occur are greatest in the long term development scenario and are predicted to be just a few centimetres rather than metres. Only in Zone 7 is a significant gradient generated but it is isolated to a local area within this zone. The potential exists therefore for the mixing of alluvial water of different quality in response to mining and gas developments.

In terms of groundwater flows, the model results show that the situation without mining or CSG development is the same in each of the Upper Namoi Alluvium Zones; more groundwater flows from the hard rock formations into the alluvium than flows in the opposite direction. This is a consequence of the lower groundwater levels in the alluvium compared to the hard rock formations. If the quality of groundwater in the hard rock formations is lower than in the alluvium, this will tend to decrease the alluvial water quality. As mining and CSG developments progress, the net amount of water flowing into the alluvium reduces, probably as a consequence of the reduced groundwater levels in the hard rock formations and the resultant reduction in the gradient between the two hydrogeological systems. For example, in Zone 7 during the period 2030 to 2060 the flow direction is actually predicted to reverse, with a net loss of water from the alluvium. Compared to the without coal and gas development case, the potential for lower quality water to be introduced into the alluvium is therefore reduced.

The modelling has shown that, at a regional scale, two significant groundwater mixing processes are likely to result from long term development of the coal resources. The ultimate effect of these processes is difficult to gauge because one (mixing within the alluvial aquifers) has the potential to reduce water quality in the alluvium and the other (reduced inflow from the hard rock into the alluvium) has the potential to mitigate the impacts.

5.5 Catchment water availability

The predicted impacts to the groundwater resource availability (in the three main groundwater systems where coal and gas developments are most likely; the hard rock west of the Hunter-Mooki Fault and the Upper and Lower Namoi Alluvium) and the surface water resource availability (measured as flow along the Namoi River in the vicinity of Narrabri) has been calculated based on model results. The analysis compares the water volume negatively impacted by mining and CSG activities and that impacted by existing practices, such as abstraction for irrigation. The volumes have been calculated based on the following:

- Impacts from existing practices are calculated as the abstraction rate minus the irrigation recharge rate. In other words, it is assumed that the majority of abstracted groundwater is used for irrigation, and as a percentage of irrigated water makes its way back to the groundwater system, this component is not counted as an impact.
- Impacts from mining and CSG developments have been calculated as:
    - Flows between each of the main groundwater systems (which can have both negative and positive impacts on the resource). This includes flows between the hard rock and Upper and Lower Namoi Alluvium and flows between the Upper Namoi and Lower Namoi Alluvium.
    - Flows to the mine voids and CSG wells.
    - Reduction in groundwater recharge (this impacts the Upper Namoi Alluvium only).
    - Reduction in river baseflow gains and increase in river leakage which are both positive impacts in terms of the groundwater system and impact only the Upper Namoi Alluvium.

- Impacts to the Namoi River flow at Narrabri is calculated as the predicted percentage impact on surface water flow compared to the average observed flow at that point in addition to the total reduction in river baseflow gains and increase in river leakage predicted along the entire surface water system in the Groundwater Model. This is compared to current surface water extraction rates in the regulated Namoi River between Keepit Dam and Walgett.

The results for Scenarios 1, 2 and 3 are shown in Figures 5.9 to 5.11. They show that:

- In the Lower Namoi Alluvium the impact of mining and CSG developments on the available groundwater is negligible in all scenarios, reaching a maximum of about 1,000 m^3/d at the end of Scenario 3.
- In the Upper Namoi Alluvium the impact on available groundwater is greater, reaching a maximum of about 10,000 m^3/d at the end of Scenario 3. This is however much less than the current groundwater abstraction impact.
- In the hard rock groundwater system, the impact from mining and gas developments on available water is much greater, and has the potential to exceed the current impacts from abstraction. This is due to the fact that this is the system where the primary impacts of mining and gas development will be focussed (from groundwater flow to mine voids and CSG wells). The maximum impact is around 100,000 m^3/d.
- The impact on the surface water system is also high when compared with current levels of surface water extraction. In the long term development scenario (Scenario 3) the coal and gas development related impacts are roughly half the surface water extraction impacts. The maximum impact is around 40,000 m^3/d.

In terms of impact of coal and gas developments on the volume of catchment water resources then by far the greatest impact will be in the hard rock groundwater system. The majority of this impact will be on the coal seams and coal bearing formations rather than the formations that are targeted for groundwater abstraction for other reasons (livestock, domestic, etc.). The other large volume impact could be to the surface water flows, which could be up to half the current surface water extraction rates in the catchment. The impact on groundwater resources in the Upper and (more so) the Lower Namoi Alluvium will be low compared to current abstraction rates.

Proportioning the impacts between either mining or CSG activities is not possible when considering the Upper and Lower Namoi Alluvium. However, based on discussions in the preceding sections it is likely that in the Upper Namoi the predominant source of impacts is mining developments and in the Lower Namoi it is CSG developments. Proportioning the impacts in the hard rock systems is much more straightforward. If the inflows between the hard rock and alluvium are discounted (a very small proportion of the total) then the impacts can be split into mining (flow into mine voids) and CSG (flow to CSG wells). This has been done for Scenarios 1, 2 and 3 in Figure 5.12. The data shows that the greatest proportion of predicted impacts (up to 80% to 90%) in the hard rock formations come from mining developments. However, the flows to mines are based on the hydraulic parameters and prevailing groundwater conditions used in the model whereas the flows to CSG wells are fixed based on industry estimates. The impacts to surface water flows come predominantly from the interception of rainfall runoff by open-cut mines.

5.6 Model utility

The Model provides predictions of the long-term, cumulative effects of mining and CSG developments on water resources at a catchment-scale, identifies those areas (sub-regionally) that are most at risk from developments, and quantifies the potential magnitude of impacts for different coal resource development options. Assessment of the sensitivity of the results to different inputs, and the level of confidence in these predictions, has also been undertaken.

Due to the very large size, the Model is more suited to these sub-catchment scale predictions than predictions of the impacts of individual mines and individual CSG wells. Additionally predictions of field scale impacts from activities such as road and pipeline construction, hydraulic fracturing etc. can only be investigated effectively using much smaller scale and more targeted studies and models, such as those developed to support project Environmental Impact Assessments.

6 MONITORING PROGRAM

6.1 Introduction

According to the Request for Tender (Section G.3.7.1.i), the Study should present an outline of a practical monitoring program to provide data for future maintenance and updating of the Model which:

- is rigorous and defensible; and
- prioritises the collection of surface water, groundwater, water quality and climate data.

The Monitoring Program may also include recommendations outlining the scope for any separate follow on investigations to enhance the Model.

In order to address the requirements described above the datasets used to calibrate the Hydrologic and Groundwater Models (the Model) are detailed in full in this section, and appropriate ongoing observation measurement frequencies are suggested. These are based on both the model conceptualisation and required numerical model data input and output frequencies. Opportunities for enhancement of the Model and investigations that will reduce uncertainty in model predictions are also identified based on any gaps within the existing datasets. These focus on the objectives of the Model (to investigate the impacts from coal and gas developments on the Namoi catchment water resources) and whilst it is acknowledged that all inputs to the Model are uncertain, those that could have the greatest influence on predictions are targeted.

6.2 Model maintenance and updates

6.2.1 *Introduction*

This sub-section defines the various monitoring types and locations that were used to calibrate the Groundwater and Hydrologic Models. For each monitoring type an optimum data collection frequency is also recommended. Data collection following this regime will allow for effective maintenance and updates to be made to both models at whatever time interval is deemed most appropriate by the Model owners.

6.2.2 *Climate*

The distribution of rainfall stations within the catchment is good, with the exception of a data gap in the Pilliga forest area. There is also a lower density of rainfall stations within the western areas of the catchment compared to the east. However, given the flatter topography in the west this is not a major concern as there is less variation in rainfall than the eastern areas which are more influenced by orographic effects.

Rainfall stations used in the Hydrologic Model are listed in Table 6.1 and shown in Figure 6.1. These stations currently record rainfall on a daily basis. Monitoring of these stations should be continued so that the modelling work can easily be updated in the future.

Table 6.1 Rainfall stations used in the Hydrologic Model

Station number	Station name	Easting (MGA 55)	Northing (MGA 55)
53026	Narrabri (Mollee)	757,756	6,649,898
53034	Wee Waa (Pendennis)	723,830	6,665,783
54003	Barraba Post Office	846,923	6,633,785
55000	Attunga (Garthowen)	868,771	6,573,844
55006	Blackville Post Office	806,880	6,494,862
55024	Gunnedah Resource Centre	812,044	6,562,914
55043	Willow Tree (Parraweena)	823,514	6,486,439
55045	Curlewis (Pine Cliff)	788,897	6,546,590
55049	Quirindi Post Office	849,470	6,508,161
55069	Yannergee (Dobroyd)	787,454	6,516,630
55136	Woolbrook (Danglemah Road)	915,139	6,565,923
55140	Somerton (Glen Burn)	854,516	6,563,356
55143	Moonbi (Bellevue)	888,231	6,561,153
55176	Loomberah (Pendene)	889,004	6,534,680
55239	Pine Ridge (Round Island)	830,296	6,499,982
55274	Kelvin (Carellan)	828,862	6,589,906
55276	Keepit Dam	833,949	6,578,157
55311	Duri Post Office	863,834	6,540,048
56075	Walcha Road (Boxley)	924,004	6,558,147

Evaporation stations are not so widespread within the catchment. Catchment specific data is limited to 4 main stations and a synthetic dataset from the Bureau of Meteorology has been used for the numerical modelling work. An updated sequence will need to be acquired for any model update for comparison with the synthetic sequence currently being used.

Assuming that data collection continues at the above stations, and that the Bureau of Meteorology continue to calculate the synthetic evaporation dataset it is not thought necessary for any additional climate data to be collected for use within the Model.

6.2.3 *Surface water*

The gauging stations in Table 6.2 and Figure 6.2 have been used in the calibration of the Hydrologic Model and/or the setup of the Groundwater Model. These stations contain the most complete datasets of the locations available and have monitoring which continues to present day. It is suggested that monitoring be continued at these stations to ensure that the Model can easily be updated in the future. As the Hydrologic Model uses a daily time step the aim of monitoring at these sites should be a minimum resolution of daily readings.

Table 6.2 Surface water gauging stations

Station number	Station name	Easting (MGA 55)	Northing (MGA 55)
419001	Namoi River at Gunnedah	810,969	6,568,952
419005	Namoi River at North Cuerindi	861,999	6,599,877
419006	Peel River at Carroll Gap	837,072	6,571,853
419007	Namoi River d/s Keepit Dam	834,236	6,577,216
419010	Macdonald River at Woolbrook	915,224	6,566,120
419012	Namoi River at Boggabri	792,989	6,603,179
419015	Peel River at Piallamore	887,628	6,543,186
419016	Cockburn River at Mulla Crossing	893.855	6,556,445
419022	Namoi River at Manilla railway bridge	855,825	6,591,998
419023	Namoi River at Turrawan (Wallah)	782,859	6,627,374
419027	Mooki River at Breeza	829,592	6,534,926
419028	Macdonald River at Retreat	894,021	6,604,594
419032	Cox's Creek at Boggabri	786,178	6,591,687
419033	Cox's Creek at Tamber Springs	774,514	6,528,188
419035	Goonoo Goonoo Creek at Timbumburi	872,899	6,533,732
419043	Manilla River at d/s Split Rock Dam	853,801	6,610,367
419045	Peel River d/s Chaffey Dam	894,324	6,525,125
419047	Ironbark Creek at Woodsreef	858,161	6,630,078
419051	Maules Creek at Avoca East	795,920	6,622,264
419053	Manilla River at Black Springs	850,756	6,628,766
419076	Warrah Creek at Old Warrah	845,580	6,491,654
419084	Mooki River at Ruvigne	818,242	6,561,720
419093	Yarraman Creek near Spring Ridge	814,417	6,522,103

6.2.4 *Groundwater*

Groundwater levels

The Groundwater Model was calibrated against groundwater level data collected from sites in the Upper Namoi Alluvium and some non-alluvial formations. The model does not extend east of the Hunter-Mooki Fault System, and though it incorporates the Lower Namoi Alluvium and other formations to the west no time variant calibration of these areas was undertaken. The monitoring network in the northern and central parts of the Upper Namoi Alluvium is extensive, and a sub-set of all available locations, based on those used in the Office of Water Upper Namoi Groundwater Model (McNeilage, 2006), was used for calibration with the datasets being extended to mid-2010 using the Pinneena 3.2 database (NSW Office of Water, 2010). In the southern areas (where the existing Office of Water model does not extend), namely Zones 1, 6, 9 and 10, additional monitoring locations where data has been recorded over a fairly long and recent time period were sourced completely from the Pinneena 3.2 GW database (NSW Office of Water, 2010). The monitoring locations used in the calibration are shown in Figure 6.3 and listed in Table 6.3. For future maintenance of the Model data from these locations should be collected and collated so that the predicted outputs can be compared against the latest data. Groundwater levels from the majority of these bores are collected four times a year. This is considered suitable for the purposes of the Study.

Table 6.3 Alluvial monitoring bores used in the calibration dataset

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW021092	815,582	6,574,821
GW030008	829,780	6,531,489
GW030029	847,413	6,504,398
GW030050	798,603	6,599,084
GW030059	841,398	6,505,431
GW030060	833,930	6,503,319
GW030081	828,975	6,520,133
GW030088	842,736	6,513,127
GW030129	792,891	6,619,373
GW030134	794,052	6,625,656
GW030145	828,125	6,512,487
GW030231	783,147	6,627,333
GW030236	790,982	6,625,561
GW030272	837,412	6,519,498
GW030297	813,423	6,568,480
GW030302	822,242	6,566,573
GW030304	825,485	6,565,675
GW030307	830,167	6,567,662
GW030343	811,168	6,569,867
GW030345	778,258	6,632,397
GW030399	775,624	6,634,706
GW030430	824,081	6,549,497
GW030434	832,256	6,548,898
GW030446	787,675	6,623,707
GW030447	787,060	6,620,816
GW030469	793,537	6,603,574
GW030478	771,289	6,639,841
GW036004	785,924	6,618,205
GW036005	786,980	6,615,648
GW036007	791,288	6,607,331
GW036011	837,582	6,548,519
GW036015	790,466	6,611,359
GW036027	831,815	6,546,414
GW036071	831,160	6,541,694
GW036096	787,770	6,616,459
GW036099	821,330	6,530,741
GW036125	833,084	6,537,347
GW036149	825,421	6,556,739
GW036152	829,906	6,539,724
GW036166	827,889	6,560,205
GW036167	828,170	6,563,404
GW036187	791,053	6,618,191
GW036189	826,471	6,547,114
GW036190	828,700	6,542,049
GW036192	833,395	6,552,016
GW036196	822,638	6,551,639
GW036202	819,289	6,555,871
GW036213	821,971	6,557,644

Table 6.3 Alluvial monitoring bores used in the calibration dataset (continued)

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW036215	825,578	6,562,774
GW036239	815,183	6,571,380
GW036260	822,459	6,563,336
GW036266	820,958	6,561,127
GW036272	816,845	6,565,503
GW036410	814,511	6,496,865
GW036432	818,096	6,582,428
GW036435	784,780	6,587,009
GW036441	782,557	6,583,361
GW036456	799,201	6,589,944
GW036457	801,121	6,585,296
GW036458	800,844	6,581,940
GW036460	806,764	6,583,681
GW036461	807,201	6,578,241
GW036463	811,523	6,581,668
GW036473	800,454	6,588,145
GW036478	782,992	6,585,691
GW036480	798,029	6,582,264
GW036484	812,518	6,586,545
GW036495	775,825	6,572,974
GW036506	776,343	6,558,346
GW036509	774,673	6,565,413
GW036510	796,647	6,591,836
GW036512	776,444	6,549,776
GW036514	795,742	6,588,897
GW036515	773,083	6,565,643
GW036545	779,428	6,572,502
GW036546	778,806	6,583,438
GW036548	797,354	6,594,158
GW036566	776,235	6,544,011
GW036568	792,071	6,594,825
GW036601	774,602	6,529,350
GW036655	795,383	6,585,278
GW036657	776,767	6,516,520
GW036658	778,278	6,507,213

There are a number of active groundwater monitoring locations in the alluvium which, due to the fact that data has only been collected over a relatively short time period, were not used in the calibration. If data collection continues at these sites they will eventually form good additional calibration opportunities. Furthermore these holes fill in some of the gaps where long term groundwater observations are not available. A selection of these bores are shown in Figure 6.3 and listed in Table 6.4. It is recommended that monitoring is continued at a quarterly frequency at these locations.

Table 6.4 Existing short record alluvial monitoring bores that can be used to supplement the calibration dataset

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW030063	835,408	6,517,008
GW030177	833,250	6,511,770
GW036547	779,245	6,543,477
GW036660	772,972	6,578,795
GW036676	771,790	6,573,766
GW041027	808,516	6,619,427
GW093101	814,721	6,516,376
GW093102	816,125	6,521,874
GW093103	818,460	6,527,576
GW965574	847,508	6,489,946
GW965576	817,852	6,521,677
GW968531	800,698	6,622,322

The government (Pinneena) calibration dataset in the non-alluvial aquifers is not as extensive (Figure 6.4) as that for the alluvium. Uncertainty remains as to which hydrostratigraphic unit many of the observations relate to as bore construction details are not available. However they do provide the only existing insight into the shallow groundwater system away from the alluvium and continued monitoring at these locations is recommended at a quarterly frequency. For the sites with unknown completions it is also recommended that additional investigations are undertaken to clarify bore construction information, so that uncertainty relating to the strata being monitored can be reduced. Even if this data cannot be confirmed these bores should still be monitored as they provide good information on background trends. The sites are listed in Table 6.5.

Table 6.5 Non-alluvial aquifer monitoring bores used in the calibration dataset

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW036506	776,343	6,558,346
GW036509	774,673	6,565,413
GW036546	778,806	6,583,438
GW030430	824,081	6,549,497
GW036011	837,582	6,548,519
GW036149	825,421	6,556,739
GW036189	826,471	6,547,114
GW036190	828,700	6,542,049
GW036260	822,459	6,563,336
GW036272	816,845	6,565,503
GW030050	798,603	6,599,084
GW036510	796,647	6,591,836
GW036548	797,354	6,594,158
GW030345	778,258	6,632,397
GW030446	787,675	6,623,707
GW036007	791,288	6,607,331
GW030236	790,982	6,625,561
GW030029	847,413	6,504,398
GW030008	829,780	6,531,489
GW030081	828,975	6,520,133
GW030088	842,736	6,513,127

Table 6.5 Non-alluvial aquifer monitoring bores used in the calibration dataset (continued)

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW030272	837,412	6,519,498
GW030121	766,605	6,643,873
GW965569	805,774	6,564,906
GW030468	792,643	6,603,133
GW040823	830,721	6,507,652
GW036976	804,350	6,540,406
GW030079	826,771	6,520,913
GW036315	804,786	6,507,946
GW030121	766,605	6,643,873
GW030271	837,857	6,520,904
GW036384	809,370	6,504,147

Monitoring of groundwater levels in association with the development of mines provides an important additional dataset for the calibration of the Groundwater Model. Data from the sites shown in Figure 6.4 and listed in Table 6.6 were used in model calibration and it is recommended that monitoring continues at these sites into the future at a quarterly frequency if the levels remain steady, reducing to a monthly frequency if any impacts start to be observed. As mentioned above it is likely that older sites, which have been adopted into the mine monitoring program, may have unknown bore construction and these should be investigated to try and increase the confidence in the data being recorded.

Table 6.6 Mine related monitoring used in the calibration dataset

Bore number	Easting (MGA 55)	Northing (MGA 55)
VNW223	803,343	6,594,489
VNW221	803,358	6,594,055
GW001613	804,153	6,596,620
GW005749	804,120	6,593,413
GW968389	797,532	6,567,605
GW968390	797,543	6,567,993
GW027356	797,960	6,569,225
GW968387	798,129	6,569,797
GW050395	814,443	6,594,991
GW044068	815,424	6,593,142
GW968537	812,681	6,593,456
GW968534	813,454	6,591,368
GW968440	772,722	6,626,025
P16	772,233	6,623,740
P18	776,826	6,621,802
GW968437	780,431	6,620,113
GW968436	777,280	6,616,355
GW052266	802,063	6,603,794
GW967851	804,618	6,605,264
Templemore A	805,988	6,604,549
GW976882	801,867	6,606,192
GW967881	800,599	6,607,364
GW967883	806,444	6,606,689

Table 6.6 Mine related monitoring used in the calibration dataset (continued)

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW002129	804,062	6,605,624
IBC2139	804,615	6,608,387
IBC2114	804,392	6,609,388
IBC2138	801,980	6,609,621
IBC2115	804,401	6,609,384
IBC2102	802,221	6,610,995
IBC2103	802,227	6,610,996
IBC2104	803,687	6,611,361
IBC2105	803,672	6,611,358
BCS3	811,322	6,607,221
GW968393	798,145	6,567,965
GW968438	777,487	6,625,549

In addition to the sites mentioned above, significant monitoring is associated with the Watermark and Caroona exploration areas. At present these sites only have short records so they have not been included as time variant observation sites in the Model. Collection of data at these sites should continue so that longer records become available. As these sites are adjacent to potential coal mine developments they are purposefully located to collect as much useful information on vertical and horizontal hydraulic properties as possible. Currently there is no development at these sites and the monitoring is recording baseline values. If the developments are approved it is expected that they will also provide a large amount of useful data on hydraulic properties.

Groundwater inflows to mines

Estimates of groundwater inflow to mine voids, derived from observations and numerical modelling, formed an important calibration dataset. It is recommended that estimates from direct observations are provided on at least a quarterly basis by all mines in the Namoi catchment. This data will supplement the current dataset, and will replace numerically derived estimates with their associated uncertainties. Estimates of zero inflow are also important to the Study.

Surface water for groundwater model

Measurements of stream water levels from six gauging stations were used to define the river boundary condition in the Groundwater Model. Continued monitoring at these stations is required for maintenance of the Model into the future. The locations of the stations can be seen in Figure 6.2 and they are listed in Table 6.7 below. Measurements are taken at daily intervals at these locations and this should be continued. While this is excessive for the Groundwater Model which uses monthly stress periods, these measurements are also used as calibration data for the Hydrologic Model which runs at a daily time step.

Table 6.7 Surface water gauging stations used to set boundary conditions in the Groundwater Model

Station number	Station name	Easting (MGA 55)	Northing (MGA 55)
419001	Namoi River at Gunnedah	810,969	6,568,952
419006	Peel River at Carroll Gap	837,072	6,571,853
419012	Namoi River at Boggabri	792.989	6,603,179
419027	Mooki River at Breeza	829,592	6,534,926
419032	Cox's Creek at Boggabri	786,178	6,591,687
419076	Warrah Creek at Old Warrah	845,580	6,491,654

6.3 Further works and investigations

6.3.1 *Introduction*

Details of additional monitoring, further investigations, and model enhancements that are considered to offer most value in terms of increasing the confidence in model predictions are provided below. The recommendations are focussed on areas where there is either little data or the predicted risks to water resources are high but uncertain.

Many of the recommendations mentioned below have previously been identified on a catchment wide generic level in studies such as Kelly et al. (2007). Key areas for further study which Kelly et al. (2007) identified but which have not been resolved since that report include:

- Improved measurements of water quality throughout the catchment.
- A better understanding of deep drainage.
- Recharge and discharge zones along the rivers and streams need to be mapped.

Other suggestions from the Kelly et al. (2007) report have been resolved by the current study. These have included:

- Quantify the impact of the proposed coal mines on groundwater allocations and water quality.
- Build a 3D model of the hydrogeology of the Namoi catchment to reduce management errors.

6.3.2 *Groundwater Model*

Groundwater levels – alluvium (general)

There are a significant number of groundwater monitoring bores in the Lower and Upper Namoi Alluvium. The density reduces towards the western extent of the Lower Namoi Alluvium, but from a model utility point of view this will not have a significant effect on outcomes. There is no requirement to increase the amount or frequency of groundwater monitoring in the Lower Namoi Alluvium.

There is a fairly low density of time variant observations in Upper Namoi Alluvium Zones 7 and 9 but if monitoring is undertaken at the locations specified in Section 6.2 of this report, this should be sufficient for this regional scale model.

There is almost no groundwater monitoring in Upper Namoi Alluvium Zones 6 and 10 and in the northeastern area of Zone 4. Additional groundwater monitoring is recommended in these zones. It is recommended that an additional four sets of alluvial monitoring bores (shallow and deep pairs) be installed in the southern area (Zones 6 and 10), and an additional two in the northern area (Zone 4) (Figure 6.5 purple areas). Over time this would provide useful data for calibration of the Model where there is currently very little information and uncertainty is high. It will also provide an opportunity (in the case of Zones 6 and 10) to collect a baseline groundwater dataset prior to major CSG or mining activities taking place. Once installed data should be collected at quarterly intervals.

Groundwater levels – alluvium (high risk)

The results of the modelling identified two areas at high risk from the cumulative effects of mining and CSG development (Management Zones 7 and 11). These areas would benefit from a more local scale and focused investigation into groundwater flows and gradients and the relationship between surface water and groundwater. This could be accomplished by installing vibrating wire piezometers at multiple locations and elevations along transects at right angles to the main river channel and through the main (most productive, thickest) part of the aquifer. The resulting data would be useful in better characterising the hydrogeological and hydrological systems.

Groundwater levels – non alluvial units

The Great Artesian Basin (GAB) sediments are not in the area where coal and gas developments are most likely and are therefore not a priority for additional monitoring. Furthermore, at a regional perspective the GAB does have a fairly good density of groundwater monitoring sites and this is sufficient for the purposes of the Study. However, the basal GAB units (Pilliga Sandstone and Purlawaugh Formation) have a very limited monitoring network. The same is true for all geological formations beneath these to the top of the Boggabri Volcanics, especially at any significant depth. The monitoring network in these formations is very limited and there is currently a limited understanding of the groundwater system within them and little opportunity to observe any migration of drawdown from mining and particularly CSG developments on a regional scale. Furthermore, as the groundwater resources in the Gunnedah Basin and Oxley Basin Management Areas have been defined as being either at high or moderate risk from coal and gas developments, better definition of the current situation and development of a monitoring network to observe the response of the system in the future should be a priority.

Where monitoring bores in these formations do exist or have existed in the past, the exact completion details are often uncertain, so assigning observations to any particular hydrostratigraphic unit is problematic. It is therefore recommended that multi-level monitoring bores (isolated over separate vertical intervals) are installed in several locations that target these deep and intermediate formations. A number of potential areas for these bores are suggested on Figure 6.5 (beige zones). It is recommended that at least three additional sites are installed within each of these areas. Each site should monitor pressure at numerous depths within ports located above and below the main seams being targeted for CSG and coal mining. Each site would preferably also include a measuring point within the main coal seam being depressurised at that location. The exact formations to be monitored will depend on the depth and thickness of the expected formations at each location.

Limited groundwater monitoring is currently being undertaken in bores that are reported as being screened (open) in formations directly beneath the alluvium. As for all of the non-alluvial monitoring bores, the accuracy of the borehole completion information is questionable. Groundwater level observations from directly under the alluvium would be very useful from both a model calibration point of view and to provide an early warning system in terms of observing impacts from coal and gas developments in these key areas before they are expressed in the alluvium itself. It is recommended that monitoring bores should be installed directly beneath the alluvium in areas that the Model has indicated as being potentially sensitive to coal and CSG developments. Candidate areas are defined in Figure 6.5 (green zones). Sites would ideally be located near to known alluvial bores so that direct vertical comparisons could be made. The new bores should measure water pressures at a depth of at least 5 m into the hard rock underlying the alluvium. If multi-level bores could be installed it would also be advantageous to include a monitoring point in any major coal seams. It is estimated that a minimum of two such installations in each area on Figure 6.5 would add much needed valuable information.

Hydraulic parameters - testing

The adopted model hydraulic parameters (hydraulic conductivity, specific yield and specific storage) have been shown to have a significant effect on both the magnitude and extent of predicted of impacts. The Model currently treats these parameters as uniform throughout the full extent of all hydrostratigraphic units other than the Gunnedah and Narrabri Formations of the Upper Namoi Alluvium. An overriding assumption of the modelling at this regional scale is the understanding that while this is not going to be the case in reality (local differences are already evident from mining and CSG investigations) it should provide a good regional average for each layer, and therefore at a regional scale the results will be valid and meet the objectives of the Study.

Unless a significant amount of hydraulic testing and monitoring is conducted throughout the Model domain this assumption will remain necessary. It would be unrealistic to assume that this amount of investigation could be economically achieved. However, there are a number of areas where additional information will make a significant difference. The area of most importance to the Model objectives but with the least data is in areas where there is potential for CSG development. The geological characterisation is supported by a relatively high density of drillhole data but the hydraulic behaviour of the rocks around the coal seams (and the coal seams themselves) is relatively untested, especially over a long time period. This information will be very important in terms of the migration of groundwater pressure changes away from the coal seams and the accuracy of predicted associated water production volumes. The pilot sites operated by Eastern Star Gas do not include any purpose drilled monitoring bores that record pressure in formations other than the coal seams. If this data had been required to be collected it would have provided a lot of useful information to the Study.

It is recommended that data from all future CSG investigations are compiled and analysed to aid in refining the model parameters in these deeper hydrostratigraphic zones. Santos has undertaken some significant testing (long term groundwater abstraction test with pressure monitoring in the coal seams and formations above) of the hydrogeological system around the Kahlua site. It is highly recommended that this data is evaluated in the context of the Model settings and assumptions as soon as it is available. The following should be considered:

- Production volumes and therefore updated estimates of long-term produced water for inclusion in the Groundwater Model.
- Estimates of hydraulic parameters especially vertical conductivity (connection) and storage characteristics.

Data from this type of investigation will add significant value to the Model but is only likely to be collected by the CSG operators when further CSG development and testing occurs. It is recommended that future CSG pilot tests should be monitored in a similar way to Kahlua in order to provide this valuable hydraulic data whenever the opportunity arises. Furthermore, discrete multi-level monitoring of a similar standard and extent should be installed within any future production fields. This will provide valuable long term data (i.e. years worth) that can be used for the calibration of the Model at a later date, and to better the understanding of the groundwater system in general. Monitoring of all CSG activity should be undertaken in the coal seams and in the formations above them. The target formations will vary depending on the location, but regardless of this, the completion of the monitoring bores should be undertaken to a degree of accuracy that allows the observed pressure data to be assigned to a particular formation with certainty.

Investigations associated with mining activity have provided some useful hydraulic information and this has been incorporated into the Model. As existing projects mature and proposed / possible projects commence careful monitoring of inflows and groundwater response will provide valuable data to enhance the Model. However, these studies are generally fairly local in nature and do not necessarily involve targeted investigation of the hydraulic characteristics of the coal seams, intervening formations and the basal alluvial material in the areas where these units interact.

One of the main factors influencing the transmission of groundwater impacts from coal and gas developments will occur at the boundary zone of the hard rock and alluvial systems, particularly where the coal seams are in close proximity to the basal alluvium. It is therefore this area that should be considered one of the highest priorities for investigative work to better define the hydraulic parameters of each unit and the degree of connection between the hard rock and alluvial systems. Test pumping of wells screened within the coal seams in these critical areas should be undertaken. The tests should be monitored with a combination of dedicated, newly drilled, monitoring bores that extend into the formations beneath the alluvium and existing monitoring bores in the Gunnedah and Narrabri Formations. This should be undertaken in areas where mining and CSG developments have the potential to come into close proximity to the alluvium and where the coal seams are interpolated as passing very close to or being in contact with the alluvium. Figures 6.6 and 6.7 display the distance between the base of the alluvium and the top of the Hoskissons Coal Seam and Maules Creek Formation respectively, and the locations of the data on which this interpolation is based. From this the main areas of focus have been identified, and these are also shown on the figures. The testing can be undertaken at the same time and with some of the same drill holes as geological investigations.

Hydraulic parameters – Office of Water Upper Namoi Model development

Most of the Upper Namoi Alluvium is incorporated in the Office of Water Upper Namoi Alluvium Groundwater Model (McNeilage, 2006). The zones that are not (Zones 1, 6, 7, 8, 9 and 10) are in the process of being integrated into a significant update to the Office of Water model. The scope of this Study did not allow for a fine detailed and lengthy calibration of the Upper Namoi Alluvium units and nor was it warranted in the areas already covered by the Office of Water model. Therefore, when the update becomes available it is highly recommended that the adopted parameters and assumptions are compared, especially in Zones 1, 6, 7, 8, 9 and 10. This will provide two advancements:

- An opportunity to maintain the similarity between the Office of Water models and the Study Model.
- An opportunity to assess the adopted hydraulic parameters and boundary conditions (most notably rivers and irrigation recharge) in the Model against those in the finer detail and more focussed Office of Water model. An assessment can then be made of the predictions and at what end of the range of potential impacts they might sit. The Model could also be updated to reflect these changes.

Hydraulic parameters - geophysics

If investigative bores are drilled they should be surveyed with a standard suite of geophysical wireline tools, incorporating:

- natural gamma,
- density,
- neutron porosity,
- induction/laterolog,
- sonic, Δtshear,
- sonic, Δtcompressional,
- acoustic televiewer/Formation Micro Imager.

This data will provide lithological, storage, geomechanical, fracturing and stress regime data for the hard rock formations. Together with the other datasets, the geophysical data will allow for a particularly thorough analysis of the hydraulic regime at depth, and may lend valuable information to the assessment of vertical connection between formations.

Hydrostratigraphy

There are significant areas within the Namoi catchment where almost no geological information is available. These areas are:

- To the west of a line drawn directly north-south through Wee Waa.
- To the east of the Hunter-Mooki Fault System (excepting the area around Werris Creek).
- The area beneath the majority of the Upper Namoi Alluvium.

The first two areas have proven to be of little significance to the coal and gas industries for the foreseeable future, due to either a lack of, or the depth to, coal seams and are predicted to be at low risk from any development. The minimal exploration undertaken in the western area of the catchment has led to differing geological interpretations. It is expected that additional information collected during future exploration works will improve the understanding of the geology in this area and narrow any differences between the different models. The Model structure should be compared against new data in these areas if / when it becomes available. If the data does show that there is a potential for CSG development here the Model should be updated to reflect this.

The last area however is of great significance to the Study. This is the area where the coal seams are inferred to approach the surface, coming very close to or in direct contact with the alluvium, and therefore where the potential for connection with the alluvium and transfer of impacts is greatest. The geological modelling undertaken as part of this Study has identified where these areas are most likely to occur and therefore where additional drilling would be most appropriate. For example the geology under Upper Namoi Alluvium Zones 2 and 9 is relatively well known and is probably adequate for a study of this nature. Furthermore these coal seams have been shown to be many hundreds of metres below the alluvium at these locations. The geology beneath Upper Namoi Alluvium Zones 3, 4, 5, 7 and 11 is, in contrast, very poorly known, but the coal seams and coal bearing formations are inferred to be within 100 m of the base of the alluvium over much of their area, and in some areas may be in direct contact (Figures 6.6 and 6.7). These are also the areas where the greatest impacts to the groundwater system are predicted. It is these areas that should therefore be subject to further investigation. The following is recommended in these zones:

- Drilling of geological investigation bores to confirm the presence and position of the coal seams and the intervening layers. Any investigation holes should be completed as permanent multi-level (discrete isolated levels) automated monitoring sites.
- Revisiting and interpreting existing seismic data or the running of additional seismic surveys to determine whether any additional refinement of stratigraphy can be interpreted.

Hydrochemistry

The Groundwater Model is not configured to simulate the transport of solutes. The potential for mixing of different quality water bodies is developed by considering the predicted flow patterns, particularly between different geological formations. The reason for this is due to the fact that there is insufficient data to characterise the water quality in most of the formations and because of the size and other demands on the Groundwater Model. It is unlikely that this situation could be improved rapidly given these constraints.

It is recommended that a water quality monitoring network be established in both the Upper Namoi Alluvium and hard rock areas. Samples should be collected from both shallow and deep bores. This could be combined with the sites used for multilevel groundwater level monitoring but would mean that they would have to be completed with screens and sampling tubes rather than vibrating wire piezometers which can only measure pressure changes.

At a minimum, sites should be sampled for major and minor ions, selected metals, temperature, pH, EC, TDS. This would eventually form a dataset that could be used to define water quality parameters for use in the Groundwater Model (or more detailed models) and also an opportunity to build a time variant dataset against which changes to groundwater quality, for whatever reason, can be identified. It is suggested that samples be taken quarterly in the first year, with a review of the findings after that time to determine if there is significant seasonal variation in results. If there is none it may then be possible to reduce the sampling frequency or number of parameters being tested. The number of sample sites in the longer term sampling rounds will depend on the variations seen in water quality parameters.

Groundwater recharge

An analysis of the contribution to predicted impacts on groundwater levels from potential changes in groundwater recharge due to mining and CSG activities was undertaken with the Model. The results suggested that a significant proportion (over half in some areas) of the predicted groundwater drawdown from coal and CSG activities was derived from the predicted reduction in groundwater recharge. The majority of this comes from the representation of the effect that open cut mining would have on recharge.

The uncertainty over both the rate of groundwater recharge and the impacts on recharge by mining and CSG activities is very high. Reduction of these uncertainties would therefore provide a significant benefit to the Model and increase confidence in predictive results. This is not straightforward as it cannot be achieved through measurement of a single parameter or process but requires several interlinked processes and parameters which will vary significantly in relatively small distances. The modelling has however shown that the Model predictions are most sensitive to these changes in the following locations (Figure 6.8) and these are where further investigations should be targeted:

- The boundary area between Upper Namoi Alluvium Zones 5 and 11.
- The central and southern areas of Upper Namoi Alluvium Zone 4.
- The central portion of Upper Namoi Alluvium 7.

The representation of the interception and diversion of rainfall by open pit mines that would usually be destined for groundwater recharge can be regarded as worst case (the mines are assumed to intercept all recharge falling within their pit footprint). This was necessary due to the significant uncertainties associated with recharge in general and the way in which mining may affect it. Reducing this uncertainty in the areas mentioned above would provide significant benefit to the Model and outcomes. Options for doing this are discussed further in relation to additional Hydrologic Model investigations.

Rivers

The settings and parameters for the main rivers in the Model have been based on those used in the Office of Water Upper Namoi Alluvium Groundwater Model (McNeilage, 2006). As with the alluvial hydraulic parameters this is considered to be appropriate as the Office of Water model is much smaller (although it shares the same grid size) and has been developed over two decades. It is understood that updates and extensions to the Office of Water model are ongoing, and it is recommended that any changes made are reviewed for possible inclusion in the Study Model. The level of detail applied to the rivers in the Model is considered to be appropriate given the scale and objectives of the Study and no specific monitoring or investigation work is recommended to improve it.

Groundwater abstraction and irrigation

The focus of the Model is to predict the impacts on the Namoi catchment water resources from coal and gas development. There are inherent uncertainties in the groundwater abstraction database and this has been discussed in the Phase 2 report. The representation (location and rate) of groundwater recharge derived from irrigation is directly derived from the calibration of pre-existing groundwater models. The uncertainty in this input is high. However, neither of these inputs will have a significant bearing on the objectives of the modelling and further monitoring and investigation designed to reduce these uncertainties is not recommended as it will have little impact on the outcomes of the Study.

It is however suggested that the Office of Water consolidate their current and historical water use data into one place which will make acquiring and processing any further requests for data a much simpler process.

Groundwater Model summary

There are many overlaps between the various investigative works recommended above. They are summarised below and focus on three main areas: gaining maximum data from CSG developments, reducing uncertainty of the impact that open cut mines will have on recharge to the alluvium, and increasing understanding of the connection between the alluvium and coal seams. The latter should involve drilling and geophysical logging of boreholes to accurately define the hydrostratigraphy and subsequently serve as pumping and multilevel monitoring holes.

The following additional works are suggested as ways of improving Study outcomes:

1. Ensure all monitoring opportunities are taken when exploring coal seams for CSG development. These are anticipated to be at high to moderate depth from surface and should be designed to provide maximum data on:

    a. Response of groundwater system to abstraction from coal seams. This will require long terms tests (30 days or more) and precise monitoring of groundwater pressures in the coal seams and specific units above (and possibly below) them. This will provide very pertinent data on the hydraulic characteristics of the units and the connection between them.

    b. The pervasiveness of fracturing in the formations above the coal seams can be derived from the above but also from analysis of core and geophysical logging of the holes. This will also provide information on hydraulic parameters.

2. Investigate the hydrogeological and geological systems directly beneath the alluvium where the Study has indicated that the alluvium and coal seams may be in close proximity (say less than 100 m apart) and where there is limited existing data. This should involve drilling and logging of pumping and multilevel monitoring bores and undertaking long term test pumping. In areas of critical importance to the potential for transmission of impacts to the alluvium, this will provide:

    a. Confirmation of the geology and relationship between the alluvium, coal seams and intervening layers.

    b. Estimates of the hydraulic connection between the coal seams and the alluvium.

3. Targeted investigation of the processes and rates of groundwater recharge occurring in areas where mining is scheduled to occur in the near future. Changes in recharge have been shown to have a significant impact on groundwater levels. This input to the Model should therefore be a priority in terms of reducing the uncertainty. Options for doing this are discussed in relation to the Hydrologic Model.

Furthermore the existing shallow groundwater monitoring network in areas away from the alluvium but within the Gunnedah Basin is limited and requires augmentation with some dedicated boreholes.

6.3.3 *Hydrologic Model*

Introduction

Outputs of the Hydrologic Model include sub-catchment recharge estimates and streamflows. Changes in sub-catchment recharge have been shown to produce significant changes in drawdown estimates in several areas of the Groundwater Model. It would therefore be beneficial to the Study to improve the confidence in the baseline understanding of recharge processes so that there is a greater confidence in any changes as a result of mining or CSG development.

Improving the understanding of recharge will also increase the understanding of surface water flows as the two systems are interconnected. Current modelled streamflow predictions suggest that there are potential gaps in the conceptualisation of the system away from the main Namoi River. Additional works to improve the understanding of surface flows are also suggested.

Climate

There is a relatively high degree of confidence in climate (rainfall) estimates throughout the catchment as there is high temporal and spatial resolution of data over the area of the Hydrologic Model. Data is collected on a daily timestep, and in addition to the stations chosen for the Model there are many other locations which can be used as a check on rainfall patterns if any of the chosen stations record potentially suspect data.

Evaporation stations are not so widespread within the catchment. Catchment specific data is limited to 4 main sites. A synthetic dataset from the Bureau of Meteorology has been used for the numerical modelling work. Whilst it would be beneficial to have additional stations within the catchment to verify the synthetic data this is not thought to be as important an issue as other parameters. An updated synthetic sequence will need to be acquired for any future modelling to compare with the synthetic sequence currently being used.

In conclusion, other than continuing with current monitoring there is little to be gained from additional climate data collection with respect to improving the Hydrologic Model.

Soil parameters

In the present model configuration uniform values have been assigned for soil thickness and hydraulic parameters across each of the sub-catchments. Detailed investigations to improve estimates of soil parameters would be a time consuming and expensive task, and at the scale of the Hydrologic Model sub-catchments, would not be appropriate.

Knowledge of soil properties across the entire catchment is limited. It is suggested that spot samples are collected for each of the major soil types and tested for specific yield and other hydraulic parameters at several locations, including areas that are not irrigated, to refine and increase confidence in model inputs.

Surface water flows and quality

Surface water flows are recorded at a number of gauging stations within the catchment. Not all of these stations are levelled in to absolute datum in mAHD or have cross sections from one bank to the other. It would be beneficial for this to be completed for all stations to the west of the fault line. Absolute levels and associated sections can be used to better understand surface water / groundwater interaction on a conceptual level by comparing stream information to nearby groundwater levels.

Assumptions relating to the depth of stream channels within the alluvium and channel properties were made in the Office of Water Upper Namoi Groundwater Model (McNeilage, 2006) and have been adopted in the Study Groundwater Model. It would be useful to check that these assumptions are correct, especially where streams have been added outside of the existing model boundaries. At locations with rapid changes in elevation and along reaches which the Model shows are likely to be strongly affected by future developments it is also suggested that intermediate sections be surveyed in.

Each gauging station should also be rated according to how accurate it is believed to be. Factors to be considered will include potential for underflow or bypass of the gauge, time since the generation of the latest rating curve, potential for subsidence or changing of the cross section profile at the station.

It would be a useful exercise to complete a flow accretion survey along the Mooki River to determine gaining and losing sections. Coupling the survey with measurements of temperature and electrical conductivity, as suggested by Kelly et al. (2007), would enhance the results of the survey. This exercise should be completed under differing flow conditions if this can be done safely, it may also be of value to the Study if this was also completed on a number of the other tributaries such as Cox's Creek and Bohena Creek which runs through the Pilliga forest. Eastern Star Gas proposed to develop their first CSG gasfield within the catchment area of the Bohena Creek, and there is already a discharge of treated produced water into the creek from the pilot well sites.

Subject to a suitable location being found downstream of the proposed gasfield area it is suggested that a permanent gauging station be installed to monitor changes in flow that may occur as the gasfield develops. The site will need to be located in an area of hard rock which has a low permeability so that groundwater flow under the gauge is minimised and all of the flow past the site can be recorded.

A similar surface water monitoring study could also be set up on streams subject to future open cut coal mine developments. This kind of study would work best on streams which have permanent flows as changes in baseflow will also be detected.

Surface water quality is generally well monitored along the main river reaches. This should be continued so that any changes can be identified. As was recommended in the Phase 2 report it is also suggested that a more rigorous water quality sampling regime is carried out upstream and downstream of coal mine or CSG discharge sites to properly characterise the baseline hydrochemistry of the receiving waters and the discharges themselves.

Long-term investigations to improve Hydrologic Model estimates

A high proportion of the total predicted impacts on both groundwater levels and surface water flows originate from the interaction between open-cut mines and rainfall runoff and recharge. There is a high level of uncertainty associated with these processes and a focus for future investigation should be on better characterising them and therefore increasing confidence in predictions.

This would require longer term studies involving extensive instrumentation in several small, discrete catchments with differing baseline characteristics to obtain a greater understanding of their water balances. Results from these studies could then be scaled up across the larger Namoi catchment to improve recharge / runoff estimates on a broader scale. If these areas were to then become the focus of additional (or a reduction in) mining or CSG interests it will be easier to assess the changes due to these activities. The Model results indicate that the most suitable locations for this type of investigation would be the Upper Namoi Alluvium Zones 7 and 11. Significant future mining developments are planned and / or possible in their vicinity, and the groundwater resource is defined as being at high risk of experiencing impacts.

Key parameters to concentrate on would be similar to those for the catchment wide conceptual model and would include:

- Climate
- Streamflows – both within river channels and though the streambed (more difficult)
- Stream-aquifer interaction
- Groundwater levels at different depths within the catchment
- Abstractions – groundwater and surface water
- Soil parameters and vegetation changes
- Geology
- Any changes in catchment use – mining, CSG, urban, agriculture etc.

Studies similar to those suggested above have been conducted over small areas of the Maules Creek catchment in recent years. However, they were only focussed on the alluvial areas and there are still large areas of the Maules Creek and wider catchment, especially away from the alluvium, which have no work completed.

Hydrologic Model / surface water summary

A number of suggestions for improving the Hydrologic Model and the general understanding of surface water processes are detailed above. These range from completing checks on the existing gauges to installation of new stations at locations which may be directly affected by future developments.

The following additional works are suggested as ways of improving Study outcomes:

1. A QA check of the existing surface water gauging sites should be completed to;
    a. Level in all sites to absolute datum so that the full dataset can be used in any model updates and ensure that each site has an up to date ratings curve available.
    b. Ensure that any uncertainties above those which are inherent in all gauging sites are identified so that calibration to more suspect sites can be weighted accordingly.
2. Carry out hydraulic testing for each of the major soil types to increase the confidence in the parameters adopted in the Hydrologic Model.
3. Installation of additional permanent flow gauging locations (if suitable sites can be found) on tributary streams which may become directly affected by either coal mining or coal seam gas development.
4. Consider full instrumentation of selected sub-catchments to better improve recharge / runoff estimates over a more controllable area.

6.4 Summary of recommendations

A summary of the main items described in the monitoring plan above is given in Table 6.8 below. The table sets out the different elements proposed, the reasoning behind each one and the priority in which they should be addressed.

Table 6.8 Summary of monitoring recommendations

Element	**Reasoning**	**Priority**
Continued data collection at specified monitoring bores	This will ensure that the current input and output datasets can be updated efficiently. These are a combination of climate, groundwater and surface water locations.	High
Drilling of additional monitoring bores in the Gunnedah and Oxley Basin Groundwater Management Areas	This will provide a monitoring network where the risk to water resources is high and where coal developments are most likely to take place. It will also add to the baseline dataset.	High
Drilling of additional bores to investigate the geology immediately beneath the alluvium, and the hydraulic connection between the alluvium and hard rock units.	This is a major uncertainty due to the limited data currently available. Drilling of the holes will provide data by which the geological model can be validated / refined in these critical areas. Monitoring and test pumping on these bores will provide hydraulic connection data.	High
Groundwater quality sampling	There is no systematic collection of water quality samples across the catchment and there is not enough data to fully characterise or model the system. This needs to be addressed.	High
Detailed sub-catchment scale investigation of runoff / recharge processes	To reduce uncertainty in the direct impacts of open-cut mines on these processes. Catchments around Upper Namoi Alluvium Management Zones 7 and 11 would be the highest priority.	High
Vibrating wire piezometer transects in and adjacent to Upper Namoi Alluvium Management Zones 7 and 11	These are the alluvial resources predicted to be at high risk from developments that are approved or possible. Much of the risk is assessed to come from uncertainties associated with the processes occurring here and the investigation would reduce this uncertainty.	High
Surface water quality sampling	More rigorous sampling upstream and downstream of coal mine or CSG discharge sites to properly characterise the baseline hydrochemistry of the receiving waters and the discharges themselves	Moderate
Comparison of model set-up to updates of the Office of Water models	An opportunity to assess the model and predictions against more focused models.	Moderate
Geophysical logging of boreholes drilled as part of the Study recommendations	This will provide lithological, storage, geomechanical, fracturing and stress regime data for the hard rock formations and potentially increase the understanding of hydraulic connection.	Moderate
Hydraulic testing of soil parameters	Increase confidence in or refine the Hydrologic Model inputs and predictions	Moderate
Quality check all existing surface water gauging sites	Allow comprehensive use of data in model and reduce uncertainties in data	Moderate
Drilling of additional monitoring bores in Upper Namoi Zones 6, 10 and 4	These alluvial zones currently have areas with little groundwater level data. The new bores will provide this and complement the baseline dataset.	Low (Zones 6 and 10) Moderate (Zone 4)
Flow accretion surveys on streams	To better understand which streams are particularly well connected to the groundwater system	Low
Additional permanent gauging stations on streams	Surface water flows are not well characterised on the smaller streams and these are the sites which could most be affected by any future developments. Sites need to be chosen based on proximity to actual and/or potential CSG or mining developments.	Low

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7 IMPACT MITIGATION AND MANAGEMENT

7.1 Introduction

The Study has shown that there are a number of potential impacts on water resources associated with coal mining and CSG development. This section details possible options for mitigation and management of potential impacts on the water resources within the Namoi catchment. A summary of the type and magnitude of predicted impacts is presented, along with some discussion of the measures being implemented or recommended in comparable situations and environments.

In order to fully understand the discussion it is worthwhile to develop a few key definitions:

- A risk is defined as the probability that a particular impact will occur multiplied by its consequence.
- The prevention of a risk reduces its probability.
- The mitigation of a risk reduces the severity of the consequence (impact).

In the context of this discussion, mitigation is the action of reducing the severity or seriousness of a negative impact. The discussion will also consider prevention, i.e. measures that can be taken to reduce the risk of impacts occurring therefore minimising the need for mitigation.

The discussion is limited to impacts occurring from mining and CSG activities and mitigation of these rather than mitigation of impacts originating from existing anthropogenic activities such as irrigation abstraction, agrochemical application, etc. It is important to note that impacts caused by mining and CSG activities happening in the same space may combine to form a cumulative impact. The identification and mitigation plan for any impact needs to be addressed by local site scale investigations to identify the actual cause(s), and which industry and operator should take responsibility.

7.2 Impact types

In general terms the following key impacts are possible;

- Water quantity / availability
    - Reduction in groundwater levels at specific points where a resource is utilised, i.e. a well or bore or spring.
    - Regional reduction in groundwater levels within an aquifer leading to reduced baseflow to streams.

  - Reduction in stream flow by a direct abstraction – this will have different consequences whether it occurs in a regulated / unregulated stream.

- Water quality
  - Compromised groundwater quality. The change in water quality could result in the water being unsuitable for the intended use or degrade the natural system that it sustains.
  - Compromised surface water quality. The change in water quality could result in the water being unsuitable for the intended use or degrade the natural system that it sustains.

The numerical modelling has shown that there is the potential for these types of impact to occur within the catchment. Based on the scenario of extensive future coal resource development (Scenario 3), key predictions are:

1. Groundwater levels in the Gunnedah Basin and Oxley Basin Management Areas are likely to be reduced by over 5 m. Depending on the development specifics the impacts may be seen locally or be more widespread within these areas.
2. Groundwater levels in small areas within some of the Upper Namoi Alluvium Management Zones may be reduced by more than 2 m.
3. Under high development scenarios, and depending on the location of mines and CSG wells, reduction in groundwater levels may occur that are greater than Queensland trigger levels. These impacts would therefore require mitigation to reduce them to more acceptable levels.
4. Groundwater quality may be reduced in the Gunnedah Formation of the Upper Namoi Alluvium by drawdown of lower quality water from the Narrabri Formation that sits above it.
5. Groundwater quality may be impacted by incidents during CSG drilling and operations and mining operations. This includes spills and leaks from surface infrastructure and operations. Although this has not been modelled and cannot be predicted, the potential is significant.
6. Long term development of the coal and gas resource could lead to a reduction in surface water flow in the Namoi River near Narrabri of about 2%. Whilst this percentage is low, this equates to a relatively high volume of water, equivalent to about half the current surface water utilisation volume.
7. Surface water quality may also be impacted by spills and leaks from surface infrastructure and operations associated with CSG and mining projects. Again, this has not been modelled and cannot be predicted, the potential is significant.

7.3 Risk reduction

Prevention of an impact is often more effective than mitigation. The ultimate prevention is not to undertake the activity at all. Assuming that the activity is already occurring then in quantity terms (i.e. aquifer pressure reductions and surface water flow reductions) the options for prevention are limited. CSG production requires that water pressure in the coal seam is removed in order to release gas so a large reduction in pumping rate is not feasible for efficient gas production. Water is a waste product in a CSG abstraction and represents a cost, so where possible operators will design well completions to optimise gas removal and decrease water production. The most effective prevention strategy therefore relies on the operators acting in their own interest and minimising water production to reduce their costs.

The same is true for mines, both open-cut and underground. Groundwater will seep into the voids due to the pressure gradients developed when maintaining dry workings. In some mining operations, groundwater can be largely excluded by grouting or ground freezing, but such examples are very technically specific and the required conditions are unlikely to be present or the economics feasible in this setting. As with the CSG scenario, water collection, treatment, and disposal is a cost to the coal mines and it is in the operator's best interest to minimise inflows and pumping.

Surface water will also have to be managed, especially runoff, and cannot necessarily be diverted into the nearest stream.

Typical prevention measures to protect water quality include:

- Separation of flows and storages into contact (impacted) and non-contact (not impacted) systems.
- Good regulation and oversight to make sure that there are no unauthorised impacts.
- Robust monitoring to identify early impacts.
- Ensuring that water management and environmental plans are comprehensive and properly implemented.
- Using the best available and economically feasible technology to manage and treat water.
- Review local groundwater conditions when identifying sites for the installation of underground infrastructure (e.g. gathering lines) (Coffey, 2012).
- Review local geographical, groundwater, and hydrological conditions when identifying sites for the installation of water storage dams, treated water facilities and associated brine storage facilities, production facilities and related storage areas (Coffey, 2012).
- Following cases of leaching lubricants, chemicals and stored water - implement make-good provisions, cap leaks and repair infrastructure.
- Use appropriate and permitted drilling fluids.

There are several engineering options for minimising the risk of water quality issues. These include ensuring all production and dewatering bores, pipelines, monitoring bores, dams and facilities are constructed in accordance with the appropriate standards, legislation and industry best practices. For monitoring wells this means in accordance with the Minimum Construction Requirements for Water Bores in Australia (NWC, 2012). Also closure provision need to be made to plug and abandon all sub-surface infrastructure at the end of site operations.

All of these aspects are usually covered in the environmental approvals and environmental management plan for a specific operation. Part of this process involves delineating a minimum safe distance between site excavations, surface infrastructure, abstraction wells etc and nearby vulnerable water resources. This is popularly known as a "buffer zone", beyond which any impacts are predicted to be acceptable. Buffer zones are an important component of risk minimisation and therefore also project planning. The practice is therefore encouraged, although, as the details of the zone will vary from location to location it is not appropriate to provide a "one size fits all" assessment here.

7.4 Baseline data

The establishment of a baseline dataset is paramount to the mitigation of potential issues. Effective impact mitigation is reliant on having a comprehensive baseline dataset for both water quantity and quality so that impacts can be defined, tracked and effective and timely mitigation methodologies put in place. Without that comprehensive dataset it is very difficult to even identify whether an impact has occurred. The expansion of monitoring networks as activity increases provides additional information to allow the recalibration of models. Monitoring provides the first evidence of change to the natural state. Early detection can significantly enhance the effectiveness of any mitigation works. Section 6 of this report outlines the recommended Monitoring Plan.

Assuming that the baseline dataset exists then there needs to be agreed trigger levels for each component. What water level decline is acceptable, and what isn’t; what water quality is acceptable and what isn’t. Trigger levels are necessary because it may be that impacts are inevitable, but a judgement needs to be made as to when an impact requires mitigation. Trigger levels must be placed in the context of natural and cyclic variations in the data; there is no need to characterise a measurement as an impact if it is part of a continuing trend. Again this highlights the importance of the baseline monitoring.

7.5 Impact mitigation

Mining and CSG operations generally occupy different spatial scales. Impacts generated from them will be site specific and local but, as has been shown with the modelling, when numerous developments occur within the same timeframe impacts can become additive (cumulative). This will need to be considered by regulators.

An important part of mitigation will be the prediction of the location and magnitude of potential impacts. The Model produced as part of the Study and other local-scale models produced in support of coal and gas development proposals are part of that process. It will be very important to revisit these predictions on a regular basis however, especially in the vicinity of new developments, so that the accuracy of predictions can be assessed. If the models on which these predicted impacts are based show a divergence from what is observed then the development plans and project management will have to be re-evaluated.

Each operation and impact will be site specific and mitigation needs to be agreed and implemented in that context. However, some general principles for mitigation of each impact type are outlined below:

Alluvial aquifer & hard rock groundwater levels

- Increase monitoring frequency; carry out a review of all available data.
- Confirm that declining levels are due to the specified activity and whether trigger levels are predicted to be exceeded.
- Review groundwater use and identify potential alternatives for both specific users and or the environment. This may include make good provision, alternate supplies or flow replacement.
- Where trigger levels are exceeded, implement make-good provisions such as:
    - substitute users original requirements with water from other source
    - deepen existing wells and/or lower pumps.
- Test boreholes for integrity - in the event of a failed test rehabilitate or decommission these wells.

Impacts resulting from groundwater abstraction associated with CSG developments may be mitigated by ad-hoc management of CSG production wells (i.e. closely managing the abstraction rate). This is only likely to be effective however in controlling very localised, short-term or unexpected impacts as the longer term impacts (in the alluvium for example) will occur many years after production has ceased.

Surface water flows

For regulated reaches the most feasible option is to 'make good' flows by additional dam releases. If this is not possible due to dam operating rules or competing interests then make good arrangements can also include discharges of comparable quality water by CSG / mining operators into rivers. This can be discharge of treated process water from the operation or by a specific water management scheme constructed to support the stream. A further alternative would be buy back of water allocations to cover for the losses.

On unregulated reaches the dam release option is not available so the only make good arrangements are the discharge of comparable quality water by CSG / mining operators into rivers and allocation buy back. This may be more achievable in unregulated streams where flow volumes are lower than the regulated streams. It is also likely to be easier to associate an impact with an individual operation on these stretches. Again discharges can be release of treated process water from the operation or by a specific water management scheme constructed to support the stream.

Groundwater quality

The first step is to increase monitoring frequency and investigate the causes of the deterioration to ensure that the source and responsibility is appropriately assigned. It is often not possible to remediate a groundwater system if there are unacceptable and extensive water quality impacts. When the source of an impact is removed then a groundwater system will often recover over time so careful investigation and site specific measures are needed. However, where specific sources e.g. abstraction bores are affected then possible measures include alternate supplies and or treatment of the affected water. It may also be possible to improve water quality over a small area through injection of higher quality water into the affected area.

Surface water quality

Accidental or emergency discharges are managed as part of an operator's environmental management and emergency plans and as part of the Environmental Protection Licence to operate. A pollution incident, such as a tailings dam overflow is required to be reported if there is a risk of 'material harm to the environment' which is defined in section 147 of the NSW Protection of the Environment Legislation Amendment Act 2011 (NSW Government, 2011). For each monitoring or discharge point the concentration of a pollutant discharged must not exceed the concentration limits specified for that pollutant in the Environmental Protection Licence to operate.

If surface water quality impacts can be attributed to a specific source or discharge the mitigation is most easily achieved by requiring the operator to change procedures and discharge in accordance with their permits and environmental management plan. For serious and negligent actions sanctions include fines and or other legal penalties under environmental legislation.

Where there are impacts from a more general or regional source, i.e. varying surface water quality due to deterioration in the quality of groundwater baseflow, then an investigation is first required to identify causes and assign responsibility. Potential mitigation measures include dilution with water of acceptable quality, the provision of alternate supplies and or treatment of affected water supply sources.

7.6 Treatment, re-injection and beneficial use

In plans for CSG operations in Queensland operators are generally proposing to treat the majority of produced water by reverse osmosis (RO). Efficient RO plants can convert over 90% of their output to very fresh water (permeate), with the remainder being highly concentrated brine. Management options for the permeate include provision of supply for aquaculture, mineral processing, dust suppression, industrial and manufacturing, irrigation and livestock water, or surface water (watercourse) augmentation. However, the State Government has communicated a preference for injection of associated water or treated associated water streams to aquifers in a manner which will maintain or improve insitu groundwater quality and pressures (DERM, 2010). Assuming that this will also be the case in New South Wales then up to 90% of abstracted water could be returned to the local or regional water environment. This will enhance mitigation in a number of ways:

- Direct injection of treated water to alluvial and hard rock units will alleviate the impacts of existing abstractions as well as CSG and mining abstractions.
- Virtual injection (the allocation of water to irrigators) will replace some irrigation abstractions allowing water levels to recover for a time.
- The introduction of high quality water into the system will moderate any existing deterioration of water quality.

The other key policy item is beneficial use where water will be treated to an appropriate standard where it can be used in agriculture, industry or potable supply.

The treatment and management of produced water represents the key mitigation of CSG impacts whereby saline water is abstracted, treated and either returned to the environment or used in place of existing fresh water abstractions. This assists in allowing the fresh groundwater system to recover from pre-existing impacts while the CSG operations are ongoing.

7.7 Australian mitigation examples

The best examples of specific mitigation measures are to be found in other parts of Australia where coal mining and CSG are more mature. The State Government in Queensland has set water level trigger levels for impacts from CSG activities to bores and springs under the Water Act (QLD) 2000. These are defined as (QLD Government, 2012):

- *Bore trigger threshold*
  a decline in the water level in the aquifer that is:
    - (a) if a regulation prescribes the bore trigger threshold for an area in which the aquifer is situated the prescribed threshold for the area; or
    - (b) otherwise
        - (i) for a consolidated aquifer – 5 m; or
        - (ii) for an unconsolidated aquifer – 2 m.

- *Spring trigger threshold*
  a decline in the water level of the aquifer that is:

  (a) if a regulation prescribes the threshold for a particular area the prescribed threshold for the area; or

  (b) otherwise – 0.2 m.

Surface water and groundwater quality trigger values are generally set from the relevant limits and standards set by a regulatory body for a particular water use e.g. stock, domestic, biodiversity. In Australia the applicable standards can be found in the ANZECC Guidelines (ANZECC, 2000).

The four major CSG operators in Queensland have documented their mitigation and management plans in their EIS documents. The identified mitigation actions are common to all four operators and are:

- Increase monitoring frequency.
- Increase monitoring locations.
- Develop improved procedures.
- Review reliance on groundwater and potential alternatives.
- Decommission, repair or convert infrastructure and wells if issues are detected.
- Re-run modelling scenarios based on new information.
- Secondary containment (bunds) for hazardous material storage.

In coal mining, numerous coal mine operators have documented mitigation and management plans as part of the approval and permitting process. Two examples from the Hunter Valley NSW are summarised below.

1. <u>Beltana No.1 Project.</u> Bulga Coal Management Pty Limited (BCM).

   As outlined in - *Development Application (DA114-05-01) for Proposed Beltana No. 1 Coal Mine* (NSW Government, 2002a).

   This a proposed (2002) longwall mining operation in an area with an alluvial aquifer (Wollombi Brook) and a hard rock aquifer (coal measures). No mining is proposed below the alluvial aquifer.

   The key potential impacts associated with longwall mining were identified as:

   - seepage of groundwater into the underground workings;
   - changes to the groundwater levels in the hard rock aquifer;
   - changes to groundwater levels in the alluvial aquifer; and
   - changes to groundwater extraction bore yields.

Specifically, BCM indicated panel extraction may potentially depressurise inter-burden layers and coal seams for a distance of 0.5 to 1.5 km beyond the panels. BCM also noted that a potential fall in groundwater pressures may invoke a change in leakage between the alluvial aquifer systems and coal measures. The required mitigation measures included:

- Prepare, or review and update the existing Site Water Management Plan in consultation with and to the satisfaction of the relevant regulators.
- This plan to include measures for the management of the quality and quantity of groundwater, and management measures and project of potential groundwater changes during mining and post-mining.
- The requirement that the operation should not have an unacceptable impact on the beneficial use of the groundwater, measures for the protection of groundwater quality, quantity and groundwater dependent ecosystems, and the implementation of a monitoring program.
- BCM was also required to recalculate the mine water balance on 6-monthly and annual intervals, and provide these details in the annual monitoring report.

2. Ashton Coal Project. White Mining Ltd (WML)

   As outlined in Report on the - *Development Application (DA 309-11-2001-i) for Proposed Ashton Coal Project* (NSW Government, 2002b).

   Specific impacts were that this proposed (2002) open-cut and underground mine was predicted to draw down groundwater in the Glennies Creek alluvium by up to 2.5 m, the Hunter River alluvium by up to 0.5 m, and the Bowmans Creek alluvium by up to 1.3 m. To mitigate the issues identified the applicant was recommended to:

   - Prepare and implement a groundwater management plan.
   - Conduct detailed monitoring of impacts on groundwater systems throughout the mining operations.
   - Revise and update groundwater impact predictions based on monitoring data and submit for approval before each group of longwall panels was approved.
   - Conduct any mitigation works on registered bore if impacts related to the project affected use of the bore.
   - Comply with the requirements of the regulators.

7.8 Summary of mitigation options

Mitigation measures are very site specific and will vary at each location depending on local conditions. In all cases the first step towards reducing any negative trends is to identify the source of the impact. If the activity can be stopped then this will shorten the length of time required to improve conditions. Potential options for mitigation of different types of impacts are suggested in Table 7.1.

Table 7.1 Potential mitigation options for different impacts

Impacted system	Scale	Potential mitigation option
Groundwater levels – single borehole	Localised	Deepening of existing bores and/or lowering of pumps. Relocating bore abstraction to another aquifer layer. Substitution of a user requirement with water from another source e.g. surface water source or treated public water supply. Purchasing of the affected allocation by the company causing the impact.
Groundwater levels – multiple boreholes	Sub-regional	Direct injection (e.g. of treated produced CSG water) into aquifer. Virtual injection* (the allocation of treated produced CSG water directly to irrigators). Cessation of source activity. Reassess pumping regime.
Groundwater levels – near springs		
Surface water flows – regulated rivers	Sub-regional	Discharge of comparable quality water into the stream to replace the water lost through the impacting activity. Additional release from the regulating dam. Discharge from an alternative source. Purchasing of the affected allocation by the company causing the impact. Cessation of source activity. Reassess pumping regime.
Surface water flows – unregulated rivers	Sub-regional	Discharge of comparable quality water into the stream to replace the water lost through the impacting activity. Discharge from an alternative source. Purchasing of the affected allocation by the company causing the impact.
Groundwater quality	Localised	Relocating bore abstraction to another aquifer layer. Substitution of a user requirement with water from another source e.g. surface water source or treated public water supply. Purchasing of the affected allocation by the company causing the impact. Treatment of the water prior to use. Cessation of source activity. Reassess pumping regime.
Groundwater quality	Sub-regional	Injection of higher quality water into the affected area to reverse / stabilise any negative trends.
Surface water quality	Localised	Change operating procedures and ensure compliance with environmental management plans. Cessation of source activity. Substitution of a user requirement with water from another source e.g. groundwater source or treated public water supply. Treatment of the water prior to use. Purchasing of the affected allocation by the company causing the impact.
Surface water quality	Sub-regional	If there is a high baseflow component to streamflow then the options are the same as for sub-regional groundwater quality. If there is a high surface runoff component, causes of the impact should be identified and procedures changed to prevent further degradation.

* Virtual injection allows water levels in an aquifer to recover as the abstractors do not need to take as much water from the affected aquifer

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APPENDIX

Model User Manual