

Prediction scenarios

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

The Test Plan comprised seven scenarios which simulate progressively greater development of the coal resources. The specifics of the scenarios are defined in Table E.1 and the distribution of coal and gas developments simulated in Scenario 3 are illustrated in Figure E11.

As per requirement G.3.7.1f.ii of the Study Terms of Reference the scenarios are run until the year 2100. However, based on the relatively small duration of calibration data available for the models this extended prediction period will increase the uncertainty associated with the results.

Table E.1 Scenario configuration

Scenario number	Project status	Mines	Coal seam gas
0	No mining	None	None
1	Approved	Six open-cut and one underground mine	Pilot holes only
2	Approved and possible	Ten open-cut and two underground mines	2 fields
3	Exploratory long term	Twenty four open-cut and seven underground mines	8 fields
4	Exploratory long term (mining only)	Twenty four open-cut and seven underground mines	Pilot holes only
5	Exploratory long term (CSG only)	Six open-cut and one underground mine	8 fields
6	Exploratory long term (50% of underground mining repositioned to beneath alluvium)	Twenty four open-cut and seven underground mines	8 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.

The output 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. These provide a check on the LASCAM output files to ensure that they are 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. 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 development.

- Graphs showing the change in modelled stream flow at selected gauging sites. 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. 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 (Upper Namoi Alluvium), Pilliga Sandstone, Garrawilla Volcanics, Hoskinssons Seam (within the Black Jack Formation) 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. These allow for 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. 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. 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. 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. 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.

Predictive analysis

The analysis has been designed to investigate aspects of the modelling methodology, potentially significant modelling assumptions and key (uncertain) parameter settings. 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. 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 to the alluvium) and the influence of climate change 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.

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.

Assessment of impacts

The coal and gas development simulated in Scenario 3 equates to about 60 Mtpa of coal output for a duration of about 85 years. The scenario also includes development of CSG fields over most of the Gunnedah Basin at the same time.

The analysis has shown that for this level of development the average impact on groundwater levels in some Upper Namoi Alluvium Management Zones could be in the order of 1 or 2 m. In localised areas within these zones the drawdown will be higher, and in some zones it may be over 5 m.

In the Lower Namoi Alluvium the impact is likely to be almost nothing, especially when that aquifer is considered as a whole.

The Model results have been shown to be most sensitive to under estimated vertical conductivity and overestimated storage, rainfall and horizontal hydraulic conductivity. These uncertainties could lead to higher or lower predicted impacts. This analysis has defined a range of impacts and highlighted which parameters have most control on the results.

For the most part the impacts in the sensitivity runs are in the same order of magnitude as the Scenario 3 run. Upper Namoi Alluvium Zone 7 is the most sensitive to parameter variations and the average predicted impacts range from 0.5 m to 4.7 m, with the basecase prediction at 1.1 m. The range in impacts in this zone therefore ranges from insignificant to significant in this analysis. This may demonstrate a weakness in the catchment scale modelling in terms of simulating mines in such proximity to the alluvium, as this zone is bounded by both the Shenhua and BHP simulated mines. This highlights that modelling at this scale cannot replace the need for detailed assessments as part of the individual project proposals.

The sensitivity of predictions to parameter variations is lower in the other zones.

Predicted drawdown is generally fairly insensitive to increased (doubled) abstraction associated with CSG fields. The greatest sensitivity is observed in Upper Namoi Zone 7, where average drawdown doubles from 1 m to 2 m.

In terms of predictive uncertainty, an analysis was undertaken that included availability and use of model precursors, calibration performance and data availability and numerical performance. This results in a relative estimate of prediction certainty within each of the Management Areas and Zones.

Generally those that are considered highly or moderately certain are also the ones where the highest pressures on the resources are focused, where the risks are greatest and where the impacts from coal and gas developments are also potentially (and predicted to be) greatest. A notable exception to this is Upper Namoi Zone 7.

Analysis of model predictions of impacts to groundwater flow and levels in the catchment from coal and gas development indicates that there is a potential both to negatively and positively impact groundwater quality in the alluvial systems. Increased drawdown of levels in the lower alluvium may lead to increased flow from the upper alluvial aquifer resulting in the mixing of different quality water, exacerbating a phenomenon that may already be occurring due to existing abstraction. However, the predicted reduction of flow from the (potentially lower quality) hard rock formations into the (potentially higher quality) alluvium could result in improved quality of the alluvial water resources. Without sufficient data to characterise the water quality in the systems it is currently impossible to quantify these impacts.

Other key results of the analyses are:

- Mining activities account for 50% or more of the predicted drawdown throughout the Upper Namoi Alluvium. CSG activities account for almost all of the predicted drawdown in the Lower Namoi Alluvium.
- In the most heavily utilised Management Areas and Zones the average predicted drawdown is generally less than 4% of the estimated saturated thickness in 2010.
- Groundwater recharge will be impacted by mining and CSG activities. The magnitude and manifestation of this is highly uncertain. The greatest impact in the recharge estimates comes from the removal of all recharge falling within the footprint of open-cut mines. This change to recharge has a significant impact on the predictions in several of the Upper Namoi Zones. In Upper Namoi Alluvium Zones 1, 4, 5 and 11 this accounts for between 70 and 80% of the predicted drawdown.
- Historical drawdown between 1980 and 2010 was generally between 2 and 4 m in the Lower and Upper Namoi Alluvium.
- Upper Namoi Alluvium Zones 1 and 10 are incorporated in only a handful of Groundwater Model cells. This makes predictions in these zones susceptible to localised numerical and conceptual inaccuracies.

The results of the analysis of model predictions, sensitivity and uncertainty are collated and presented in Table E2, based on Scenario 3 results. This summarises the analyses and concludes a relative severity of potential impacts from coal and gas development and a confidence in those predictions. The confidence is decided based on the relative uncertainty and sensitivity of the model in those areas. By Upper Namoi Alluvium Zone, the conclusions are:

- Zone 1. Predicted impacts are limited but show some significant sensitivity. For a number of reasons confidence in these predictions is low.
- Zones 2 and 3. Resource utilisation is very high in these zones however, predicted impacts are limited (average and maximum mostly less than 1 m) as are the sensitivity of these predictions to parameter variations. The confidence in these predictions is high.
- Zone 4. Resource utilisation is high and predicted impacts are moderate (about 1 m average drawdown). The predictions show only limited sensitivity to variations in parameters and the confidence in the predictions is high.

- Zone 5. Resource utilisation is high and predicted average impacts are moderate (0.8 m average drawdown) and localised impacts can be high. Certainty in model set-up is high but the predictions are relatively sensitive to variations in parameters. Therefore the certainty in these predictions is classed as moderate.
- Zone 6. Resource utilisation is low. Predicted impacts are limited but show some sensitivity to variations in key model settings. Uncertainty in the set-up in this zone is also high. Confidence in these predictions is therefore low.
- Zone 7. Resource utilisation is low. Predicted average impacts are moderate (1.1 m average drawdown) and localised impacts can be high. Under almost all indicators sensitivity and uncertainty in the predictions in this zone is very high therefore these predictions are also low confidence.
- Zone 8. Resource utilisation is high but predicted impacts are quite low (0.5 m average). The model set-up in this zone is classed as moderately uncertain and the predictions are moderately sensitive to parameter variations. The predictions are therefore moderately certain.
- Zone 9. Resource utilisation is low and there is no direct connection to coal bearing formations. Average impacts are low but localised maximum impacts are high. Confidence in the predictions is relatively low.
- Zone 10. Resource utilisation is low as are the predicted impacts. However due to both high sensitivity and uncertainty, these predictions are classed as low confidence.
- Zone 11. Resource utilisation is low and predicted impacts are high (average drawdown of 1.6 m). The zone is subject to moderate uncertainty and sensitivity so the predictions are classed as moderately certain.

Only very limited drawdown is predicted in the Lower Namoi Alluvium. The maximum in any one model cell is limited to 0.3 m and the average over the whole area is virtually zero. Even though no calibration of this zone was undertaken, as the parameters were based on the calibrated Lower Namoi Alluvium Model (Merrick, 2001) and the results show limited sensitivity to variations in key parameters, the predictions are considered to be relatively certain.

Changes to surface water flows caused by coal mining and CSG developments were calculated using the Hydrologic Model at selected gauging stations within the Gunnedah Basin. There are many uncertainties associated with the Model. Many of these relate to the simplifying and averaging that has to occur whilst creating the model sub-catchments and populating them with data.

Calibration of the Hydrologic Model is most certain on the main Namoi River, although the calibration could be improved as average modelled flows are higher than observed at all three stations. There is less certainty inherent in the results for the Mooki as there is less consistency of calibration. This could be related to factors such as different groundwater / surface water interaction mechanisms or the methods by which the Namoi River is regulated.

Modelled flows at the gauging stations are predicted to fall by up to nearly 2% under the current model calibration. Falls are greatest when there is more development. The results suggest that open-cut mining has the greatest influence on surface water flows, with little change being observed from both underground mining and CSG development.

Uncertainty analysis has shown the Hydrologic Model to be relatively insensitive to the parameters tested. The greatest change was observed at a single site when a drier climate scenario resulted in a predicted of flow reduction of 3.3% compared to 1.8% reduction in the calibrated model.

Table E.2 Summary of groundwater level impacts in the Namoi catchment alluvial aquifers

	Context		Average saturated thickness *	Predicted impacts						
	Resource Utilisation	Historic drawdown		Certainty	Predominant cause	Sensitivity	Maximum average	Maximum in zone	Relative Severity	Confidence
Upper Namoi Alluvium Zone 1	High	3.2 m	1	Low	Mining	High	0.2 m	0.4 m	Low	Low
Upper Namoi Alluvium Zone 2	High	2.5 m	23	Moderate	Both	Low	0.1 m	0.6 m	Low	High
Upper Namoi Alluvium Zone 3	High	6.2 m	28	High	Mining	Low	0.1 m	1.3 m	Low	High
Upper Namoi Alluvium Zone 4	High	3.2 m	25	High	Mining	Low	1.0 m	2.4 m	Moderate	High
Upper Namoi Alluvium Zone 5	High	3.6 m	26	High	Both	High	0.8 m	4.3 m	Moderate	Moderate
Upper Namoi Alluvium Zone 6	Low	1.3 m	2	Low	Both	Moderate	0.1 m	0.4 m	Low	Low
Upper Namoi Alluvium Zone 7	Low	+1.4 m	2	Low	Mining	High	1.1 m	6.1 m	High	Low
Upper Namoi Alluvium Zone 8	High	7.9 m	15	Moderate	Mining	Moderate	0.5 m	1.5 m	Moderate	Moderate
Upper Namoi Alluvium Zone 9	Low	+1.1 m	18	Low	Both	Moderate	0.5 m	6.9 m	Moderate	Low
Upper Namoi Alluvium Zone 10	Low	2.8 m	2	Low	Both	High	0.1 m	0.1 m	Low	Low
Upper Namoi Alluvium Zone 11	Low	2.2 m	10	Moderate	Mining	Moderate	1.6 m	3.8 m	High	Moderate
Lower Namoi Alluvium	Moderate / high	4.7 m	39	Moderate	CSG	Low	0.0 m	0.3 m	Low	High

Monitoring

A practical monitoring program was developed which:

- Aims to provide data for future updating and maintenance of the Model.
- Includes recommendations outlining the scope for separate follow on investigations designed to enhance the Study.

Each of the datasets used to calibrate the Model were detailed and appropriate ongoing observation measurement frequencies suggested. Investigations are also recommended that would enhance the Model by reducing uncertainty in predictive outputs. Key recommendations are that:

- Climate monitoring continues as it is at present, with no additional sites required.
- Monitoring should be continued at the surface water gauging stations used in the model on at least a daily frequency. Each site should be subject to quality assurance to ensure that uncertainties associated with the raw data are fully understood.
- Investigations are completed to look at the feasibility of adding additional permanent gauging stations on streams with catchments that are going to be disturbed by mining or CSG developments. Sites will have to be chosen based on 'added value' to the Study outcomes.
- Groundwater level data should continue to be collected at all of the sites used for Model calibration. Additional sites which currently have short datasets should be added where required to fill in calibration gaps (Figure E12).
- Additional bores are drilled in the areas shown on Figure E12 to improve the understanding of:
 - Water levels in Upper Namoi Zones 6, 10 and 4.
 - Water pressures and hydraulic data in the hard rock aquifers across the full geological sequence.
 - The interactions between the alluvium and hard rock where coal seams are at or very close to the alluvium.
- Water quality samples should be taken at a spread of locations in the alluvium and shallow and deep hard rock units. Samples should be taken quarterly for the first year, following a review of the data this may be reduced to a lower frequency or sampling suite.
- A consideration should be made to fully instrument selected sub-catchments to better improve recharge / runoff estimates over a more controllable area.

Mitigation

Although prevention of an impact is preferable to mitigation, for the sub-regional scale potential water-related impacts, options for prevention are limited. Many prevention measures to minimise smaller scale risks, especially those associated with water quality (spills, discharges etc.), do exist and these are usually included in the approvals and environmental management plan for specific operations.

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 methodologies put in place. Associated with this is the definition of appropriate trigger levels for both water quantity and quality components. These will define at what magnitude of impact the mitigation measures are activated.

In terms of groundwater quantity, mitigation options include substitution of a user requirement with water from another source, or the deepening of existing bores and/or lowering of pumps. Surface water flows can be mitigated on regulated reaches by dam releases. If this is not possible, then make good arrangements include discharges of comparable quality water by CSG / mining operators into rivers. On unregulated reaches this is the only available option.

Groundwater quality issues are more difficult to mitigate if the area involved is very large. However, where specific sources such as abstraction bores are affected then possible measures include alternate supplies and or treatment of the affected water. Where surface water quality impacts can be attributed to a specific source or discharge, mitigation is most easily achieved by changing operating procedures and ensuring compliance with environmental management plans. Where impacts result from a more general or regional source, for example varying surface water quality due to deterioration in the quality of groundwater baseflow, then it is important to first identify causes. Potential mitigation measures include dilution with water of acceptable quality, the provision of alternate supplies and / or treatment of affected water supply sources.

Re-injection of treated CSG associated water can be used to enhance mitigation in several ways, including:

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

1 INTRODUCTION

1.1 Study Background

Project Synopsis

In response to community concerns regarding the potential impacts of coal and gas mining and development in the Namoi Catchment, the then NSW Minister for Mineral and Forest Resources commissioned a study (the Study) to investigate the potential impacts on water resources in the Namoi catchment from mining and CSG activities. The Study was to consider the whole of the Namoi catchment and the long-term, cumulative effects of coal resources development on catchment water resources.

A working group of key stakeholders was established and produced a draft Terms of Reference (ToR) for the Study in May 2009.

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.

In April 2010 the Study was tendered via a Request for Tender (RfT) that was produced based on the Study ToR. In August 2010 Schlumberger Water Services (Australia) Pty Ltd (SWS) were appointed as the Independent Expert for the Study.

A Stakeholder Advisory Group (SAG) was 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.

According to the RfT, the Study would involve collation of existing and new data to investigate the risks and to support the construction of a three-dimensional physical based numerical model (the Model) of the catchment water resources that could be used to develop scenarios of mining and gas development and predict their effects.

The Model would consider all the important physical processes relating to surface water and groundwater aquifers, the interactions between flow and water quality between them and the processes relating to coal and gas development. The Model should also represent these at spatial and time scales sufficient to realistically simulate the processes while taking account of the computing power and time required for model runs.

The Study should also consider the spatial distribution of water resources in relation to the spatial distribution of coal and gas resources in their geological context.

Project Organisation

The original plan was to organise the Study into four phases to be conducted over a time period of up to 18 months. The phases were as follows:

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

Phase 1 – Scoping & 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

Completion of Phase 2 of the project was delayed by approximately 6 months while a Confidentiality Agreement was set up between the NSW Department of Trade and Investment, Regional Infrastructure and Services (DTIRIS) and the various Industry Partners. In August 2011, the revised Phase 2 report (also known as Phase 2.5), entitled “Namoi Catchment Water Study: Independent Expert, Phase 2 Report” was released. The Phase 2.5 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.

Phase 3 - Modelling

Phase 3 is the numerical modelling component and was carried out between June 2011 and December 2012. Originally the Phase 3 outputs were to comprise a Model Reference Manual and a Phase 3 report. However, these were combined into one document that describes the entire modelling process, from conceptualisation to sensitivity analysis, thus avoiding unnecessary duplication. It provides a detailed description of the Model(s) 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.

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 and 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 are 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 GSC 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.

1.2 Setting and context

The Namoi catchment covers an area of approximately 42,000 km² 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 southeast of Gunnedah, the largest being Lake Goran. There are some small lagoons and billabongs on the river flood plain.

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. They are mapped on Figure 1.3. The alluvium upstream (south) of Narrabri is collectively 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 studies.

1.3 Study requirements

To establish the methods by which each Phase of the Study was to be implemented, a detailed scoping exercise was undertaken with stakeholders. The Study Terms of Reference were a product of this. This provided the background for the Request for Tender document, specifically Section G, which specifies the

Study deliverable and requirements. As the Study progressed and an improved understanding of the study area was gained, this enabled the specific tasks to be defined with increasing detail and relevance. A summary of the study requirements, as identified in the Request for Tender and improved during each phase of work is provided in the following paragraphs.

Phase 1

An initial set of wide-ranging aims were defined 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 sources 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 2

Following the completion of initial tasks associated with Phase 2 (data collation, analysis and conceptualisation) a more comprehensive understanding of the study area was developed. As a result it was possible to define the modelling strategy in more detail. Critically, it became clear that there were fundamental differences between the characteristics of coal and CSG developments. Principally these differences are separate impact pathways, different primary environmental receptors and local versus regional scales of potential impact. Due to these and many other factors it was decided that an appropriate modelling methodology was to produce separate models to address different aspects. Those separate models were defined as:

- The GIS Model - a simplified GIS / spreadsheet based analysis of potential risks associated with coal or gas development, focusing on factors such as proximity, geology and system water balance, and providing a first pass indication of potential impacts.

- The Coal Seam Gas Model - a 3D groundwater flow model of the entire catchment west of the Hunter-Mooki Fault, incorporating all hydrogeological from ground surface to the volcanic basement.
- The Hydrologic Model - a “lumped parameter model” that simulates the hydrologic processes that control recharge to the groundwater system and runoff to the surface water system.
- The Coal Mine Model - a 3D groundwater flow model(s) of areas limited to sub-catchments within the Upper Namoi Alluvium and Gunnedah-Oxley Basins).

Phase 3

During the model construction tasks, it was found that it was possible to combine the Coal Seam Gas Model with the Coal Mine Model, without compromising the Study objectives in terms of detail of coverage and model run times. In addition, the proposed GIS based first pass risk assessment tool was not constructed as the combined Groundwater Model provided a more reliable tool which achieved all of the objectives assigned to the GIS tool with acceptable run times.

As a result, the modelling plan proposed in the Phase 2 report was modified, and the models developed in Phase 3 comprise:

- The Hydrologic Model – a lumped parameter of key surface water processes including runoff and recharge.
- The Groundwater Model – a single groundwater flow model was constructed to simulate both the effects of coal mine operation and the development of CSG operations.

In combination, the Hydrologic Model and the Groundwater Model form the Model and meet all of the objectives proposed in the Terms of Reference for the Study.

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:

- The scale of the “area of interest” (very large). Data and understanding in large study areas is often always 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).

The above key elements were critical to prioritising the development of the Model.

In addition, the scope 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 Model should not aim to replace those site specific models as the objectives, scale, data coverage and schedule of the Study do not allow for this. 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.

This, therefore, should be the focus of the Model produced for the Namoi Catchment Water Study; a set of robust tools that can provide 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.

DRAFT

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 organize 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 CGS 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 is provided below:

- The Devonian to Carboniferous strata of the New England Fold Belt are located in the eastern and south eastern 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.
- 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 overlie the consolidated Gunnedah and Surat Basin sediments. The alluvium can be over 100 m thick although this can vary depending on the depth to the top of the hard rock units present beneath the alluvium. In some locations isolated 'ridges' of harder rock occur beneath the alluvial plains.

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)

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.

In the eastern part of the Gunnedah Basin, the Boggabri Ridge separates the Maules Creek sub-basin from the main basin. The Maules Creek basin contains many of the existing coal mines. To the west, the Rocky Glen Ridge truncates the main Gunnedah basin which is further sub-divided into three smaller basins (Bellata, Mullaley and Bando) by three minor east to west trending 'basin highs'. Much of the mining and CSG activity is focused in the Mullaley Basin

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.
- 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 subdivision 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 model 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.

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

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.

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

2.3 Hydrology

Information regarding the geographical setting of the catchment and the characteristics of the surface water system was necessary to complete the development of the Hydrological 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 Chapters 3 and 8 of the Phase 2 Report and summary is provided in the following sections.

2.3.1 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 north by the elevated and rugged topography of the Nandewar Ranges and the New England Plateau and to the south and west by the Liverpool Plains and Warrumbungle Range

Extensive soils mapping has been undertaken within the catchment and has been used by the Namoi Catchment Management Authority (CMA 2011a) 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 km², 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) (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 is a series of regulating weirs within the catchment. They are designed to regulate flows and 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.

2.3.2 *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 per year in the southeast, to over 2,100 mm per year 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 GL/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%. The size of events has decreased and the average annual flood volume is now lower.

2.3.3 *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 GL/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 253.5 GL/yr. The Upper Namoi accounts for 9.7 GL/yr while the Peel catchment has 48.3 GL/yr of water allocation. Currently 115 GL/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 abstraction for each area of the catchment. Abstractions 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 **Hydrygeology**

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.

2.4.1 *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 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 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 km².

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
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
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
GAB intake beds	Recharge rates of 0.5 to 10 mm/yr estimated using chloride mass balance techniques.	GAB sustainability initiative, 2010

Table 2.3 Recharge summary table (continued)

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, 2011a
Narrabri North coal mine	Calibrated model values: Variable from 0.5% (~3 mm/yr) to 5% (~30 mm/yr) of rainfall	Aquaterra, 2009

2.4.2 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. 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 only.

An understanding of the groundwater flow directions is also important for defining flow conditions around the edges of the catchment (Boundary conditions). 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, 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. Groundwater flow in upland areas occurs mainly through fractures in the rock matrix and there are no significant aquifers. There is expected to be minimal groundwater flow across the Hunter-Mooki Fault System 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).

2.4.3 *Groundwater surface water interactions*

A thorough introduction to the principles of groundwater-surface water interaction is provided in Winter et al. (2002).

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 is 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 is high and water flows 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.

2.4.4 *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 or vertically (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 propagates 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).

2.4.5 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 provides 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 (Golders Associates 2010). From the data it can be seen that coal seam water is very different from Gunnedah 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	---	7.97	7.27
EC	µS/cm	5337	2463
TDS	mg/L	3240	1712
Calcium	mg/L	6.78	55.1
Magnesium	mg/L	8.07	84.1
Sodium	mg/L	1337	313
Potassium	mg/L	11	9.51
Bicarbonate	mg/L	3166	698
Chloride	mg/L	297	349
Sulphate	mg/L	2.56	126
Carbonate	mg/L	102	N/A

(Golder Associates, 2010)

2.4.6 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 Upper Namoi and Lower Namoi Groundwater Models are considered to be the most complete set of abstractions records as early paper records were added to the electronic dataset.

These datasets were therefore taken forward and used in the Phase 3 modelling phase in the areas which they covered.

In areas not covered by the Upper and Lower Namoi Groundwater Models the digital dataset provided by NSW Office of Water was used. However it was not possible to include every single one of the abstractions listed in the groundwater flow model and the following approach was taken:

- Sites within the hard rock systems lacking data on actual usage were omitted;
- Sites with only small sporadic abstractions were omitted;
- Sites which had an average abstraction of less than 30 ML/month or a maximum of abstraction of less than 50 ML/month were omitted;

This left a dataset of 50 abstraction sites located in the area of the hard rock system that account for 90% of the total licensed volume/abstraction. Locations of abstractions that have been used in the numerical model are shown on Figure 2.21 and the volumes abstracted are shown in Table 2.6.

Table 2.6 Groundwater abstractions

	Abstraction shares, 2009- 2010	Abstraction in 2009 ML/yr
Upper Namoi Zone 1	3,405	1,237
Upper Namoi Zone 2	10,772	11,468
Upper Namoi Zone 3	22,139	14,137
Upper Namoi Zone 4	33,875	19,950
Upper Namoi Zone 5	18,708	12,868
Upper Namoi Zone 6	11,448	563
Upper Namoi Zone 7	3,704	676
Upper Namoi Zone 8	18,935	6,647
Upper Namoi Zone 9	11,342	1,471
Upper Namoi Zone 10	1,420	3
Upper Namoi Zone 11	2,218	622
Upper Namoi Zone 12	2,774	506
Upper Namoi total	140,739	70,149
Lower Namoi	98,525	63,800
Hard rock	---	14,355

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 ~1,000 ML/month between January 2002 and December 2009. Abstraction from the alluvium over the same period averaged ~17,200 ML/month. Peak abstraction from the alluvium in the dataset reached ~45,400 ML/month in October 2002. The highest abstraction rate in the Upper and Lower Namoi models was 67,700 ML/month.

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. Coal and gas developments both interact with the water resources in the catchment, although the scales of the areas affected are likely to be significantly different.

The effects of individual mines or CSG wells are likely to be extremely localised within the catchment and 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. A summary of the groundwater modelling and water balance calculations of mines and CSG investigations is provided in Section 6 of the Phase 2 report and Section 2.9 in the Phase 3 report.

It is not the aim of this study to replace models developed for specific sites as the objectives, scale, data coverage and schedule of the Study do not allow for this. These 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.

Of more relevance to this study are the cumulative impacts from multiple mines and potentially extensive CSG wellfields. The aim of the Study is to produce a set of robust tools that can provide an indication of what magnitude and where the cumulative impacts might be within the entire catchment.

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 Formation 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, 2011a). 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	Operation		
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 target coal at up to about 300 m below ground level.

Open-pit mines are generally developed when deposits of commercial minerals or rock are found relatively close to the surface. Open pit mining usually involves blasting and removing surface layers of soil and rock to reach the deposit.

Historically underground mining used the 'bord and pillar' method in which coal was extracted from the base of a highwall (steep face) using horizontal drilling whilst pillars were left in place to support the roof from collapsing. This method has largely been replaced by the longwall mining technique that involves the mining of an extended wall (normally about 250-400 m long) of coal in a single slice (generally 1-2 m thick) (Greatmining, 2011). The roof is temporary 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).

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 but may have to be stored and treated prior to release. Underground mining may also cause subsidence of the ground surface as the cavity behind the longwall collapses. Potential impacts associated with water management and subsidence are discussed in more detail in Section 3.3.

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 focussed 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 development. 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 Formation (Hoskissons) and the Maules Creek Formation (Namoi and Bohenia) 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, 2011d).

Except for one pilot scheme operated by Santos at Kalhua, 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 Fm	Since Nov 2006 in present configuration	Three vertical wells in a straight line
Bibblewindi 9-spot	Bohena seam, Maules Creek Fm	Early 2007	Nine vertical fracture stimulated wells
Bibblewindi multi-lateral	Bohena seam, Maules Creek Fm	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 Fm	Nov 2009	Tri-lateral pilot with four vertical production wells
Tintsville	Hoskissons seam, Black Jack Group	Apr 2011	Three parallel lateral wells with three vertical production wells
Dewhurst	Bohena seam, Maules Creek Fm	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. 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 (Queensland 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 (Queensland Government, 2011).

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 surface and groundwater resources and quality. 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 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 of groundwater gradients and flow directions;
- Pit runoff water and pumped groundwater can be contaminated with suspended solids and/or dissolved minerals and metals, and needs to be treated before discharge into the local drainage system;
- Surface subsidence, a possible consequence of underground mining, this 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 surface and groundwater resources and quality. 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 water pressure that holds the gas in the coal (Parsons Brinckerhoff, 2004). This will have an effect on the groundwater system surrounding it, as groundwater will then flow towards the zone of dewatering (Parsons Brinckerhoff, 2004).

Large quantities of water 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 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 (which varies 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 can be used for irrigation through water blending or nutrient supplementation. This water treatment process is currently in use for Narrabri CSG project (Eastern Star Gas, 2006).

CSG extraction may require hydraulic fracturing in order to increase the gas recovery (Queensland Government, 2011). The process involves pumping fluid and sand, under pressure, into a coal seam. This action fractures the coal seam, which provides a pathway that increases the ability of gas to flow through the coal (Queensland Government, 2011). This activity may result in fracturing beyond the target coal seams resulting in increased connection between the seams and the surrounding groundwater systems. The chemical make-up of the fluid may also have an impact (Queensland Government, 2011).

4 NUMERICAL MODELLING

4.1 Introduction

The aim of this chapter is to provide a summary of the numerical modelling undertaken and includes:

- An outline of the modelling rationale.
- An overview of the modelling objectives.
- A review of the assumptions that have been made.
- A description of the two models (Hydrologic and Groundwater) that have been developed.
- A summary of the calibration processes used to test the accuracy of the models.
- A summary of the testing that was carried out to predict the response of the physical system to various coal and CSG development scenarios together with the results.
- A synopsis of the sensitivity and uncertainty testing of the model testing.

Numerical models are simplifications of physical systems. The physical controls on groundwater flow, surface water flow and rainfall / runoff processes are very complex and varied. These controls are often poorly understood and measurement of them can be problematic. All numerical models therefore are subject to three assumptions, uncertainties and limitations that must be understood and explored so that the model results can be used and reported appropriately. A detailed discussion of these modelling concepts is provided in Section 3 of the Phase 3 report.

Assumptions within numerical models are unavoidable given the requirement to simplify the natural system. In most cases, these assumptions are unlikely to have a major effect on model outcomes, especially at the scale of outputs required, i.e. regional to sub-regional rather than local scale. Those assumptions which do have the potential to significantly affect model outcomes were assessed and quantified with a sensitivity analysis.

Model calibration is the process by which the initial parameter and boundary condition settings used in historical numerical models are varied in order to produce a better match between model output (predictions) and the observed conditions. The aim is to improve the accuracy of the model set-up, reduce uncertainty and improve the (future) predictive capability of the model.

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 be able to:

“Allow investigation of the nature and extent of potential effects on the catchment’s water resources from coal and gas developments” and, specifically:

- Is 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.
- Accounts for the activities of the agricultural industry, resources sector and broader community.
- Generates outputs that enable quantification of the likelihood of potential effects.
- Takes no more than one day to execute.
- Models the potential effect of coal and gas development.
- Provides for the management and display of spatial data.
- Generates outputs that enable consideration of ongoing economic, environmental and social sustainability.
- Is acknowledged by the MOC as the most appropriate methodology.
- Is capable of being readily transferred to a third party.
- Is designed for reliable and efficient ongoing operation and maintenance beyond conclusion of the Study.
- Is suitable for incorporation of future data (post-Study).

4.3 Model Rationale

A 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, although based on further research and discussions with peer reviewers, the model was updated to use the LASCAM package.
- A single groundwater flow model was constructed to simulate both the effects of coal mine operation and the development of CSG operations.

4.4 Model assumptions

General assumptions associated with the Groundwater and Hydrologic Models are listed below. Most would apply to any model of this nature and are therefore not specific to this study. For the discussion below, the assumptions are grouped based on whether they are related to the numerical code itself or to the system conceptualisation.

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 valid.

- Hydraulic parameters, inputs (e.g. wells), 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 km². 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.
- If unsaturated flow is simulated with any of the models it is assumed to be 1D (vertical) flow only. This is a major simplification of unsaturated flow which is necessary to reduce the numerical demands of this type of simulation. At a regional and sub-regional scale this is unlikely to cause any major issues. Furthermore, as the focus of unsaturated flow modelling is between the stream bed and saturated groundwater this assumption is valid in the key areas of interaction.
- 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.

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:
 - Stream bed elevation and width values 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.
- 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 Hydrologic Model domain has been divided into zones within which key hydrologic parameters have been assumed to be roughly the same. The divisions have been justified based on observed data but any errors would have major impacts on model outcomes.
- The geological model has been assumed to present an accurate depiction of the sub-surface of the Namoi catchment 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, however the geological model has been subject to auditing and quality checks and there is high confidence in it.
- The development of mines (either open pit or underground) has been simulated with constant head boundary conditions configured to act as “drains”. The reference elevation has been modified at yearly or bi-yearly intervals to reflect the development of the mine. This results in the modelled mine developing in discrete stages, rather than gradually. At the regional and sub-regional scale, model results are unlikely to be particularly sensitive to this simplification.
- 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 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 has been assumed that there is no connection of “hard rock” groundwater systems across the Hunter-Mooki Fault. The assumption itself is significant and model results are sensitive to it. With insufficient data to determine whether this is valid, the assumption provides a conservative case in terms of impacts, and is appropriate.

4.5 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 km². Within this area, 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.

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.

Efforts were focussed on the processes and inputs deemed to have the greatest control on the impacts. Therefore, the priority was to accurately simulate the interactions of mine voids and CSG abstraction with the groundwater system as this was understood to have 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 mines and the majority of potential CSG abstractions are in the Upper Namoi Alluvium of the Gunnedah Basin.
- There are no coal mines located beneath 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 (losing rivers) and any decrease in groundwater level does not create a change in flow within the rivers.

Accordingly, 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.

4.6 Simulation of water quality

4.6.1 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 2 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 and into 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 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.

- Connective cracking associated with underground mines resulting in a greater connection to units above. 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 some 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 there are multiple monitoring points in one borehole (nested piezometers) there is mostly 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 numerical descriptions.

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.

Whilst 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 then the model can be used to directly investigate water quality.

4.6.2 *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. However, 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 (Mawhinney, 2011) identified that there were no significant threats to the water environment in the catchment and recommended no ongoing or urgent water quality management initiatives. A review of the latest data was also undertaken as part of Phase 2 of the Study and, showed that although there was some exceedance of trigger and guidance levels, there were no obvious significant rising or falling trends in surface water quality.

The authorised discharge of mine and CSG related water is assumed to only occur if the discharged water is of a similar or 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.

4.7 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. Hydraulic fracturing can therefore locally increase the magnitude of hydraulic parameters in the immediate well vicinity 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, is done on a well by well basis following well completion (casing, cementation, perforation, etc.).

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.

4.8 Model development

4.8.1 Hydrologic model

A lumped parameter hydrologic model (LASCAM) 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 km². This area was chosen as it includes all of the areas which could potentially be affected by coal mining, which was identified in the Phase 2 report as having the greatest potential for influencing the surface water system. 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, the inaccuracies in flow forecasting at the extremes is not considered important.

The types of output that were used to compare the predicted versus the 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).

4.8.2 Groundwater model

The MODFLOW 2000 numerical code along with the user interface Groundwater Vistas, Version 6 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 km². 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 the upper areas of the Groundwater Model were taken from the outputs of the Hydrologic Model. Where calibrated recharge values were available from existing models (Office of Water Model for the Upper Namoi Alluvium) these were used. An estimate for irrigation recharge was used as reported in Section 2.

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 (Upper Namoi Groundwater Flow Model and the Lower Namoi Alluvium Model) 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 (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 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 Tintfield 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.

4.9 Model operation

4.9.1 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 groundwater model was 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 predictive scenarios were sensitive to these variables.

4.9.2 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 Chapter 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, an 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 are 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.

4.9.3 *Predictive scenarios*

The Hydrologic and Groundwater Models were used together to investigate the potential cumulative impacts. 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 Caroonia	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 the 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.

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 2 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 (Upper Namoi Alluvium), Pilliga Sandstone, Garrawilla Volcanics, Hoskinssons Seam (within the Black Jack Formation) and Maules Creek Formation (Figure 4.22). 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.

4.9.4 *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.

- 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 to the alluvium) and the influence of climate change 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.

5 ASSESSMENT OF MODEL RESULTS

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 Namoi catchment 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. This will include an assessment of the value of the Model for the various predictive requirements and the results of this analysis will provide guidance as to where or when predictions may be most or least accurate.
- 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.

Furthermore, as so much predictive data is produced by the model, the output has to be summarised to a suitable level to allow for this analysis. This is necessary anyway and is a function of the very large scale of the Model both in spatial and temporal extents. To do this the output will be considered to the following level of detail:

- Impacts to groundwater levels will be considered by averages and maximums within Groundwater Management Areas and the Upper Namoi Groundwater Management Zones.

- Impacts to groundwater / surface water interaction will be considered along the 14 river reaches defined for the Model.
- Impacts to surface water flow will be considered against five of the gauging stations located along the main alluvial valley.
- Since water quality is not explicitly modelled, potential changes in water quality will be considered based on the conceptual model and the impacts as outlined above.

This is undertaken in the following sub-sections, first for surface water related predictions and then for groundwater related predictions. The findings are then brought together for the water resources as a whole in the final sub-section and overriding conclusions made.

The analysis is based almost entirely on Scenarios 3, 4 and 5. These provide an indication of how the impacts would manifest and migrate under long term and widespread development of the coal and gas resources. The magnitude and timing of impacts will be highly dependent on 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. Therefore the analysis is focused primarily on deriving the likelihood of impacts occurring and where they might occur. Analysis of the magnitude of potential impacts is included but the discussion is limited to what they might be and not when they might occur. Using Scenario 3 also allows for an analysis of the proportions of impacts generated by either coal mines or CSG activities (as provided by Scenarios 4 and 5).

In many of the analyses a scoring system is adopted. This is used to allow for a rapid understanding of the significance of each indicator on model predictions and for simple comparison between results in other areas and zones. It also allows for different indicators to be brought together to undertake an overall assessment of model predictions, sensitivity or uncertainty in the conclusions.

5.2 The impacts on surface water

5.2.1 Introduction

The impacts of coal mining and coal seam gas developments on surface water flows within the catchment have been assessed in both the Hydrologic Model and Groundwater Model.

One of the outputs from the Hydrologic Model is modelled daily stream flows at selected gauging stations. These outputs were used to calibrate the historical LASCAM model and were continued as output locations for the predictive models. Stream flow outputs for the various scenario and sensitivity runs were compared against basecase flows in the Phase 3 report.

The Groundwater Model has been used to predict changes in stream flow due to groundwater - surface water interaction and this is reported in Section 4.

5.2.2 Uncertainty

Uncertainty within the Model results is inherent in any modelling work. Simplifications have to be made in order to limit the computing times and file sizes. In the case of the LASCAM model the simplifications 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 within the LASCAM model is 252 km². This immediately limits the scale at which results can be reported. For each parameter 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 unrealistic to believe that a single value used over such large areas will produce a perfect fit to observed streamflows. 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 uncertainty in the modelled outcomes can be addressed by completing sensitivity runs. These assess the changes in model outputs that would result from a measured increase or decrease in key parameter values. The sensitivity analysis is discussed later in this section.

It was recognised in the Phase 3 report that there are spatial and temporal inaccuracies within the LASCAM calibration. Analysis of the calibration shows that the higher flows in the lower half of the catchment are generally over-predicted and temporally the model over-predicts flows post-2000. This was thought to be related to the exclusion of the 'complex' releases from the three main water storages within the catchment - Keepit Dam, Split Rock Dam, and Chaffey Dam. Historical releases from these dams were not available for inclusion in the model, and high uncertainties would surround any hypothetical releases made in future years as they are highly dependent on abstraction requests by downstream users. The model code is not designed to model these 'on demand' releases from storages so it would have to be re-written to allow them to be included. This is something that could potentially be investigated for any future model upgrades.

Five gauging stations have been chosen for further analysis of results in the context of this Study. These are all located along the main alluvial channel within the Gunnedah Basin (Figure 4.4). Flows at the gauging stations to the east of the Hunter-Mooki fault will not change between scenarios as there are no coal or gas developments in this area. Where possible, sub-catchment boundaries were placed to coincide with the locations of the stream gauging stations. This ensured that the actual and modelled catchment areas upstream of the gauge were similar. Of the five gauging stations, four are located close to boundaries and the fifth is located further towards the centre of the catchment. The modelled catchment area generating flow at this gauge will therefore be slightly larger than the actual area on the ground. This will lead to an additional uncertainty to the calibration of this location.

Table 5.1 summarises the model calibration for each of the five sites. This confirms that 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. The Ruvigne gauge is also not located at a sub-catchment boundary so the modelled catchment area will be slightly greater than observed.

Table 5.1 Surface water flow sites chosen for analysis

Gauging station	Site name	Years of calibration data available	Total modelled flow as % of actual flow (over available calibration period)	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	Medium
419012	Namoi River at Boggabri	1990 - 2009	174	Yes	Medium
419023	Namoi River at Turrawan	1996 - 2009	252	Yes	Medium

From Table 5.1 it can be concluded that there is a greater degree of confidence in the results from the gauges on the Namoi River.

5.2.3 Impacts

Model results from the six different scenarios were provided in Section 7 of the Phase 3 report. The Model assumes that all of the open-cut coal mines (approved, possible, and hypothetical) are operating at their full footprint area throughout the entire model run, and that all water falling within the footprint area is removed by the mine. Underground mines are also assumed to be at full footprint area for the entire model, but unlike the open-cut mines the footprint area can still receive recharge. It is assumed that 1% of the underground mine surface footprint area is susceptible to additional surface ponding due to ground subsidence. These assumptions on the life of the mines were necessary because of model coding. It will lead to an over estimation of the impacts of each development as they will assumed to be fully active for the entire 90 years of the model simulation.

CSG developments are introduced to the Model by assuming that the surface infrastructure areas become impermeable. This will reduce the area of each sub-catchment that could receive recharge, but increase runoff potential.

Time variant background parameters such as rainfall are repeated on a twenty year cycle. The Phase 3 report showed that once the Model has had time to equilibrate these repeated cycles lead to stable results over the remainder of the simulation. As there is no long term variation in outputs they have been presented as a single average value for each site.

Table 5.2 summarises the average percentage flow change from basecase for the five chosen gauging stations over the period 2010 - 2099. These values are also shown graphically on Figure 5.1.

Table 5.2 Average flow change 2010 to 2099 (% change from basecase)

	Gauging station				
	419027	419084	419001	419012	419023
Scenario 1	0.0	-0.1	-0.2	-0.1	-0.6
Scenario 2	0.0	-0.3	-0.3	-0.2	-0.7
Scenario 3	0.0	-1.3	-1.1	-1.2	-1.7
Scenario 4	0.0	-1.3	-1.1	-1.1	-1.7
Scenario 5	0.0	-0.1	-0.1	-0.1	-0.4
Scenario 6	0.0	-1.2	-1.1	-1.2	-1.7

Station 419027 is located on the Mooki River at Breeza. The only approved development above this site is the open-cut mine at Werris Creek. There are a number of possible and hypothetical coal mines located in the vicinity of the gauging station, and there is also a small corner of one of the hypothetical Narrabri CSG wellfields upstream of the gauge. The changes made within the Model to the catchment areas above this gauge are very small compared to catchment size. Baseflow changes are not incorporated into the LASCAM model so the outputs generated are a sensible conclusion for this station.

For the other gauging stations there is a pattern to the flow changes seen. The smallest changes in flow compared to basecase 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 predictive results do indicate that there will be less than a 0.5% change in flow at each of the sites due to CSG infrastructure.

Scenarios 3, 4, and 6 include approved, possible, and hypothetical mines. These scenarios 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. Changes in flow range from approximately 1 to 2% reductions compared to modelled basecase.

5.2.4 Context – In relation to other pressures

The surface water resource is utilised by a diverse range of stakeholders. Surface waters along the Namoi and Peel Rivers are regulated below the three large dams to primarily support irrigation water supplies. The dams also act as flood mitigation, storing water from heavy rainfall events and damping out the downstream responses to them. The stored water is then released throughout the year as requested by downstream users – a combination of high and general security users which includes irrigators. Water is also released for environmental reasons to keep the main river flow above a prescribed minimum value at Walgett (gauging station number 419091). In June, July and August this flow has been set at 75% of the natural 95th percentile daily flow, unless the combined storage of the Keepit and Split Rock Dams is below 120,000 ML (NSW DIPNR, 2004a), this equates to approximately 21 ML/d in June, 24 ML/d in July, and 17 ML/d in August (NSW DWE, 2008). Two replenishment flows, to provide visible flow for 5 or more consecutive days, are also required on the Pian Creek at Waminda gauge (419049) within the Lower Namoi management area each year.

A Water Sharing Plan for the regulated Namoi River below Split Rock Dam was put in place in 2004. Long term annual average extraction limits (LTAAEL) of 238,000 ML/yr have been set for the regulated river (NSW DIPNR, 2004a). Historical abstraction is above this limit in the Lower Namoi Regulated River, which stretches from the Keepit Dam outflow to Walgett. Supplementary abstraction licences have been allocated to

temporarily cover this additional allocation but these are being reduced to zero over the 10 year life of the plan to bring total allocated abstraction down to sustainable levels (NSW DIPNR, 2004a). It can therefore be inferred that the regulated surface water resources of the catchment are fully allocated using current criteria.

A Water Sharing Plan has also been prepared for the unregulated Phillips Creek, Mooki River, Quirindi Creek and Warrah Creek areas. These are all regarded as stressed rivers, meaning that potential extraction by water users is high compared to the natural flows, and if all extractors were to pump at the same time there would not be enough water for all existing extractors and the environmental needs of the rivers (NSW DIPNR, 2004b). It can therefore be assumed that the surface water resources in this area of the catchment are also fully allocated using current criteria and any reduction in flows would impact current users.

Although water resources are fully allocated in large areas of the catchment this does not mean that water is not available. Licence trading can occur and a number of pre-existing water allocations have been bought by several of the approved and possible mines within the catchment to secure water for future needs. Maules Creek mine, for example, bought 3,000 units of regulated river surface water entitlement in May 2010. The licence was originally granted for irrigation purposes, requiring the mine to apply for a change of purpose to mining and industrial use before it could be utilised for the development (Hansen Bailey, 2011a).

Shenhua have also noted that sufficient share components will have to be acquired from the market prior to the taking of any water from any source to which the Water Management Act applies for their Watermark project (Hansen Bailey 2011b).

5.2.5 Sensitivity

Scenario models are carried out using the same baseline parameters as the calibrated historical model. As previously mentioned these parameters would in reality be a continuum of values rather than one single value. To determine if any of the averaging processes used to generate the calibrated model values have a significant effect on model outcomes the Model was tested using sensitivity analyses.

Seven additional model pairs were run to look at the sensitivity of model outputs to changes in the Hydrologic Model parameters. The same parameter was changed in both the Scenario 0 and Scenario 3 models each time, the calculated difference between the two models was taken as the change caused by each parameter. Table 5.3 and Figure 5.2 summarises the results of these sensitivities. The table also includes the change predicted for Scenario 3 using the calibrated model. Results are a summary of the changes between 2040 and the end of the Model. This period was chosen as some of the models took several years to stabilise. All models were all on a stable trend by 2040. Changes in flow outputs from the sensitivity models are very similar to those seen in the calibrated Scenario 3 model (a maximum difference of 1.5%). 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.

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

	Gauging station				
	419027	419084	419001	419012	419023
Scenario 3	0.0	-1.4	-1.2	-1.3	-1.8
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

5.3 Groundwater / surface water interaction

5.3.1 Introduction

The Groundwater Model simulates the interaction between surface water carried in rivers and streams and the groundwater system. The interaction can occur in the following two ways and both are simulated:

- as baseflow (water entering the river from groundwater) if the groundwater level is higher than the water level in the river, or
- as river leakage (water leaving the river and entering the groundwater system) if the groundwater level is beneath the river water level.

The degree to which this interaction occurs is controlled by the gradient between the groundwater and surface water levels and the hydraulic characteristics of the river bed material and the material between the river bed and the groundwater. The latter is known as the connection and rivers can be categorised into poorly connected (limited interaction potential), variably or moderately connected (high interaction potential in some lengths, low in others or moderate potential along the full length) and well connected (high interaction potential).

Reductions in groundwater level will have the effect of reducing the baseflow and increasing the river leakage (if connection to the river exists). Both will result in less flow in the river. Therefore, for simplification, in some of the analysis below, the impacts are summed to provide a “reduction in interaction flow” which equates to the reduction in river flow due to impacts on groundwater levels.

The interaction impacts will be analysed in the following order:

1. Uncertainty. An assessment of model limitations, calibration opportunity etc.
2. Results. The variation in magnitude and spatial distribution of impacts.
3. Context. What the results mean in terms of observed flows or existing pressures on the resource.
4. Sensitivity. The sensitivity of predictions to changes in key inputs or model parameters.

5.3.2 Uncertainty

River reach settings

Due to the size of the Model the domain encompasses existing models that have been developed, calibrated and improved over many years. The most significant and relevant models to the Study is the Upper Namoi Groundwater Model (McNeilage, 2006). Where possible the settings of river boundary conditions used in these models (river bed and water elevations, conductance etc.) have been incorporated directly in the Groundwater Model. Table 5.4 outlines the river reaches covered by the existing Upper Namoi Groundwater Model and those that are not.

Table 5.4 Heritage of modelled river reaches

Reach	Based on previous model	Heritage score 1 = low 2 = medium 3 = high
1	Yes	3
2	Yes	3
3	Yes	3
4	Partially	2
5	Yes	3
6	Yes	3
7	Yes	3
8	No	1
9	No	1
10	No	1
11	No	1
12	No	1
13	No	1
14	No	1

Where river reaches were not, or 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. However, due to the scale of the model, the scale of the Study and the schedule, improving the calibration and further testing simulated river behaviour in the Groundwater Model was not possible. Therefore predictions of the interaction in the river reaches not based on existing model settings is more uncertain than those that are.

Interaction type

In order to put the predicted impacts on groundwater / surface water into context, the amount of flow associated with the interaction and the interaction type (baseflow / river leakage) must be defined. This is provided for each simulated river reach in Table 5.5 and Figure 5.3 and is derived from the average predictions for each reach in 2030, 2060 and 2100 in the Scenario 0 model (i.e. with no mining or CSG development).

Table 5.5 Type and magnitude of simulated groundwater / surface water interaction (no mining or CSG development)

Reach	Flow volume	Average interaction flow (m ³ /d)	Dominant behaviour
1	High	19,000	Variable
2	Low	200	River leakage
3	Low	600	River leakage
4	High	48,000	Baseflow
5	Moderate	2,500	Baseflow
6	Moderate	2,000	Baseflow
7	Moderate	3,700	River leakage
8	High	11,000	Baseflow
9	High	11,000	Baseflow
10	High	10,000	Baseflow
11	Moderate	2,500	Variable
12	Moderate	2,700	Baseflow
13	Low	600	River leakage
14	Moderate	2,400	Baseflow

The analysis shows that there are three main categories of reach in terms of the average interaction flow volume in the no mining or gas development condition:

- Low interaction flow reaches with simulated flows measured in hundreds of cubic metres per day. These are disconnected reaches with little interaction potential with the groundwater system.
- Moderate interaction flow reaches with simulated flows in the region of 2,000 to 3,000 m³/d. These are either fairly short reaches with a good connection to the groundwater system or longer reaches that show a variable connection.
- High interaction flow reaches with simulated flows above 10,000 m³/d. These reaches show a good connection to the groundwater system.

The lowest flow is simulated in Reach 2 at 200 m³/d and the highest in Reach 4 at 48,000 m³/d. In terms of flow volume therefore, there is significant variability.

In terms of the type of interaction, in all of the high flow reaches apart from Reach 1, the dominant contribution is from baseflow. In Reach 1 it is from both baseflow and river leakage. Most of the moderate flow reaches are also dominated by baseflow. 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).

5.3.3 Impacts (Scenario 3)

The predicted impacts on groundwater and surface water interaction in the Scenario 3 model, as compared with the Scenario 0 model results (Table 5.5, Fig 5a), are summarised in Table 5.6 and Figures 5.4a to 5.4c. Included in the table is an indication of what magnitude the flow interaction is simulated to change by (in comparison with Scenario 0) along each reach.

Table 5.6 Impacts of coal and gas development on groundwater / surface water interaction (Scenario 3)

Reach	Flow volume	Predicted reduction on interaction flow (%)			
		2030	2060	2100	Maximum
5	Moderate	7	12	18	18
3	Low	0	1	14	14
12	Moderate	6	9	8	9
7	Moderate	0	3	8	8
13	Low	1	6	6	6
1	High	5	4	5	5
2	Low	0	0	4	4
4	High	0	1	2	2
6	Moderate	0	1	2	2
8	High	0	1	1	1
11	Moderate	1	1	1	1
9	High	0	0	0	0
10	High	0	0	0	0
14	Moderate	0	0	0	0

The analysis shows the following:

- The most significant reaches in terms of the proportion of flow impacted are 3 and 5 where the 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 m³/d). This reduction therefore equates to about 350 m³/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 m³/d this equates to a loss of 950 m³/d from the river.
- The maximum impact on Reaches 8, 9, 10, 11 and 14 is less than 1%.

In the majority of cases the maximum impact on groundwater / surface water interaction occurs at the end of the simulation.

Table 5.7 shows what proportion of the total interaction impacts come from reductions in either baseflow or river leakage. These are based on the average prediction from 2030, 2060 and 2100.

Table 5.7 Baseflow and river leakage components of predicted impacts on interaction flows (Scenario 3)

Reach	Average reduction in flow (m ³ /d)	Baseflow (%)	River leakage (%)	Baseflow (m ³ /d)	River leakage (m ³ /d)
1	955	77	23	735	220
2	0	0	100	0	0
3	40	59	41	24	16
4	520	79	21	411	109
5	311	75	25	233	78
6	23	68	32	16	7
7	150	45	55	68	83
8	101	86	14	87	14
9	27	98	2	26	1
10	10	72	28	7	3
11	27	90	10	24	3
12	210	90	10	189	21
13	27	98	2	26	1
14	0	100	0	0	0
Total	2,401	-	-	1,846	555

The data shows that for most simulated reaches the predominant impact is on baseflow. Only along Reaches 3 and 7 are they derived from less than about 70% from the baseflow contribution and only in Reach 7 is it less than 50%. Along Reach 2 the impact is 100% from an increase in river leakage, but the impact is virtually zero in terms of a measureable flow.

The predominant impact therefore, whether measured as a proportion of the total or flow, is on the baseflow component of groundwater / surface water interaction.

Although the situation is complex, 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.

To what extent this may be an issue is demonstrated in Table 5.8. This shows the range of measured flows in the Narrabri River at the Narrabri gauging station. The 14 simulated river reaches in the Groundwater Model all flow to this point. Therefore the impacts predicted at each of these will be combined at this location. This provides an opportunity to compare the predictions against measured flows and provides an indication of the consequences for the Lower Namoi River system and the management of dam releases to compensate any impacts.

Table 5.8 Flow statistics and Scenario 3 impacts for the Namoi River at Narrabri

	ML/yr	m ³ /d	Reduction in interaction flow	
			m ³ /d	% of measured river flow
Median	403,500	1,104,723	2,401	0.2%
Mean	629,000	1,722,108	2,401	0.1%
Min	19,000	52,019	2,401	4.6%
Max	3,624,000	9,921,971	2,401	0.0%

(after Thoms et al., 1999)

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 nearly 5% of the total flow.

Water quality

The analysis above shows that most predicted impacts are on baseflow, or in other words water leaving the groundwater system and entering the rivers and that the impacts are generally low when compared to the total interaction flows and very low when compared to average river flows.

At this level of analysis therefore it is not apparent that there is any major opportunity for groundwater quality or surface water quality to be impacted adversely by this pathway.

5.3.4 *Sensitivity*

The sensitivity of predictions of impacts to groundwater / surface water interaction is illustrated in Figures 5.5, 5.6 and 5.7. The plots show the maximum sensitivity displayed in each reach, both increases and decreases to the predicted impact and the parameter or setting change that caused it. The analysis shows that:

- Reaches 11 and 12 are the most sensitive to the doubling of CSG associated water production with about 25 and 10% extra impact predicted. The other reaches are less sensitive, generally experiencing less than a 5% increase in impacts.
- Rainfall (groundwater recharge) has a very significant control on the predicted impacts along Reach 3 and less so along Reaches 5 and 6.
- Rainfall has virtually no control on the predictions along Reaches 4, 8, 9, 10, 11, 13 and 14.
- The sensitivity of interaction impact predictions to parameter properties is dominated by Hydraulic conductivity. For many of the reaches the change results in an increase in predicted impacts of between 20 and 40%.

5.3.5 *Conclusions*

The average reduction in interaction flow predicted along each of the river reaches included in the Groundwater Model is provided in Table 5.9 along with an assessment of the confidence in these predictions that is based on the discussion above.

Table 5.9 Summary of predicted impacts on groundwater / surface water interaction

Reach	Maximum reduction on flow (% of total interaction flow)	Average reduction in flow (m ³ /d)	Confidence score 3 = high 2 = moderate 1 = low
1	5	955	3
2	4	0	3
3	14	40	3
4	2	520	2
5	18	311	3
6	2	23	3
7	8	150	3
8	1	101	1
9	0	27	1
10	0	10	1
11	1	27	1
12	9	210	1
13	6	27	1
14	0	0	1
Total		2,401	

The main impacts in terms of absolute flow reduction are seen in Reaches 1, 4 and 5. The data shows that over 80% of the predicted reduction in flow occurs along river reaches that are classified as being of either moderate or high confidence (based on whether or not model settings were derived from existing calibrated models or not).

There are other uncertainties however that may be significant but are much harder to quantify at this scale of analysis. The interaction process is very intricate and there are feedback mechanisms operating which are not incorporated in MODFLOW. Furthermore the river levels are not explicitly simulated and have been estimated for the period 2010 to 2100 from historical levels.

However as the predictions will be heavily dependent on where the mines and CSG fields are being developed (i.e. location and schedule) and the precise water levels in the rivers and groundwater system, analysis to a level of detail greater than reported here is beyond what is possible. This is also why an analysis based on the average impacts over the prediction time, rather than impacts at any one time, are more appropriate.

The sensitivity of interaction impact predictions to 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 rainfall, but the increases in predicted impacts are all less than about 50% of the Scenario 3 case. The results do not suggest that there is any significant potential for impacts on groundwater / surface water interaction to impact either groundwater or surface water quality. The flows involved are very small relative to the total flows in the river system.

5.4 The impacts on groundwater

5.4.1 Introduction

The impacts of mining and coal seam gas development on the groundwater levels in the Namoi catchment will be assessed to a regional and sub-regional scale, i.e. to the level of Management Area and Upper Namoi Management Zone. The primary model output that will be used to assess these impacts and the sensitivities associated with them will be the predicted drawdown contours which were produced in Layer 2 of the Groundwater Model. This model layer represents the Gunnedah Formation of the Upper Namoi Alluvium and the entirety of the Lower Namoi Alluvium. This output was produced at model times equivalent to the years 2030, 2060 and 2100.

The assessment of uncertainty will also use this data but will rely more heavily on qualitative assessments of the model capability and performance based on modelling experience and calibration robustness.

The significance of uncertainty, context and sensitivity indicators will be ranked based on a simple scoring system. These can provide a rapid assessment of the variability of each indicator and can be brought together when developing conclusions on overall model sensitivity and uncertainty.

5.4.2 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 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, nor the thickness of those coal seams, but the depth to the potential for coal seams of any thickness. Furthermore the data does not provide any indication on the economic potential of the coal or the gas contained within them.

The proximity analysis is summarised in the following forms:

- Table 5.10 provides the summaries by Upper Namoi Alluvium Zones and for the Lower Namoi Alluvium Management Area. Based on the criteria above, a 'proximity score' has also been assigned to the assessment zones.
- Figure 5.8 displays the regional relationship between the groundwater resources and the coal bearing formations

Table 5.10 Proximity of coal bearing formations to Namoi catchment groundwater resources

Groundwater Management Area or Zone	Minimum depth to seam, (m)	Average depth to seam, (m)	% of zone vertically underlain by seam	Proximity score 1 = low 2 = medium / variable 3 = high
Upper Namoi Alluvium Zone 1	2	31	100	3
Upper Namoi Alluvium Zone 2	0	176	100	3
Upper Namoi Alluvium Zone 3	0	129	50	2
Upper Namoi Alluvium Zone 4	0	25	80	3
Upper Namoi Alluvium Zone 5	0	135	70	3
Upper Namoi Alluvium Zone 6	54	347	100	1
Upper Namoi Alluvium Zone 7	0	132	100	3
Upper Namoi Alluvium Zone 8	0	210	100	3
Upper Namoi Alluvium Zone 9	195	364	85	1
Upper Namoi Alluvium Zone 10	40	223	100	2
Upper Namoi Alluvium Zone 11	0	36	90	3
Lower Namoi Alluvium	360	556	40	1
Gunnedah Basin	0	142	78	3
Oxley Basin	75	441	89	2
Liverpool Ranges Basalt	2	806	57	3
GAB Alluvial	194	526	44	1
GAB	99	344	81	1

The analysis shows that:

- Most Upper Namoi Alluvium zones are assessed as being in direct contact with coal bearing formations over a significant proportion of the zone. However, Zones 6, 9 and 10 are separated from the top of coal bearing formations by at least 50, 195 and 40 m respectively. These zones therefore could be considered at a lower risk of the transmission of groundwater impacts from mining and CSG directly through the coal seams than the other zones.
- The Lower Namoi Alluvium is not assessed as being in direct contact with a coal bearing formation. In fact there is a minimum separation of over 350 m between the alluvial water resource and the nearest potential coal bearing formation.
- The average distance between the coal bearing formations and the Upper Namoi Alluvium zones and the Lower Namoi Alluvium is greater than 100 m in all cases other than in Zones 1, 4 and 11. These zones are therefore potentially at higher risk of direct impacts than the others.

- Zones 3, 4, 5, 9 and 11 and the Lower Namoi Alluvium are not completely underlain by coal bearing formations. Most significantly, perhaps less than half the area of Zone 3 and the Lower Namoi Alluvium is underlain by coal bearing formations. These zones are therefore potentially at a lower risk of direct propagation of groundwater impacts.

The Gunnedah Basin and Liverpool Ranges Basalt Management Areas are interpreted as being underlain directly by coal bearing formations. The other Management Areas however are not.

The discussion of proximity above is summarised in terms of risk below:

- High risk: Zones 1, 2, 4, 5, 7, 8 and 11 can be considered to be at higher risk from the direct transfer of groundwater impacts from coal seams to the water resources due to their proximity to coal bearing formations.
- Medium / variable risk: Zone 3 and 10 can be considered to be at a medium risk or show variable risk.
- Low risk: Zones 6 and 9 and the Lower Namoi Alluvium present a low risk due to the fact that the coal bearing formations are unlikely to have direct contact with them and they are actually separated by a significant distance.

5.4.3 *Uncertainty*

Introduction

The Model provides predictions of groundwater level at every active cell within its domain. The accuracy of the predictions will vary from cell to cell, from layer to layer and through time. This is also known as model uncertainty. These issues must be considered before the predicted impacts are discussed in any great detail. The analysis will be undertaken in a relatively qualitative way, by looking at the model design, calibration and numerical performance at the level of the Lower Namoi Alluvium and the Groundwater Management Zones within the Upper Namoi Alluvium. This analysis will enable the predictions to be tempered with a judgement on the likely accuracy of the model in these specific areas. If predicted impacts are particularly high or low in a zone for example, it will be important to qualify this against an estimate of the accuracy of the prediction.

Model heritage

Due to the size of the Groundwater Model the active model domain encompasses existing models that have been developed, calibrated and improved over many years. The most significant and relevant models to the Study are the Lower Namoi Groundwater Model (Merrick, 2001) and the Upper Namoi Groundwater Model (McNeilage, 2006). Where possible the settings of these models (parameters, boundary conditions etc.) have been incorporated directly in the Groundwater Model.

For a number of reasons, including the fact that most calibration data is confined to the areas occupied by these two pre-existing models, areas outside of the existing Upper and Lower Namoi Model domains cannot be said to have been developed to the same degree of certainty as the areas within them. This gives a fairly simple appreciation of the potential uncertainty in model predictions in these areas. The result is an uncertainty (heritage) score for each management area or zone. Table 5.11 outlines the areas covered by the existing models (and those that are not) and includes a heritage score for each zone.

Table 5.11 Basis of model input parameters on existing models (model heritage)

Groundwater Management Area or Zone	Parameters	Boundary conditions	Model heritage 1 = low 2 = medium 3 = high
Upper Namoi Alluvium Zone 1	Yes	Yes	3
Upper Namoi Alluvium Zone 2	Yes	Yes	3
Upper Namoi Alluvium Zone 3	Yes	Yes	3
Upper Namoi Alluvium Zone 4	Yes	Yes	3
Upper Namoi Alluvium Zone 5	Yes	Yes	3
Upper Namoi Alluvium Zone 6	No	No	1
Upper Namoi Alluvium Zone 7	No	No	1
Upper Namoi Alluvium Zone 8	No	No	1
Upper Namoi Alluvium Zone 9	No	No	1
Upper Namoi Alluvium Zone 10	No	No	1
Upper Namoi Alluvium Zone 11	Yes	Yes	3
Lower Namoi Alluvium	Yes (simplified)	No	2
Gunnedah Basin	No	No	1
Oxley Basin	No	No	1
Liverpool Ranges Basalt	No	No	1
GAB and GAB Alluvial	No	No	1

Calibration

The uncertainty of the Model can be assessed by analysing the calibration data and calibration performance within the Groundwater Management Areas and Zones. Two concepts can be considered:

- The availability of data for use in the calibration. Only groundwater level monitoring positions with continuous or nearly continuous data from 1990 to 2010 were used.
- The match between observed and simulated groundwater levels (the calibration performance). This can be looked at objectively in terms of how well the model reproduced observed groundwater levels. The first priority for the model is the correct reproduction of trends in groundwater level through time, rather than absolute levels.

The number of monitoring positions available for use in calibration of the groundwater model is analysed in Table 5.12. An assessment of how well the model reproduced the observations is included. This analysis shows where the model predictions are likely to be most accurate and where they may be least accurate. It also describes the calibration opportunity and performance in areas outside of existing model domains (i.e. the Upper and Lower Namoi Models).

Table 5.12 Assessment of Groundwater Model calibration data and calibration performance

Groundwater Management Area or Zone	Number of calibration locations used	Zone area	Area per single calibration location	Calibration performance	Calibration score 1 = low 2 = moderate 3 = high
Upper Namoi Alluvium Zone 1	1	37	37	Poor	1
Upper Namoi Alluvium Zone 2	5	482	96	Variable	2
Upper Namoi Alluvium Zone 3	14	556	40	Good	3
Upper Namoi Alluvium Zone 4	16	852	53	Variable	2
Upper Namoi Alluvium Zone 5	7	289	41	Good	3
Upper Namoi Alluvium Zone 6	3	464	155	Variable	1
Upper Namoi Alluvium Zone 7	1	141	141	Poor	1
Upper Namoi Alluvium Zone 8	3	322	107	Variable	1
Upper Namoi Alluvium Zone 9	4	304	76	Variable	1
Upper Namoi Alluvium Zone 10	1	54	54	Poor	1
Upper Namoi Alluvium Zone 11	1	174	174	Poor	1
Lower Namoi Alluvium	0	5,897	-	-	1
Gunnedah Basin	2	3,534	1,767	Variable	1
Oxley Basin	2	3,231	1,615	Variable	1
Liverpool Ranges Basalt	0	1,716	-	-	1
GAB and GAB Alluvial	0	11,110	-	-	1

The analysis shows that Upper Namoi Alluvium Zones 2, 3, 4 and 5 are judged to be either moderately or well calibrated based on both the availability of calibration data and the match between observed and simulated groundwater levels at these locations.

However the other zones and the Lower Namoi Alluvium are judged to be poorly calibrated due to having a low number of observation locations and / or a poor calibration result. For example, in the case in Zone 9, although the model reproduces observed groundwater levels to a variable standard (i.e. sometimes well and sometimes poorly), only 4 locations were available to the calibration. The zone occupies an area of 300 km². This presents a low density of calibration points for this zone, roughly 1 per 75 km², so the zone cannot be considered calibrated to the extent that the confidence in predictions could be definitively classed as high.

Time variant calibration data is limited in the Gunnedah Basin, Oxley Basin, Liverpool Ranges Basalt and GAB / GAB Alluvial Management Areas to the extent that none of these can be considered calibrated.

The calibration score shows that the locations that can be considered to provide high to medium confidence predictions, are concentrated in the areas where most mining development is likely to take place. There are however a few notable exceptions; Zones 7 and 8 in the south and Zone 11 in the north of the Upper Namoi Alluvium. These zones are important due to their proximity to the potential for coal mine and CSG development, but the combination of a limited number of calibration opportunities and a poor or mixed calibration performance mean confidence in predictions will be lower.

Numerical performance

The numerical performance of the Groundwater Model within the various management areas and zones is assessed in Table 5.13. This is a qualitative assessment of consistency of the model outputs through the full temporal extent of the predictive model. For example, outputs such as drawdown at the alluvial and hard rock hypothetical monitoring positions that illustrate less consistent model predictive results could indicate potentially poorer numerical performance. Data from both the historical and predictive models can therefore be used to derive this score.

Table 5.13 Assessment of Groundwater Model numerical performance

Groundwater Management Area or Zone	Numerical performance score	
	1 = poor	
	2 = variable	
	3 = good	
Upper Namoi Alluvium Zone 1	2	
Upper Namoi Alluvium Zone 2	2	
Upper Namoi Alluvium Zone 3	2	
Upper Namoi Alluvium Zone 4	3	
Upper Namoi Alluvium Zone 5	3	
Upper Namoi Alluvium Zone 6	2	
Upper Namoi Alluvium Zone 7	1	
Upper Namoi Alluvium Zone 8	3	
Upper Namoi Alluvium Zone 9	2	
Upper Namoi Alluvium Zone 10	2	
Upper Namoi Alluvium Zone 11	1	
Lower Namoi Alluvium	2	
Gunnedah Basin	2	
Oxley Basin	2	
Liverpool Ranges Basalt	2	
GAB and GAB Alluvial	2	

The analysis shows that most areas perform consistently in the Model and, based on this indicator at least, suggest medium to high confidence in model predictions in most places. However, Zones 7 and 11 are in significant locations in terms of potential proximity to coal mines (especially) and CSG development and are assessed as performing less well (numerically). The less consistent model performance in these locations could be due to a number of factors. For example if the location is in an area of very thin alluvium that switches often between confined and unconfined behaviour, this could be erroneously interpreted as less consistent model performance.

Level of detail

A simple indicator of the ability of the model to make accurate regional scale predictions is the number of model cells that the Management Zone or Area occupies (Table 5.14). A low number may mean that the predictions will be more susceptible to local numerical instability or conceptual inaccuracies whereas a high number should mean that local effects such as these are averaged out and do not impact model predictions.

Table 5.14 Number of model cells by Management Area and Zone

Groundwater Management Area or Zone	Number of model cells	
	Layer 1 (Narrabri Formation)	Layer 2 (Gunnedah Formation)
Upper Namoi Alluvium Zone 1	35	42
Upper Namoi Alluvium Zone 2	494	229
Upper Namoi Alluvium Zone 3	561	197
Upper Namoi Alluvium Zone 4	864	571
Upper Namoi Alluvium Zone 5	260	86
Upper Namoi Alluvium Zone 6	474	189
Upper Namoi Alluvium Zone 7	139	136
Upper Namoi Alluvium Zone 8	331	320
Upper Namoi Alluvium Zone 9	264	258
Upper Namoi Alluvium Zone 10	59	36
Upper Namoi Alluvium Zone 11	182	69
Lower Namoi Alluvium	-	5383

The analysis shows that Upper Namoi Alluvium Zones 1 and 10 are represented only in very few model cells. From this point of view the predictions in these zones should be treated with caution.

Recharge estimates

To test the effect of Groundwater Model recharge changes due to the interception of rainfall by open pits, a version of Scenario 3 was run with the recharge inputs set to equal those defined for Scenario 0 (the no mining or CSG case). The difference between the predicted drawdown in these two versions of Scenario 3 results provides an indication of the role that the recharge changes play in the Scenario 3 drawdown predictions. These changes in recharge are simulated by the Hydrologic Model which assumes the interception of all incident rainfall (and therefore recharge) over open cut mines and then provides the recharge input values for the Groundwater Model predictive scenarios. The results are provided in Table 5.15 and Figure 5.9.

Table 5.15 Estimated proportion of drawdown impacts due to changes to Groundwater Model recharge inputs

Groundwater Management Area or Zone	Estimated proportion of drawdown impacts derived from recharge modifications
Upper Namoi Alluvium Zone 1	77%
Upper Namoi Alluvium Zone 2	45%
Upper Namoi Alluvium Zone 3	68%
Upper Namoi Alluvium Zone 4	76%
Upper Namoi Alluvium Zone 5	76%
Upper Namoi Alluvium Zone 6	12%
Upper Namoi Alluvium Zone 7	21%
Upper Namoi Alluvium Zone 8	17%
Upper Namoi Alluvium Zone 9	0%
Upper Namoi Alluvium Zone 10	1%
Upper Namoi Alluvium Zone 11	82%
Lower Namoi Alluvium	8%

The analysis above shows that the changes (generally reductions) made to recharge inputs in the Groundwater Model to incorporate potential impacts from open pit mines and surface infrastructure associated with CSG development have a significant control on the predicted groundwater level changes in many of the Management Zones.

The majority of the impact to recharge is derived from open cut mines which are assumed to intercept the full component of rainfall landing within their active pit areas. This component of the model produces an average of between 70 and 80% of the predicted drawdown in Upper Namoi Alluvium Zones 1, 4, 5 and 11. In Upper Namoi Alluvium Zone 2, 45% of the drawdown is derived from this input. In the remaining alluvial areas the significance of recharge changes is less than 20% and in Upper Namoi Alluvium Zone 9 and the Lower Namoi Alluvium it is zero.

The accuracy in the estimates of impacts to groundwater recharge from open cut mines is therefore of significance in a number of areas of the model as it dominates predicted drawdown in these locations.

Uncertainty summary

The three main uncertainty indicators (heritage, calibration and numerical performance) can be combined to give an approximate estimate on the relative confidence in model predictions in each of the Management Areas and Zones. This is summarised in Table 5.16 and the result illustrated in Figure 5.10.

Table 5.16 Uncertainty summary

Groundwater Management Area or Zone	Model heritage 1 = low 2 = medium 3 = high	Calibration score 1 = low 2 = medium 3 = high	Numerical performance score 1 = poor 2 = variable 3 = good	Uncertainty score 6 = low to 0 = high
Upper Namoi Alluvium Zone 1	1	1	2	1
Upper Namoi Alluvium Zone 2	3	2	2	4
Upper Namoi Alluvium Zone 3	3	3	2	5
Upper Namoi Alluvium Zone 4	3	2	3	5
Upper Namoi Alluvium Zone 5	3	3	3	6
Upper Namoi Alluvium Zone 6	1	1	2	1
Upper Namoi Alluvium Zone 7	1	1	1	0
Upper Namoi Alluvium Zone 8	1	1	3	2
Upper Namoi Alluvium Zone 9	1	1	2	1
Upper Namoi Alluvium Zone 10	1	1	2	1
Upper Namoi Alluvium Zone 11	3	1	1	2
Lower Namoi Alluvium	2	1	2	2
Gunnedah Basin	1	1	2	1
Oxley Basin	1	1	2	1
Liverpool Ranges Basalt	1	1	2	1
GAB and GAB Alluvial	1	1	2	1

The analysis shows that:

- The most uncertain predictions will be in Upper Namoi Alluvium Zones 6, 7, 9 and 10 and the Gunnedah Basin, Oxley Basin, Liverpool Ranges Basalt and GAB / GAB Alluvial Management Areas.
- Moderately certain predictions are likely in Upper Namoi Alluvium Zones 1, 2, 8 and 11 and the Lower Namoi Alluvium.
- The most certain predictions in Upper Namoi Alluvium Zones 3, 4 and 5.

5.4.4 Groundwater level impacts

Introduction

The analysis of predicted groundwater impacts is undertaken using the results from Scenario 3. This simulates long term and widespread development of the coal and gas resources from 2010 until 2100.

The greatest uncertainty in the modelling exercise is the scenario construction. Fundamental settings such as mine location, CSG abstraction volume, timing, mine size and target seam are all estimates as they cannot be accurately predicted. The further into the future the scenario goes the more incorrect these settings are likely to be and errors will be compounded. At any one time the predictions in a certain area will depend both on what has been simulated regionally up to that time, and what is active in that area at that time. It is therefore certain that the mine and CSG settings in Scenario 3 will prove to be incorrect.

Regardless of all the other uncertainties described and quantified in preceding discussions, the Groundwater Model cannot therefore be used to determine exactly what impacts might occur at specific times. However, the main output from the model presented in the Study Phase 3 report was produced at times equivalent to 2030, 2060 and 2100. The analysis will use the data produced at these times to provide an estimate of the maximum or the average impacts and not explicitly associate these with a particular time in the future. These results are also averaged within Management Areas and Zones to allow for a comparison with some key indicators, such as average drawdown from 1980 to 2010 or the average saturated thickness, and to provide a summary of impacts at this sub-regional scale.

Scenario 3 impacts

The average of groundwater level drawdown predictions from Scenario 3 within the Management Areas and Zones is presented in Table 5.17 and Figure 5.11 to 5.13.

The analysis shows that there are three main impact groups within the alluvial aquifers. They are:

- The Upper Namoi Alluvium Zones 1, 2, 3, 6 and 10 and the Lower Namoi Alluvium are predicted to experience a maximum average drawdown in groundwater levels of less than 0.2 m in 2030, 2060 and 2100.
- The Upper Namoi Alluvium Zones 5, 8 and 9 are predicted to experience a maximum average drawdown between 0.5 and 0.8 m.
- The Upper Namoi Alluvium Zones 4, 7 and 11 are predicted to experience a maximum average drawdown between 1.0 and 1.6 m.

In all cases, apart from Zone 11, the maximum predicted drawdown occurs in 2100.

Table 5.17 Average predicted drawdown from coal and gas development (Scenario 3)

Groundwater Management Area or Zone	Average predicted drawdown from coal and gas development (m)			
	2030	2060	2100	Max
Upper Namoi Alluvium Zone 1	0.0	0.0	0.2	0.2
Upper Namoi Alluvium Zone 2	0.0	0.0	0.1	0.1
Upper Namoi Alluvium Zone 3	0.0	0.0	0.1	0.1
Upper Namoi Alluvium Zone 4	0.1	0.5	1.0	1.0
Upper Namoi Alluvium Zone 5	0.1	0.6	0.8	0.8
Upper Namoi Alluvium Zone 6	0.0	0.1	0.1	0.1
Upper Namoi Alluvium Zone 7	0.6	1.1	1.1	1.1
Upper Namoi Alluvium Zone 8	0.1	0.4	0.5	0.5
Upper Namoi Alluvium Zone 9	0.0	0.2	0.5	0.5
Upper Namoi Alluvium Zone 10	0.0	0.0	0.1	0.1
Upper Namoi Alluvium Zone 11	0.2	1.6	1.5	1.6
Lower Namoi Alluvium	0.0	0.0	0.0	0.0
Gunnedah Basin	1.0	3.2	6.5	3.6
Oxley Basin	0.1	0.7	1.6	0.8
Liverpool Ranges Basalt	0.0	0.1	0.3	0.1
GAB Alluvial	0.0	0.2	0.2	0.1
GAB	0.0	0.1	0.3	0.2

The maximum drawdown predicted in any model cell within the Management Areas and Zones is presented in Table 5.18 and Figures 5.14 and 5.15. This data may be more susceptible to model error and uncertainty than the average data, but nonetheless it provides an indication of the potential maximum impact within these areas.

Table 5.18 Maximum predicted drawdown from coal and gas development (Scenario 3)

Groundwater Management Area or Zone	Maximum predicted drawdown from coal and gas development (m)			
	2030	2060	2100	Max
Upper Namoi Alluvium Zone 1	0.0	0.0	0.4	0.4
Upper Namoi Alluvium Zone 2	0.1	0.4	0.6	0.6
Upper Namoi Alluvium Zone 3	0.5	1.2	1.3	1.3
Upper Namoi Alluvium Zone 4	0.7	1.4	2.4	2.4
Upper Namoi Alluvium Zone 5	4.3	1.8	4.1	4.3
Upper Namoi Alluvium Zone 6	0.2	0.4	0.4	0.4
Upper Namoi Alluvium Zone 7	4.7	6.1	2.2	6.1
Upper Namoi Alluvium Zone 8	0.7	1.5	1.4	1.5
Upper Namoi Alluvium Zone 9	2.4	6.9	5.6	6.9
Upper Namoi Alluvium Zone 10	0.0	0.0	0.1	0.1
Upper Namoi Alluvium Zone 11	0.8	3.8	3.7	3.8
Lower Namoi Alluvium	0.0	0.1	0.3	0.3
Gunnedah Basin	23.8	50.6	204.7	93.0
Oxley Basin	4.3	8.8	21.5	11.5
Liverpool Ranges Basalt	1.5	1.9	2.3	1.9
GAB Alluvial	0.8	4.4	4.6	3.2
GAB	4.9	11.0	7.0	7.7

The analysis shows that at the three output times:

- The Upper Namoi Alluvium Zones 1, 2, 6 and 10 and the Lower Namoi Alluvium Zone are predicted to experience a maximum drawdown in groundwater levels no greater than 0.6 m.
- The Upper Namoi Alluvium Zones 3 and 8 are predicted to experience a maximum drawdown of between 1.0 and 2.0 m.
- The Upper Namoi Alluvium Zones 4, 5, 7, 9 and 11 are predicted to experience a maximum drawdown of between 2.0 and 7.0 m.

As opposed to the average drawdown predictions, the maximum drawdown does not necessarily occur in 2100, and may actually occur in 2060. This result is likely to be sensitive to the timing of mines in close proximity to these areas.

The impacts in the hard rock Management Areas are greatest in the Gunnedah Basin Area. The average will be high here due to the fact that active mines and CSG fields will be simulated in this area causing very high drawdown in their vicinity. This is illustrated in Table 5.18.

Proportion from mining and CSG

The proportion of the predicted average drawdown from Scenario 3 that is estimated to originate from either coal mining or CSG activities is summarised in Table 5.19. This data is calculated based on the predictions from Scenarios 4 and 5 which are based on Scenario 3 but have either mining or CSG inputs removed. The analysis considers the average result from 2030, 2060 and 2100 and proportions of impacts above 70% as being dominated by either industry.

Table 5.19 Source of groundwater level impacts

Groundwater Management Area or Zone	Score 1= Mining > 70% 2 = Roughly even 3 = CSG >70%
Upper Namoi Alluvium Zone 1	1
Upper Namoi Alluvium Zone 2	2
Upper Namoi Alluvium Zone 3	1
Upper Namoi Alluvium Zone 4	1
Upper Namoi Alluvium Zone 5	2
Upper Namoi Alluvium Zone 6	2
Upper Namoi Alluvium Zone 7	1
Upper Namoi Alluvium Zone 8	1
Upper Namoi Alluvium Zone 9	2
Upper Namoi Alluvium Zone 10	2
Upper Namoi Alluvium Zone 11	1
Lower Namoi Alluvium	3

This 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.

5.4.5 *Groundwater quality impacts*

Introduction

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 will therefore inevitably affect the accuracy of any model predictions. 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 much 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 is investigated through 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. This will provide an indication as to whether the groundwater systems in the two formations are isolated (gradients can exist) or connected (gradients do not exist) and whether there is therefore the potential for mixing of these waters.
- The predicted groundwater flows between the alluvium and the hard rock formations. This will provide an indication as to what impact the coal and gas developments might have on the relationship between these potentially differing quality groundwater systems.

Alluvial groundwater mixing

The difference between the Scenario 3 predicted groundwater levels in the Gunnedah and Narrabri Formations in the Upper Namoi Alluvium are displayed in Table 5.20.

Table 5.20 Difference between predicted groundwater levels in the Narrabri and Gunnedah Formations (Scenario 3)

Groundwater Management Area or Zone	Average (m)	Maximum (m)
Upper Namoi Alluvium Zone 1	0.00	0.00
Upper Namoi Alluvium Zone 2	0.00	0.40
Upper Namoi Alluvium Zone 3	0.01	1.58
Upper Namoi Alluvium Zone 4	0.00	0.62
Upper Namoi Alluvium Zone 5	0.01	1.69
Upper Namoi Alluvium Zone 6	0.00	0.06
Upper Namoi Alluvium Zone 7	0.13	4.70
Upper Namoi Alluvium Zone 8	0.00	0.55
Upper Namoi Alluvium Zone 9	0.00	0.02
Upper Namoi Alluvium Zone 10	0.00	0.00
Upper Namoi Alluvium Zone 11	0.01	0.41

The analysis shows that the groundwater gradient between the two formations remains relatively unchanged throughout the Scenario 3 simulation. The changes that do occur are predicted to be just a few centimetres rather than metres and they show that in all Upper Namoi Alluvium Zones the model predicts that the groundwater levels in the Gunnedah and Narrabri Formations change in unison. Only in Zone 7 is a significant gradient generated but the difference between the average and maximum values shows that it is isolated to a local area within this zone.

Whilst the observational data is not sufficient to take this analysis further, it does show that where water quality issues derived from the mixing of lower and higher quality water within these formations are currently being observed, the potential additional drawdown caused by mining and CSG developments could augment this process.

Groundwater flows

Predicted flows between the alluvium and the hard rock formations in the Management Zones with the greatest predicted average groundwater level impacts (Zones 4, 7 and 11) are provided in Table 5.21.

Table 5.21 Predicted net flows into or out of the alluvium in selected Management Zones

		Net flow (m ³ /d) into the alluvium from the hard rock formations		
		2011-2030	2030-2060	2060-2100
Zone 11	Scenario 0	1,460	1,689	1,880
	Scenario 3	1,452	1,414	1,096
	Difference	-7	-275	-784
	% difference	0	-16	-42
Zone 4	Scenario 0	1,553	2,824	3,330
	Scenario 3	1,475	2,374	2,575
	Difference	-78	-450	-755
	% difference	-5	-16	-23
Zone 7	Scenario 0	524	725	891
	Scenario 3	428	-7 (out of alluvium)	383
	Difference	-96	-732	-508
	% difference	-18	-101	-57

This data shows that the predicted situation without mining or CSG development is the same in each zone; 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 (as a result of existing abstraction) 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.

Scenario 3 results show that 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. 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 reduced.

5.4.6 Context

Introduction

The findings of the hydrogeological conceptualisation which has been ongoing throughout the Study that are pertinent to the analysis of impacts are discussed here. This is done so that the impacts predicted by the Model can be put into context against the size of the resource, the existing stresses and the historical impacts to the resource.

Groundwater abstraction

Groundwater abstraction in the catchment in 2009 is provided in Table 5.22 and Figure 5.16. This illustrates which Management Areas or Zones are most heavily utilised and where impacts from coal and gas developments would be most sensitive in these terms. The majority of this abstraction is associated with irrigation.

Table 5.22 Groundwater utilisation in the catchment

Groundwater Management Area or Zone	Total GW abstraction 2009 ML/yr	GW abstraction per km²	Groundwater utilisation score 1 = low 2 = moderate 3 = high
Upper Namoi Alluvium Zone 1	1,237	33	3
Upper Namoi Alluvium Zone 2	11,468	24	3
Upper Namoi Alluvium Zone 3	14,137	25	3
Upper Namoi Alluvium Zone 4	19,950	23	3
Upper Namoi Alluvium Zone 5	12,868	44	3
Upper Namoi Alluvium Zone 6	563	1	1
Upper Namoi Alluvium Zone 7	676	5	1
Upper Namoi Alluvium Zone 8	6,647	21	3
Upper Namoi Alluvium Zone 9	1,471	5	1
Upper Namoi Alluvium Zone 10	3	0	1
Upper Namoi Alluvium Zone 11	622	4	1
Lower Namoi Alluvium	70,149	12	2

The analysis shows which Management Areas and Zones are most heavily abstracted and how this compares to their surface area. This does not take into account other factors such as yield, saturated thickness or data completeness. However, it shows clearly that:

- By volume abstracted, the Upper Namoi Alluvium Zones 2, 3, 4 and 5 and the Lower Namoi Alluvium are by far the most heavily utilised in the catchment.
- Very little abstraction comes from Upper Namoi Alluvium Zones 1, 6, 7, 10 and 11.
- By volume abstracted by area, Upper Namoi Alluvium Zones 2, 3, 4 and 5 as well as Zones 1 and 8 are the most heavily utilised resources. By this indicator, Zone 1 is actually the second most utilised groundwater resource after Zone 5.
- By volume abstracted by area the Lower Namoi Alluvium is less significant than when considered by volume alone.

Therefore the most significant groundwater resources as determined by their utilisation are contained within the Upper Namoi Alluvium Zones 1, 2, 3, 4, 5 and 8 and the Lower Namoi Alluvium. Further impacts in these zones would have potentially the greatest impact on the groundwater utilisation for irrigation in the catchment.

Historical drawdown

Average observed drawdown from 1980 to 2010 in the Management Areas and Zones is provided in Table 5.23 and Figure 5.17. This represents the measured impact from existing groundwater utilisation that has occurred during that time. It also incorporates changes that have occurred in response to variations in climate (i.e. rainfall) over that and preceding times. This data can be used to put the predicted impacts into context with contemporary and ongoing stresses on the groundwater system.

Table 5.23 Observed historical groundwater drawdown

Groundwater Management Area or Zone	Change in water level (m) 1980 to 2010	Number of data points
Upper Namoi Alluvium Zone 1	-3.2	9
Upper Namoi Alluvium Zone 2	-2.5*	30
Upper Namoi Alluvium Zone 3	-6.2	55
Upper Namoi Alluvium Zone 4	-3.2	32
Upper Namoi Alluvium Zone 5	-3.6	39
Upper Namoi Alluvium Zone 6	-1.3	17
Upper Namoi Alluvium Zone 7	+1.4	1
Upper Namoi Alluvium Zone 8	-7.9	50
Upper Namoi Alluvium Zone 9	+1.1*	9
Upper Namoi Alluvium Zone 10	-2.8	1
Upper Namoi Alluvium Zone 11	-2.2	9
Lower Namoi Alluvium	-4.7	5
Gunnedah Basin	-2.0*	2
Oxley Basin	+1.0	7
Liverpool Ranges Basalt	No data	0
GAB and GAB Alluvial	-4.3	1

* 1986 to 2010 due to data limitations

The data shows that:

- Drawdown has occurred in most of the catchment groundwater resources over this time.
- This drawdown is measured in metres, and is generally in the range of 2 to 4 m.
- The highest drawdown is observed in Upper Namoi Alluvium Zones 3 and 8 and in the Lower Namoi Alluvium (6, 8 and 5 m respectively). This result is based on data from a significant number of monitoring locations.
- Groundwater level increases have been observed in Zones 7 and 9 over this period. However, the result in Zone 7 is based on data from a single monitoring location.
- Given the size of the Gunnedah Basin, Oxley Basin, Liverpool Ranges Basalt and GAB / GAB Alluvial Management Areas the data on which these historical drawdown estimates are based is very limited. It seems relatively certain however that groundwater levels have increased by about 1 m in the Oxley Basin over this time period.

Saturated thickness

In order to put any predicted impacts on groundwater levels into context, it is important to know the saturated thickness of aquifer being impacted. For example, a 5 m drawdown impact on an aquifer with a saturated thickness of 10 m is quite different to the same impact on a saturated thickness of 100 m. In an unconfined aquifer the saturated thickness corresponds to the height of the water table above the base of the aquifer. In a confined aquifer the saturated thickness corresponds to the thickness of the aquifer. Both of these situations may be found in the Gunnedah Formation of the Upper Namoi Alluvium. Table 5.24 details estimates of the saturated thickness of the Gunnedah and Narrabri Formations in each of the Management Zones based on the observed groundwater levels in 2010 and the layer elevations from the Groundwater Model.

Table 5.24 Difference between Scenario 3 and sensitivity predictions of average drawdown

Groundwater Management Area or Zone	Saturated thickness 2010			
	Gunnedah Formation		Narrabri Formation	
	Average (m)	Maximum (m)	Average (m)	Maximum (m)
Upper Namoi Alluvium Zone 1	1	4	1	8
Upper Namoi Alluvium Zone 2	23	86	9	45
Upper Namoi Alluvium Zone 3	28	80	22	51
Upper Namoi Alluvium Zone 4	25	132	13	55
Upper Namoi Alluvium Zone 5	26	65	16	42
Upper Namoi Alluvium Zone 6	2	15	16	54
Upper Namoi Alluvium Zone 7	2	15	11	36
Upper Namoi Alluvium Zone 8	15	49	18	59
Upper Namoi Alluvium Zone 9	18	71	11	51
Upper Namoi Alluvium Zone 10	2	9	13	33
Upper Namoi Alluvium Zone 11	10	61	2	17
Lower Namoi Alluvium	39	125	n/a	n/a

The analysis shows that:

- Upper Namoi Alluvium Zones 2, 3, 4 and 5 and the Lower Namoi Alluvium have the greatest average saturated thicknesses of Gunnedah Formation (23, 28, 25, 26 and 39 m respectively). In these locations it is the Gunnedah Formation that presents the greatest permeability and therefore yield.
- The saturated thickness of the Upper Namoi Alluvium Zones 8, 9 and 11 is between 10 and 20 m in the Gunnedah Formation. This will make these zones more sensitive to drawdown. Of these Zone 11 would be the most sensitive.
- The saturated thickness of the Gunnedah Formation in the Upper Namoi Alluvium Zones 1, 6, 7 and 10 is limited to almost nothing (less than 2 m). Zones 6, 7 and 10 have more significant saturated thicknesses in the Narrabri Formation (averaging just over 10 m).
- The saturated thickness calculated in Zone 1 is unlikely to be accurate and is probably due to the very low number of model cells that represent it.

Context conclusion

In terms of the regional groundwater resource context, Table 5.25 compares the average saturated thickness and average maximum average drawdown predicted in Scenario 3 in the Management Areas / Zones with the highest current groundwater utilisation.

Table 5.25 Comparison of saturated thickness and predicted drawdown

Groundwater Management Area or Zone	Total GW abstraction 2009 ML/yr	Average Gunnedah Formation saturated thickness, 2010 (m)	Predicted drawdown	
			Average (m)	Proportion of saturated thickness
Upper Namoi Alluvium Zone 1	1,237	1	0.2	20.0%
Upper Namoi Alluvium Zone 2	11,468	23	0.1	0.4%
Upper Namoi Alluvium Zone 3	14,137	28	0.1	0.4%
Upper Namoi Alluvium Zone 4	19,950	25	1.0	4.0%
Upper Namoi Alluvium Zone 5	12,868	26	0.8	3.1%
Upper Namoi Alluvium Zone 8	6,647	15	0.5	3.3%
Lower Namoi Alluvium	70,149	39	0.0	0.0%

The analysis shows that the most significant result in terms of the proportion of saturated thickness impacted is in Upper Namoi Alluvium Zone 1. However this must be tempered somewhat by some of the analyses above which have shown the predictions in this zone to be very uncertain.

Significant impacts are predicted in Zones 4, 5 and 6, where between 3 and 4% of the saturated thickness is predicted to be lost if the predictions of maximum drawdown are accurate.

The maximum average drawdown predicted in Zones 2 and 3 and the Lower Namoi Alluvium are insignificant when compared to the saturated thickness of aquifer in those locations.

5.4.7 Sensitivity

Introduction

A sensitivity analysis was undertaken on the Groundwater Model by varying key input parameters and concepts. The parameters were horizontal and vertical hydraulic conductivity and storage. The concepts were the uncertainty in CSG abstraction volumes, re-injection of CSG treated water and dry or wet climates. The analysis can provide an assessment of:

- How the predicted impacts vary, given the uncertainties in the model parameters, and
- Which parameters exert the greatest control over the predictions.

The results are analysed in the same way as the impacts have been and are summarised in tables, maps and graphs.

Impact range – CSG abstraction volume

The uncertainty in the estimated volumes of abstracted groundwater assigned to the possible and hypothetical CSG fields was tested in Sensitivity A. In this run the abstraction rates were doubled in all CSG fields compared to the rates used in Scenario 3. The results of the sensitivity in terms of impacts in the Management Areas and Zones are provided in Table 5.26 and Figure 5.18.

Table 5.26 Difference in average predicted drawdown in Scenario 3 with average predicted drawdown in Sensitivity run A

Groundwater Management Area or Zone	Scenario 3 max average* (m)	Max increase (m)	Increase as %
Upper Namoi Zone 7	1.1	1.1	103%
Upper Namoi Zone 5	0.8	0.5	58%
Upper Namoi Zone 9	0.5	0.3	65%
Upper Namoi Zone 4	1.0	0.3	27%
Upper Namoi Zone 1	0.2	0.2	97%
Upper Namoi Zone 11	1.6	0.1	9%
Upper Namoi Zone 6	0.1	0.1	99%
Upper Namoi Zone 8	0.5	0.1	18%
Upper Namoi Zone 2	0.1	0.1	70%
Upper Namoi Zone 3	0.1	0.1	55%
Lower Namoi Alluvium	0.0	0.0	96%
Upper Namoi Zone 10	0.1	0.0	2%

* The maximum average corresponds to the maximum average drawdown predicted within each area or zone at either 2030, 2060 or 2100

The analysis shows that in terms of absolute levels of predicted drawdown most areas show very little sensitivity to this uncertainty. Only Upper Namoi Alluvium Zone 7 experiences additional drawdown in excess of 1 m. In all other areas the additional drawdown from a doubling of the CSG abstraction estimate is less than 0.5 m.

In terms of predicted alluvial drawdown then, the estimate of CSG abstraction volume (within the ranges tested) will have relatively little impact on the results in all areas apart from Upper Namoi Alluvium Zone 7.

Impact range – CSG associated water re-injection

The impact of re-injection of treated CSG associated water on the predicted groundwater drawdown was considered in Sensitivity B. In this run 80% of the abstracted water associated with CSG fields Bando 1, 3 and 4 and Narrabri 1, 3 and 4 was re-injected into the Gunnedah Formation of the Upper Namoi Alluvium or the Lower Namoi Alluvium around Wee Waa and Narrabri. The results of the sensitivity in terms of the impacts in the Management Areas and Zones are provided in Table 5.27 and Figure 5.19.

Table 5.27 Difference in average predicted drawdown in Scenario 3 with average predicted drawdown in Sensitivity run B

Groundwater Management Area or Zone	Receiving re-injected water	Scenario 3 max average [^] (m)	Max decrease (m)	Reduction as %*
Upper Namoi Zone 7	Yes	1.1	-0.5	-48%
Upper Namoi Zone 5	Yes	0.8	-0.3	-33%
Upper Namoi Zone 9	No	0.5	-0.1	-27%
Upper Namoi Zone 10	No	0.1	-0.1	-100%
Upper Namoi Zone 1	No	0.2	0.0	-18%
Upper Namoi Zone 6	Yes	0.1	0.0	-38%
Upper Namoi Zone 3	Yes	0.1	0.0	-25%
Upper Namoi Zone 4	Yes	1.0	0.0	-3%
Lower Namoi Alluvium	Yes	0.0	0.0	-98%
Upper Namoi Zone 8	No	0.5	0.0	-1%
Upper Namoi Zone 2	Yes	0.1	0.0	-2%
Upper Namoi Zone 11	No	1.6	0.0	0%

* A reduction of 100% equates to no predicted impact. In terms of a reduction therefore 100% is the maximum possible.

[^] The maximum average corresponds to the maximum average drawdown predicted within each area or zone at either 2030, 2060 or 2100

In terms of the impact on groundwater levels at this sub-regional perspective, the re-injection can have a significant impact on the drawdown predictions and this is partly dependent on the location of the reinjection. The greatest absolute change in impact is seen in Upper Namoi Alluvium Zone 7 where the predicted average drawdown is reduced by a maximum of about half a metre (48%).

Impact range – high / low rainfall

The control that high or low rainfall conditions might have on the magnitude of predicted impacts was tested in Sensitivities C and D. In these the 20 wettest and 20 driest years in the long term rainfall records for each rainfall gauging station was used in the Hydrologic Model as climate inputs from 2010 to 2100. The predicted recharge was then used in the Groundwater Model and the Scenario 3 and Scenario 0 models re-run. The results of the sensitivity in terms of the impacts in the Management Areas and Zones are provided in Table 5.28 and Figure 5.20.

Table 5.28 Difference in average predicted drawdown in Scenario 3 with average predicted drawdown in Sensitivity runs C and D

Groundwater Management Area or Zone	Max decrease (m)	Max increase (m)	Scenario 3 max average (m)	Reduction as % *	Increase as %	Range (m)	Score 1 = low 2 = mod 3 = high
Upper Namoi Zone 5	-0.2	1.8	0.8	-19%	222%	2.0	3
Upper Namoi Zone 11	-0.6	1.1	1.6	-34%	68%	1.7	3
Upper Namoi Zone 1	-0.2	0.7	0.2	-86%	311%	0.9	2
Upper Namoi Zone 7	-0.1	0.6	1.1	-8%	58%	0.7	2
Upper Namoi Zone 4	-0.4	0.3	1.0	-44%	28%	0.7	2
Upper Namoi Zone 9	-0.1	0.2	0.5	-30%	49%	0.4	2
Upper Namoi Zone 8	-0.1	0.0	0.5	-10%	9%	0.1	1
Upper Namoi Zone 3	0.0	0.0	0.1	-22%	37%	0.1	1
Upper Namoi Zone 10	0.0	0.0	0.1	-96%	2%	0.1	1
Upper Namoi Zone 2	0.0	0.0	0.1	-12%	13%	0.0	1
Upper Namoi Zone 6	0.0	0.0	0.1	-17%	0%	0.0	1
Lower Namoi Alluvium	0.0	0.0	0.0	-2%	0%	0.0	1

* A reduction of 100% equates to no predicted impact. In terms of a reduction therefore 100% is the maximum possible.

This analysis shows that:

- Under these varying recharge situations the impacts tend to increase rather than decrease, i.e. the effect of dry periods is more pronounced than the effect of wetter periods.
- The main increases are predicted in Upper Namoi Zones 5, 11, 1 and 7. These results come from the low rainfall sensitivity (Sens D) and have a noticeable impact on the average drawdown predicted when compared to the Scenario 3 basecase. For example, the impact in Upper Namoi Zone 5 increases 1.8 m from 0.8 m to 2.6 m.
- In Upper Namoi Zones 9, 8, 3, 10, 2 and 6 and the Lower Namoi Alluvium there is virtually no sensitivity of predictions to variations in rainfall.

Impact range – parameter sensitivities by zone

The sensitivity of model predictions to key model input parameters was tested. This involved increasing and decreasing horizontal and vertical hydraulic conductivity and storage (specific yield and specific storage) within realistic bounds. Hydraulic conductivity values were changed by one order of magnitude and storage values were doubled or halved. All the changes were made to hard rock formations. No changes were made to the alluvial parameters. The results of the sensitivity in terms of the impacts in the Management Areas and Zones are provided in Table 5.29 and Figure 5.21 to 5.23.

Table 5.29 **Difference in average predicted drawdown in Scenario 3 with range of average predicted drawdown in Sensitivity runs E to J**

Groundwater Management Area or Zone	Max decrease (m)	Max increase (m)	Scenario 3 max average (m)	Reduction as % *	Increase as %	Range (m)	Score 1 = low 2 = mod 3 = high
Upper Namoi Zone 7	-0.6	3.6	1.1	-52%	325%	4.1	3
Upper Namoi Zone 11	-1.6	0.4	1.6	-96%	27%	2.0	3
Upper Namoi Zone 9	-0.4	0.9	0.5	-91%	187%	1.4	2
Upper Namoi Zone 8	-0.3	0.8	0.5	-65%	162%	1.2	2
Upper Namoi Zone 5	-0.6	0.4	0.8	-71%	48%	1.0	2
Upper Namoi Zone 10	-0.1	0.9	0.1	-99%	1706%	0.9	2
Upper Namoi Zone 4	-0.3	0.3	1.0	-32%	28%	0.6	1
Upper Namoi Zone 1	-0.2	0.3	0.2	-100%	141%	0.6	1
Upper Namoi Zone 6	-0.1	0.3	0.1	-71%	320%	0.4	1
Upper Namoi Zone 3	-0.1	0.1	0.1	-45%	84%	0.2	1
Upper Namoi Zone 2	0.0	0.1	0.1	-26%	99%	0.1	1
Lower Namoi Alluvium	0.0	0.0	0.0	-99%	122%	0.1	1

The analysis shows that Upper Namoi Zone 7 is by far the most sensitive in terms of model predictions to the uncertainties in model hydraulic parameters. In this zone the highest average drawdown in any of the sensitivities was 4.7 m, 3.6 m greater than the Scenario 3 prediction of 1.1 m.

The sensitivity of predicted average drawdown in the other areas is significantly less than this. The next most significant zone in terms of sensitivity of predictions to model hydraulic parameters is Upper Namoi Zone 11. Interestingly this zone is sensitive in the opposite way and the most significant impact of the sensitivity analysis is a lower drawdown (almost zero compared with 1.6 m in Scenario 3).

Another important result is the fact that Upper Namoi Zone 10 shows the potential for a much larger average impact in the sensitivities of about 1 m drawdown than in Scenario 3 which returns an average of about 0.1 m.

If the analysis is undertaken only on the significance of percentage deviation from Scenario 3 impacts then it appears that:

- In terms of the potential for impacts to be higher than predicted, only Upper Namoi Zones 4, 5 and 11 show a limited sensitivity (less than maximum 50% variation from Scenario 3). Impacts in all other zones are shown to have the potential to be more than about 100% greater than the Scenario 3 impacts. This is most evident in the predicted impacts in Zones 6 and 7 which the sensitivities have shown could be as much as 320% higher and in Zone 10 where they could be as much as 1700% higher (but compared against a very low basecase change of 0.1 m).
- In terms of the potential for impacts to be lower, the results expressed are percentages of Scenario 3 impacts and are therefore limited to a maximum of 100% (which equates to no impact). The analysis shows that the average impacts reduce to zero in at least one of the sensitivity runs in Upper Namoi Zones 1, 9, 10 and 11 and the Lower Namoi Alluvium. Upper Namoi Zones 2 and 4 show limited sensitivity in this regard.

Parameter sensitivity

The deviation of predicted groundwater drawdown between the sensitivity runs and Scenario 3 is presented in Table 5.30 and Figure 5.24. This is the highest deviation (both higher than and lower than) experienced in any of the Upper Namoi Alluvium Zones or in the Lower Namoi Alluvium. This analysis therefore gives a regional sense of the significance of these parameters and inputs to the predicted impacts.

Table 5.30 Difference between Scenario 3 and sensitivity predictions of average drawdown

Sensitivity	Sensitivity run	Difference to Scenario 3 average predicted drawdown		
		Min	Max	Range
High Kv	G	-0.9	3.6	4.4
Low storage	J	-1.6	1.4	3.0
Low rainfall	D	-0.1	1.8	2.0
Low Kh	F	-1.4	0.3	1.7
High storage	I	-1.1	0.3	1.4
Low Kv	H	-1.2	0.1	1.3
Doubled CSG abstraction	A	-0.1	1.1	1.3
High rainfall	C	-0.6	0.6	1.2
High Kh	E	-0.3	0.8	1.1
CSG re-injection	B	-0.5	0.2	0.8

The data in the table has been ranked by the range of impacts produced by the parameter change. Therefore the high hydraulic conductivity run, which produced the highest deviation from the Scenario 3 results is at the top, and the CSG re-injection run is at the bottom with the lowest deviation.

In general terms the model predictions show most sensitivity to increasing the vertical hydraulic conductivity, decreasing the storage, decreasing the rainfall (and therefore groundwater recharge) and decreasing the horizontal hydraulic conductivity. These changes result in a range of departure from the Scenario 3 results (average by zone or area) of between about 4.4 m and 1.7 m. All other variations result in a range of difference between 1.4 m and 0.8 m.

Additional analysis highlights a few important features of the Model and these results:

- The Model predictions in the alluvium are most sensitive to increased vertical hydraulic conductivity (i.e. connection between the alluvium and the formations beneath). The overriding impact of this change is to increase the drawdown predicted compared to Scenario 3.
- Lowering the storage also has a significant control on the predictions. However, at the three times analysed the change is roughly equal between a reduction in impacts and an increase.
- The low rainfall case shows that the predictions are sensitive to this input and the change results in higher groundwater drawdown. The high rainfall shows that the model predictions are less sensitive to this change, but it results in both lower and higher impacts than the Scenario 3 case.
- Lowering the hydraulic conductivity (vertical and horizontal) and increasing the storage each have the effect of reducing the predicted drawdown.
- Doubling the abstraction associated with CSG activities adds a maximum of about 1 m predicted drawdown to any of the Upper Namoi Alluvium Zones.

5.5 Conclusions

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 expected output of coal mines in the catchment in 2014, on which the future development was based. Unfortunately the level of development of the CSG resource is harder to quantify due to the very early stage of resource investigation. However, the analysis above has shown that for this level of development the average impact on groundwater levels in the Upper Namoi Alluvium Management Zones could be in the order of 1 or 2 m. In localised areas within these zones the drawdown will be higher, and in some zones it may be over 5 m.

In the Lower Namoi Alluvium the impact is likely to be almost nothing, especially when that aquifer is considered as a whole.

The Model results have been shown to be most sensitive to under estimated vertical conductivity and overestimated storage, rainfall and horizontal hydraulic conductivity. These uncertainties could lead to higher or lower predicted impacts. This analysis has defined a range of impacts and highlighted which parameters have most control on the results.

For the most part the impacts in the sensitivity runs are in the same order of magnitude as the Scenario 3 run. Upper Namoi Alluvium Zone 7 is the most sensitive to parameter variations and the average predicted impacts range from 0.5 m to 4.7 m, with the basecase prediction at 1.1 m. The range in impacts in this zone therefore ranges from insignificant to significant in this analysis. This may demonstrate a weakness in the catchment scale modelling in terms of simulating mines in such proximity to the alluvium, as this zone is bounded by both the Shenhua and BHP simulated mines. This highlights that modelling at this scale cannot replace the need for detailed assessments as part of the project proposals.

The sensitivity of predictions to parameter variations is lower in the other zones.

Predicted drawdown is generally fairly insensitive to increased (doubled) abstraction associated with CSG fields. The greatest sensitivity is observed in Upper Namoi Zone 7, where average drawdown doubles from 1 m to 2 m.

In terms of predictive uncertainty an analysis was undertaken that included availability and use of model precursors, calibration performance and data availability and numerical performance. In these terms the zones fall into three categories:

- Highly certain: Upper Namoi Alluvium Zones 3, 4 and 5.
- Moderately certain: Upper Namoi Alluvium Zones 2, 8 and 11 and the Lower Namoi Alluvium.
- Highly uncertain: Upper Namoi Alluvium Zones 1, 6, 7, 9 and 10.

An analysis of the proximity between potential coal resources and groundwater resources shows that most of the Upper Namoi Alluvium Zones are in close proximity to coal bearing formations. Less than half of the area of Upper Namoi Zone 3 however is underlain by coal bearing formations and Upper Namoi Alluvium Zones 6, 9 and 10 and the Lower Namoi Alluvium are separated by more than 100 m from coal bearing formations. This analysis suggests that these zones are at less risk from direct groundwater impacts from development of the coal resource than the others.

Analysis of model predictions of impacts to groundwater flow and levels in the catchment from coal and gas development indicates that there is a potential both to negatively and positively impact groundwater quality in the alluvial systems. Increased drawdown of levels in the lower alluvium may lead to increased flow from the upper alluvial aquifer resulting in the mixing of different quality water, exacerbating a phenomenon that may already be occurring due to existing abstraction.

However, the predicted reduction of flow from the (potentially lower quality) hard rock formations into the (potentially higher quality) alluvium could result in improved quality of the alluvial water resources. Without sufficient data to characterise the water quality in the systems it is currently impossible to quantify these impacts.

Other key results of the analyses are:

- Mining activities account for 50% or more of the predicted drawdown throughout the Upper Namoi Alluvium. CSG activities account for almost all of the predicted drawdown in the Lower Namoi Alluvium.
- In the most heavily utilised Management Areas and Zones the average predicted drawdown is generally less than 4% of the estimated saturated thickness in 2010.
- Groundwater recharge will be impacted by mining and CSG activities. The magnitude and manifestation of this is highly uncertain. The greatest impact in the recharge estimates comes from the removal of all recharge falling within the footprint of open-cut mines. This change to recharge has a significant impact on the predictions in several of the Upper Namoi Zones. In Upper Namoi Alluvium Zones 1, 4, 5 and 11 this accounts for between 70 and 80% of the predicted drawdown.
- Historical drawdown between 1980 and 2010 was generally between 2 and 4 m in the Lower and Upper Namoi Alluvium.
- Upper Namoi Alluvium Zones 1 and 10 are incorporated in only a handful of Groundwater Model cells. This makes predictions in these zones susceptible to localised numerical and conceptual inaccuracies.

The results of the analysis of model predictions, sensitivity and uncertainty are collated and presented in Table 5.31. This summarises the analysis and concludes a relative severity of potential impacts from coal and gas development and a confidence in those predictions. The confidence is decided based on the relative uncertainty and sensitivity of the model in those areas. By Upper Namoi Alluvium Zone, the conclusions are:

- Zone 1. Predicted impacts are limited but show some significant sensitivity. For a number of reasons confidence in these predictions is low.
- Zones 2 and 3. Resource utilisation is very high in these zones, however, predicted impacts are limited (average and maximum mostly less than 1 m) as are the sensitivity of these predictions to parameter variations. The confidence in these predictions is high.
- Zone 4. Resource utilisation is high and predicted impacts are moderate (about 1 m average drawdown). The predictions show only limited sensitivity to variations in parameters and the confidence in the predictions is high.
- Zone 5. Resource utilisation is high and predicted average impacts are moderate (0.8 m average drawdown) and localised impacts can be high. Certainty in model set-up is high but the predictions are relatively sensitive to variations in parameters. Therefore the certainty in these predictions are classed as moderate.
- Zone 6. Resource utilisation is low. Predicted impacts are limited but show some sensitivity to variations in key model settings. Uncertainty in the set-up in this zone is also high. Confidence in these predictions is therefore low.

- Zone 7. Resource utilisation is low. Predicted average impacts are moderate (1.1 m average drawdown) and localised impacts can be high. Under almost all indicators sensitivity and uncertainty in the predictions in this zone is very high therefore these predictions are also low confidence.
- Zone 8. Resource utilisation is high but predicted impacts are quite low (0.5 m average). The model set-up in this zone is classed as moderately uncertain and the predictions are moderately sensitive to parameter variations. The predictions are therefore moderately certain.
- Zone 9. Resource utilisation is low and there is no direct connection to coal bearing formations. Average impacts are low but localised maximum impacts are high. Confidence in the predictions is relatively low.
- Zone 10. Resource utilisation is low as are the predicted impacts. However due to both high sensitivity and uncertainty, these predictions are classed as low confidence.
- Zone 11. Resource utilisation is low and predicted impacts are high (average drawdown of 1.6 m). The zone is subject to moderate uncertainty and sensitivity so the predictions are classed as moderately certain.

Only very limited drawdown is predicted in the Lower Namoi Alluvium. The maximum in any one model cell is limited to 0.3 m and the average over the whole area is virtually zero. Even though no calibration of this zone was undertaken, as the parameters were based on the calibrated Lower Namoi Alluvium model and the results show limited sensitivity to variations in key parameters, the predictions are considered to be relatively certain.

Changes to surface water flows caused by coal mining and CSG developments were calculated using the Hydrologic Model at selected gauging stations within the Gunnedah Basin. There are many uncertainties associated with the Model. Many of these relate to the simplifying and averaging that has to occur whilst creating the model sub-catchments and populating them with data.

Calibration of the Hydrologic Model is most certain on the main Namoi River, although the calibration could be improved as average modelled flows are higher than observed at all three stations. There is less certainty inherent in the results for the Mooki as there is less consistency of calibration. This could be related to factors such as different GW-SW interaction mechanisms or the methods by which the Namoi River is regulated.

Modelled flows at the gauging stations are predicted to fall by up to 1.7% under the current model calibration. Falls are greatest when there is more development. The results suggest that open-cut mining has the greatest influence on surface water flows, with there being little change recorded from both underground mining and CSG development. These results relate purely to outputs from the Hydrologic Model, which does not take into account the effects of GW-SW interaction.

Uncertainty analysis has shown the Hydrologic Model to be relatively insensitive to the parameters tested. The greatest change from the calibrated model was seen at site 419023, when a drier climate scenario resulted in a prediction of flow reduction of 3.3% compared to 1.8% in the calibrated model. Given the other uncertainties in the model this is considered to be a minor difference.

Table 5.31 Summary of groundwater level impacts in the Namoi catchment alluvial aquifers

	Context			Predicted impacts						
	Resource Utilisation	Historic drawdown	Average saturated thickness *	Certainty	Predominant cause	Sensitivity	Maximum average	Maximum in zone	Relative Severity	Confidence
Upper Namoi Alluvium Zone 1	High	3.2 m	1	Low	Mining	High	0.2 m	0.4 m	Low	Low
Upper Namoi Alluvium Zone 2	High	2.5 m	23	Moderate	Both	Low	0.1 m	0.6 m	Low	High
Upper Namoi Alluvium Zone 3	High	6.2 m	28	High	Mining	Low	0.1 m	1.3 m	Low	High
Upper Namoi Alluvium Zone 4	High	3.2 m	25	High	Mining	Low	1.0 m	2.4 m	Moderate	High
Upper Namoi Alluvium Zone 5	High	3.6 m	26	High	Both	High	0.8 m	4.3 m	Moderate	Moderate
Upper Namoi Alluvium Zone 6	Low	1.3 m	2	Low	Both	Moderate	0.1 m	0.4 m	Low	Low
Upper Namoi Alluvium Zone 7	Low	+1.4 m	2	Low	Mining	High	1.1 m	6.1 m	High	Low
Upper Namoi Alluvium Zone 8	High	7.9 m	15	Moderate	Mining	Moderate	0.5 m	1.5 m	Moderate	Moderate
Upper Namoi Alluvium Zone 9	Low	+1.1 m	18	Low	Both	Moderate	0.5 m	6.9 m	Moderate	Low
Upper Namoi Alluvium Zone 10	Low	2.8 m	2	Low	Both	High	0.1 m	0.1 m	Low	Low
Upper Namoi Alluvium Zone 11	Low	2.2 m	10	Moderate	Mining	Moderate	1.6 m	3.8 m	High	Moderate
Lower Namoi Alluvium	Moderate / high	4.7 m	39	Moderate	CSG	Low	0.0 m	0.3 m	Low	High

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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 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 even 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. 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 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 this Study.

Table 6.3 Alluvial monitoring bores used in the calibration dataset

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW021092	815582	6574821
GW030008	829780	6531489
GW030029	847413	6504398
GW030050	798603	6599084
GW030059	841398	6505431
GW030060	833930	6503319
GW030081	828975	6520133
GW030088	842736	6513127
GW030129	792891	6619373
GW030134	794052	6625656
GW030145	828125	6512487
GW030231	783147	6627333
GW030236	790982	6625561
GW030272	837412	6519498
GW030297	813423	6568480
GW030302	822242	6566573
GW030304	825485	6565675
GW030307	830167	6567662
GW030343	811168	6569867
GW030345	778258	6632397
GW030399	775624	6634706
GW030430	824081	6549497
GW030434	832256	6548898
GW030446	787675	6623707
GW030447	787060	6620816
GW030469	793537	6603574
GW030478	771289	6639841
GW036004	785924	6618205
GW036005	786980	6615648
GW036007	791288	6607331
GW036011	837582	6548519
GW036015	790466	6611359
GW036027	831815	6546414
GW036071	831160	6541694
GW036096	787770	6616459
GW036099	821330	6530741
GW036125	833084	6537347
GW036149	825421	6556739
GW036152	829906	6539724
GW036166	827889	6560205
GW036167	828170	6563404
GW036187	791053	6618191
GW036189	826471	6547114
GW036190	828700	6542049
GW036192	833395	6552016
GW036196	822638	6551639
GW036202	819289	6555871
GW036213	821971	6557644
GW036215	825578	6562774

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW036239	815183	6571380
GW036260	822459	6563336
GW036266	820958	6561127
GW036272	816845	6565503
GW036410	814511	6496865
GW036432	818096	6582428
GW036435	784780	6587009
GW036441	782557	6583361
GW036456	799201	6589944
GW036457	801121	6585296
GW036458	800844	6581940
GW036460	806764	6583681
GW036461	807201	6578241
GW036463	811523	6581668
GW036473	800454	6588145
GW036478	782992	6585691
GW036480	798029	6582264
GW036484	812518	6586545
GW036495	775825	6572974
GW036506	776343	6558346
GW036509	774673	6565413
GW036510	796647	6591836
GW036512	776444	6549776
GW036514	795742	6588897
GW036515	773083	6565643
GW036545	779428	6572502
GW036546	778806	6583438
GW036548	797354	6594158
GW036566	776235	6544011
GW036568	792071	6594825
GW036601	774602	6529350
GW036655	795383	6585278
GW036657	776767	6516520
GW036658	778278	6507213

There are a number of active groundwater monitoring locations in the alluvium that, 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 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	835408	6517008
GW030177	833250	6511770
GW036547	779245	6543477
GW036660	772972	6578795
GW036676	771790	6573766
GW041027	808516	6619427
GW093101	814721	6516376
GW093102	816125	6521874
GW093103	818460	6527576
GW965574	847508	6489946
GW965576	817852	6521677
GW968531	800698	6622322

The government (Pinneena) calibration dataset in the non-alluvial aquifers is not as extensive (Figure 6.4) as that for the alluvium and 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 provide 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	776343	6558346
GW036509	774673	6565413
GW036546	778806	6583438
GW030430	824081	6549497
GW036011	837582	6548519
GW036149	825421	6556739
GW036189	826471	6547114
GW036190	828700	6542049
GW036260	822459	6563336
GW036272	816845	6565503
GW030050	798603	6599084
GW036510	796647	6591836
GW036548	797354	6594158
GW030345	778258	6632397
GW030446	787675	6623707
GW036007	791288	6607331
GW030236	790982	6625561
GW030029	847413	6504398
GW030008	829780	6531489
GW030081	828975	6520133
GW030088	842736	6513127

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

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW030272	837412	6519498
GW030121	766605	6643873
GW965569	805774	6564906
GW030468	792643	6603133
GW040823	830721	6507652
GW036976	804350	6540406
GW030079	826771	6520913
GW036315	804786	6507946
GW030121	766605	6643873
GW030271	837857	6520904
GW036384	809370	6504147

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	803343	6594489
VNW221	803358	6594055
GW001613	804153	6596620
GW005749	804120	6593413
GW968389	797532	6567605
GW968390	797543	6567993
GW027356	797960	6569225
GW968387	798129	6569797
GW050395	814443	6594991
GW044068	815424	6593142
GW968537	812681	6593456
GW968534	813454	6591368
GW968440	772722	6626025
P16	772233	6623740
P18	776826	6621802
GW968437	780431	6620113
GW968436	777280	6616355
GW052266	802063	6603794
GW967851	804618	6605264
TemplemoreA	805988	6604549
GW976882	801867	6606192
GW967881	800599	6607364
GW967883	806444	6606689

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

Bore number	Easting (MGA 55)	Northing (MGA 55)
GW002129	804062	6605624
IBC2139	804615	6608387
IBC2114	804392	6609388
IBC2138	801980	6609621
IBC2115	804401	6609384
IBC2102	802221	6610995
IBC2103	802227	6610996
IBC2104	803687	6611361
IBC2105	803672	6611358
BCS3	811322	6607221
GW968393	798145	6567965
GW968438	777487	6625549

In addition to the sites mentioned above there is a lot of monitoring associated with the Watermark and Caroonna exploration areas. At present these sites only have short records so they have not been included as time variant sites in the Model. Monitoring data at these sites should continue to be collected 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 so 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 6 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 work that will provide data where there is currently very little and focus attention on parts of the Model that are most influenced by predictions but currently incorporate significant uncertainty.

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.
- Increased frequency of groundwater level monitoring.
- 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

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 this section, 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 north eastern portion of Zone 4. Additional groundwater monitoring is recommended in these zones. It is recommended that an additional four sets of monitoring bores (shallow and deep alluvial) be installed in the southern area (Zones 6 and 10), and an additional two in the northern area (Zone 4). 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. The areas are defined in Figure 6.5.

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. The basal GAB units (Pilliga Sandstone and Purlawaugh Formation) however could potentially experience significant impacts but currently 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, as they form the intervening layers between the coal seams and the shallower alluvial and non-alluvial aquifers, there is currently very limited understanding of the groundwater system within them and little opportunity to assess the migration of drawdown from mining and particularly CSG developments on a regional scale. It is also unfortunate that where monitoring bores in these formations do exist or have existed in the past, the exact completion details are uncertain, so assigning observations to any particular hydrostratigraphic unit is problematic.

It is therefore recommended that multilevel 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 an additional three 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.

Some groundwater monitoring is currently being undertaken in bores that are recorded 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 3.1 (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 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 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 fact 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 was 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 have 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 undertaken and widespread within 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 the highest priority for investigative work in terms of defining 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 in the area of the base of 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 (McNeillage, 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 Namoi 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, Δt_{shear} ,
- sonic, $\Delta t_{\text{compressional}}$,
- 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. 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 Zones 5, 11, 4, 3 and 7 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 multilevel (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. However, 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 should 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 VWP's 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 with which changes to groundwater quality, for whatever reason, can be monitored. 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. 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 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 6.6) and these are where further investigations should be targeted:

- The boundary area between Zones 5 and 11.
- The central and southern portion of Zone 4.

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 however, and it is recommended that any changes made are reviewed for possible inclusion in the Namoi 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.

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 that can be used variously to accurately log 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 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 and 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 of 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 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 try and increase confidence in or refine the model inputs.

Surface water

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.

The Model calibration has also suggested that it would be a useful exercise to complete a flow accretion survey along the Mooki River to determine gaining and losing sections. 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.

Long term investigations to improve Hydrologic Model estimates

Longer term studies would take several small, discrete catchments with differing baseline characteristics and instrument them extensively 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. In essence these would be small scale conceptual models.

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 through 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 in areas such as Maules Creek in recent years. However, there are still large areas of the 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.

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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. Potential impacts of mining and CSG developments not associated with water resources are not within the scope of the Study. 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 or impact is defined as the probability that a particular action will occur multiplied by its consequence.
- The prevention of a risk or impact reduces its probability.
- The mitigation of a risk or impact reduces the severity of the consequence.

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 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 with mining and CSG activities happening in the same space, impacts may be combined from multiple operations and multiple operators. The identification and mitigation plan for any impacts needs to be addressed by local site scale investigations to identify the actual cause(s), which industry and which operator should take responsibility.

7.2 Impact types

In general terms the following key impacts are possible;

Water quantity / availability

- Reduction in groundwater pressure / water level – at specific points where a resource is utilised i.e. a well or bore or spring.

- Regional reduction in groundwater pressure over an aquifer/groundwater body leading to reduced baseflow to streams.
- Reduction in stream flow where there is 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.

7.3 Specific predicted impacts

The Model has predicted the following potential specific impacts.

Groundwater levels

There is a potential for groundwater pressures in the deep confined groundwater systems in the catchment to drop by many tens of metres. These are the units from where there is direct abstraction for CSG and mining and this degree of pressure drop is expected. These resources are however limited and are not utilised for groundwater supply. There is no necessity for mitigation of direct impacts to these units.

There is the potential for groundwater pressures and water levels to be reduced in the alluvial aquifers. The Model suggests that these impacts can be most obvious in Management Zones that make up the Upper Namoi Alluvium. Section 5 describes the modelled impacts but as a guide, average groundwater level drawdown by aquifer management zone is predicted to be of the order of 0 – 2 m for Scenario 3. This is a cumulative impact coming from several mines and CSG operations. Maximum drawdowns can be as high as 5 or more metres and these may be easier to attribute to a particular operator.

Surface water flows

Where there are predicted impacts on surface water flow, typical flow decreases are of the order of 2%. These may vary in consequence between insignificant at high and average flow periods, but become more significant in low flow periods. It should be noted that most open channel flow measurements operate to an accuracy of $\pm 5\%$ of the actual flow so it would be difficult to identify and measure impacts at this level (AS 2009).

Groundwater quality

The potential impacts to groundwater quality can vary between the regional and local scale. Whilst the observational data is not sufficient to predict actual groundwater quality impacts, it does show that where water quality issues derived from the mixing of low and high quality water within these formations are currently being observed the additional drawdown caused by mining and CSG developments has the potential to enhance this process. However, the predicted reductions in groundwater flow from the hard rock formations to the alluvium that partly cause the increased drawdown (lower alluvium) could also have the effect of improving water quality in the alluvial aquifers.

Regional variations are most likely to be caused by regional changes in groundwater flows / pressures resulting in mixing of different quality water bodies. Data limitations are such that characterisation of the water quality and the controlling physical features has not been possible and modelled predictions of this mixing are impossible. However, the predictive results have shown that it may occur, especially in the areas where current groundwater abstraction is having the same impact.

Localised water quality impacts may also be associated with isolated incidents during CSG drilling and operations and mining operations, especially the handling of low quality water, and can occur at the surface or in the subsurface. This includes spills and leaks from surface infrastructure and operations. Such localised impacts are often managed by environmental permits and site management plans which are aimed at preventing such incidents before they occur. For example, where drilling will initially penetrate or be proximal to the alluvial water resources, the methodology and procedure should reflect the risk and be designed to provide full isolation.

Localised events in the deeper formations will move relatively slowly through the groundwater system. Localised events in the alluvium and highly fractured rocks will move relatively rapidly through the system. These variations can therefore be considered separately in terms of mitigation and methods are highly site and impact specific but are well understood in the environmental management sector and can be rapidly implemented as required.

Surface water quality

As with groundwater, direct simulation of surface water quality has not been possible. The introduction of lower quality water into higher quality surface water will result in rapid mixing and transport in comparison to groundwater mixing. Mitigation options will therefore be different.

The main potential risk to surface water quality is from unlicensed / emergency discharges of low quality water directly into the surface water system. These are best managed by reference to a site specific environmental management plan with oversight by the relevant regulator.

7.4 Risk reduction

Prevention of an impact is often better than the mitigation. The ultimate prevention is not to undertake the activity at all. Assuming that it is going ahead 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. Reducing the risk of pressure reductions in other locations would most obviously involve removing less water. However, 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, open-cut and underground. Groundwater will seep into the voids due to the pressure gradients developed by maintain 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 scenario. Similarly to the CSG scenario, water 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).
- Consider local groundwater conditions when identifying sites for water storage dams, treated water facilities and associated brine storage facilities, production facilities and related storage areas. (Coffey 2012).
- Review local geographical 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.

All these aspect are usually covered in the environmental approvals and environmental management plan for a specific operation.

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 and 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.

7.5 Baseline data

The establishment of a baseline data set 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 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 in the natural state. Early detection can significantly enhance the effectiveness of any mitigation works. Section 6 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.

7.6 Impact mitigation

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

Alluvial aquifer & hard rock groundwater pressures

- 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 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 of pumps.
- Test boreholes for integrity - in the event of a failed test decommission, repair or convert these wells.

Surface water flows

For regulated reaches the most feasible option is to make good flows by dam releases. If this is not possible due to dam operating rules or competing interests then make good arrangements 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. If flow losses are of the order of 2% then releases need not be significant.

On unregulated reaches the dam release option is not available so the only make good arrangement is the discharge of comparable quality water by CSG / mining operators into rivers. 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 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.

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.

7.7 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). Greater than 90% of RO output is 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.

7.8 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. For example, in Queensland, the State Government 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. Beltana No.1 Project. 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.

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NAMOI CATCHMENT WATER STUDY

INDEPENDENT EXPERT

PHASE 1 REPORT



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NAMOI CATCHMENT WATER STUDY

INDEPENDENT EXPERT

PHASE 1 REPORT

November 2010

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REPORT REVIEW SHEET

NAMOI CATCHMENT WATER STUDY - INDEPENDENT EXPERT PHASE 1 REPORT			
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APPENDIX

Project Plan

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EXECUTIVE SUMMARY

Schlumberger Water Services (Australia) Pty Ltd has been appointed as the Independent Expert for the Namoi Catchment Water Study and has been charged with the development of an integrated suite of models for the assessment of the nature and extent of potential effects from coal and gas developments on the water resources of the catchment. The purpose of the Study is to collate and analyse quality data to assist in identifying and quantifying risks associated with the coal mining and coal seam gas developments on catchment water resources.

The models will have the capability to represent past, current and future water use scenarios at spatial and temporal scales that realistically represent those processes. The model will also have the capability to account for coal and gas developments, their spatial relationship to water resources and the potential effects of those developments.

The Study is to be conducted in four phases:

- Phase 1: Scoping and literature review;
- Phase 2: Data collation and analysis;
- Phase 3: Modelling; and
- Phase 4: Reporting.

The purpose of this report is to document the results of Phase 1 work which commenced on 1st September 2010. These activities have included:

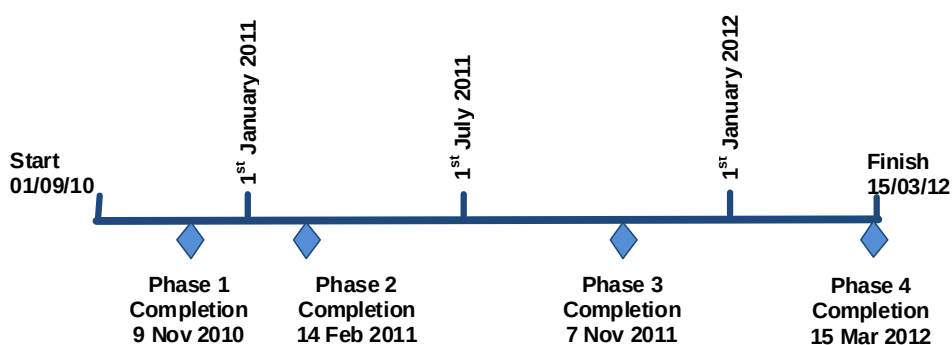
- In conjunction with the Ministerial Oversight Committee (MOC) and Stakeholder Advisory Group (SAG), participation in the Study Inception Meeting and Phase 1 Commencement Meeting held in Gunnedah on 1st September;
- Between 6th to 8th October, participation in a 3 day tour and review of the Namoi catchment organised by the MOC and SAG, including meeting with various stakeholders and review of agricultural and industrial operations in the catchment;
- Development of the Study Scope of Work, Project Plan and Flowchart;
- Completion of a review of relevant literature for the Namoi catchment; and
- Preparation of the Phase 1 report (this document).

The Study Scope of Work is detailed in Section 2 and includes an initial general discussion of potential model-related focus, priorities and constraints. However, prior to completion of conceptual model development (Phase 2 & 3) it is not appropriate or possible to detail the configuration of models, nor potential assumptions or limitations.

Section 3 documents the Study Plan which has been completed using the Microsoft Project software and is presented in the form of a Gantt chart as the Appendix to this report. The Project Plan includes the allocation of time and resources for the tracking of project progress, assists with project management and planning and demonstrates the target dates for key processes. The Project Plan presents a detailed schedule for the completion of the Study and includes:

- Start and end dates for each phase of the Study;
- Key tasks required to deliver the deliverables;
- Identification of key personnel involved in each task;
- Milestone dates for the deliverables;
- Tasks that are critical to the completion of the Study within 18 months of commencement;
- Identification of tasks that are critical to meeting the end dates of each Study phase; and
- Those tasks that require participation by the MOC and the SAG.

The timeline immediately below is representative of the Project Plan and defines the key dates such as commencement and completion of each phase. Further detail is presented in the Project Plan.



An updated Study Flowchart is also provided at the end of Section 3 which:

- Maps the phases of the Study to show the progression from the commencement through to the conclusion and identifies overlaps between phases;
- Shows the key elements of the program and scope diagrammatically, including key tasks, milestones, and responsible personnel;
- Illustrates the interrelations between key tasks, key stakeholders, and also between tasks and stakeholders; and
- Identifies governance processes that will be implemented during the Study.

The literature review is presented as succinctly as possible in Section 4 and includes subsections on the geological setting, hydrology, hydrogeology, water resources and their management, water quality, and potentially relevant previous and pre-existing modelling studies and numerical models. The literature review therefore covers a wide range of topics and summarises relevant published literature which is readily available in the public domain. The review facilitates an initial interpretation of data, information and knowledge so that a targeted-approach to data collection, model conceptualisation and modelling can be undertaken.

An overview of the coal and coal seam gas (CSG) operations and exploration leases within the catchment is also presented within the literature review section. This includes a preliminary discussion of how these industries may interact with and influence the catchment water resources. The information contained within this section will expand significantly when the coal and CSG Study partners are able to provide the Study with historical monitoring data, test data and other relevant information resulting from their exploration and operational activities.

The subsequent sections (unnumbered) of this document list the references cited and also provide a bibliography of information reviewed but not referenced in this report.

The current phase of the Study will terminate with the Phase Completion Meeting to be held in Gunnedah on 9th November 2010. The Phase 2 Commencement Meeting will be held the same day, followed by community information sessions on 10th November in Gunnedah and Quirindi. Phase 2 will focus on data acquisition, data collation, the development of a relational database and geographic information system (GIS) which will form the foundation of the hydrogeological conceptual model for the whole of Namoi catchment.

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1 INTRODUCTION

1.1 Background

Schlumberger Water Services (Australia) Pty Ltd (SWS) has been appointed as the Independent Expert for the Namoi Catchment Water Study and has been charged with the development of an integrated suite of models for the assessment of the nature and extent of potential effects from coal and gas developments on the water resources of the catchment. The purpose of the Study is to collate and analyse quality data to assist in identifying and quantifying risks associated with the coal mining and coal seam gas (CSG) developments on water resources. The scope of the study is to include the whole of the Namoi Catchment and the project will be conducted in four phases:

- Phase 1: Scoping and literature review;
- Phase 2: Data collation and analysis;
- Phase 3: Modelling; and
- Phase 4: Reporting.

This document presents the Phase 1 report by the Independent Expert.

1.2 Setting and context

The Namoi Catchment is an irrigation and agricultural area of significance in New South Wales (NSW) and Australia. Covering an area of approximately 5,400,000 ha, the catchment has a variety of land uses including natural vegetation, grazing, cropping, forestry, nature conservation, water, urban and irrigated pastures. The Namoi River flows in a generally westerly direction over a distance of 659 km from its source in the southeast margin of the catchment to its confluence with the Barwon River near Walgett (Figure 1.1).

The Namoi Catchment is a part of the Murray Darling Basin (MDB) covering approximately 3.8% of the total basin area. Significant tributary streams to the Namoi River include the Macdonald River, Peel River, Cockburn River and the Manilla River. Smaller tributaries of the Namoi River include the Cobrabald River, Cocks Creek, Maules Creek, Mooki River and Bundock Creek. Three key water supply storages are present in the Namoi Catchment; the Split Rock Dam on the Manilla River (397,000 ML), the Keepit Dam on the Namoi River (423,000 ML) and the Chaffey Dam on the Peel River (62,000 ML).

The river plain merges with the Gwydir, Castlereagh, and Barwon River flood plains near Walgett. A number of wetlands are situated south east of Gunnedah, the largest being Lake Goran with some small lagoons and billabongs on the river flood plain.

The catchment is reportedly one of the most intensively developed groundwater resources in NSW. Groundwater is a significant resource in the Namoi Catchment and has been extensively developed with the highest rate of groundwater extraction in NSW.

A large part of the catchment is underlain by the Sydney - Gunnedah Basin containing significant coal resources and a potentially viable CSG resource. Coal is currently extracted from a number of mines throughout the region, both from open cut and underground operations with substantial developments planned or being investigated. The Gunnedah Basin is currently subject to a number of CSG developments in various ranges of exploration and pre-developmental studies.

The Study requires the development of models to facilitate assessment of the potential effects from coal and gas developments on catchment water resources. The model(s) is to be a three dimensional transient model capable of simulating surface water and groundwater flow and quality characteristics. The model(s) will have the capability to represent past, current and future water use scenarios at spatial and temporal scales that realistically represent those processes. The model will also have the capability to account for coal and gas developments, their spatial relationship to water resources and the potential effects of those developments.

The model or models (to be determined in the course of the Study) is to be a whole of catchment model in order to account for all sectors of the community including agriculture, industry, resources, and the broader community. The model outputs will enable the quantification of current and potential effects on surface water and groundwater flow and quality. It is understood that the modelling methodology must be discussed with the MOC prior to commencement. It is further acknowledged that the completed model will be:

- Designed to be readily transferred to 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);
- Capable of the management and display of spatial data.

1.3 Phase 1 objectives and scope

The aim of Phase 1 of the Study is to produce a detailed plan for the completion of the work program. Within Phase 1 a detailed Scope of Work will be prepared, a Study Plan including a flowchart and Project Plan will be developed, and a Literature review of pre-existing studies and reports undertaken.

1.3.1 Scope

The Scope of Work will address the following:

- A discussion of the high level technical parameters and the way in which these will be addressed in the Study including the assumptions which the Independent Expert proposes to make for modelling purposes;
- A description of the areas of water resources to be prioritised;
- The spatial location/distribution of water resources and coal and gas resources;
- A current understanding of the nature, extent and condition of water, coal and gas resources in the catchment; and,
- A detailed view on the current monitoring programs including baseline, during operation and post-closure monitoring programs for past, current and proposed coal and gas developments.

The Strategic Terms of Reference under which the Study is commissioned are:

- To provide a spatial understanding of underground and surface water flows in the catchment through the most appropriate methodology (potentially a three dimensional understanding).
- 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 groundwater resources in the catchment.
- Within this strategic context, to 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 to be considered as factors in modelling.
 - Identifying the likelihood of potential impacts posed by coal and gas development.
- To enhance the technical foundation for government and government agencies' actions, decisions and policies in relation to coal and gas resource development within the catchment.
- To 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.
- To make recommendations as to practical measures that could be considered in mitigating or managing potential impacts of coal and gas development.

1.3.2 Study plan

A detailed Study plan (the Program) will be developed for undertaking the Study. The Program must:

- include start and end dates for each phase of the Study;
- include key tasks required to deliver the deliverables;
- identify key personnel involved in each task;
- identify milestone dates for the deliverables; and
- identify tasks that are critical to the completion of the Study within 18 months of commencement;
- identify tasks that are critical to meeting the end dates of each Study phase; and
- identify those tasks that require participation by the Ministerial Oversight Committee (MOC) and the Stakeholder Advisory Group (SAG).

As a part of the program a flowchart will be developed as a diagrammatic representation of the process undertaken for the study. The Study Plan flowchart will:

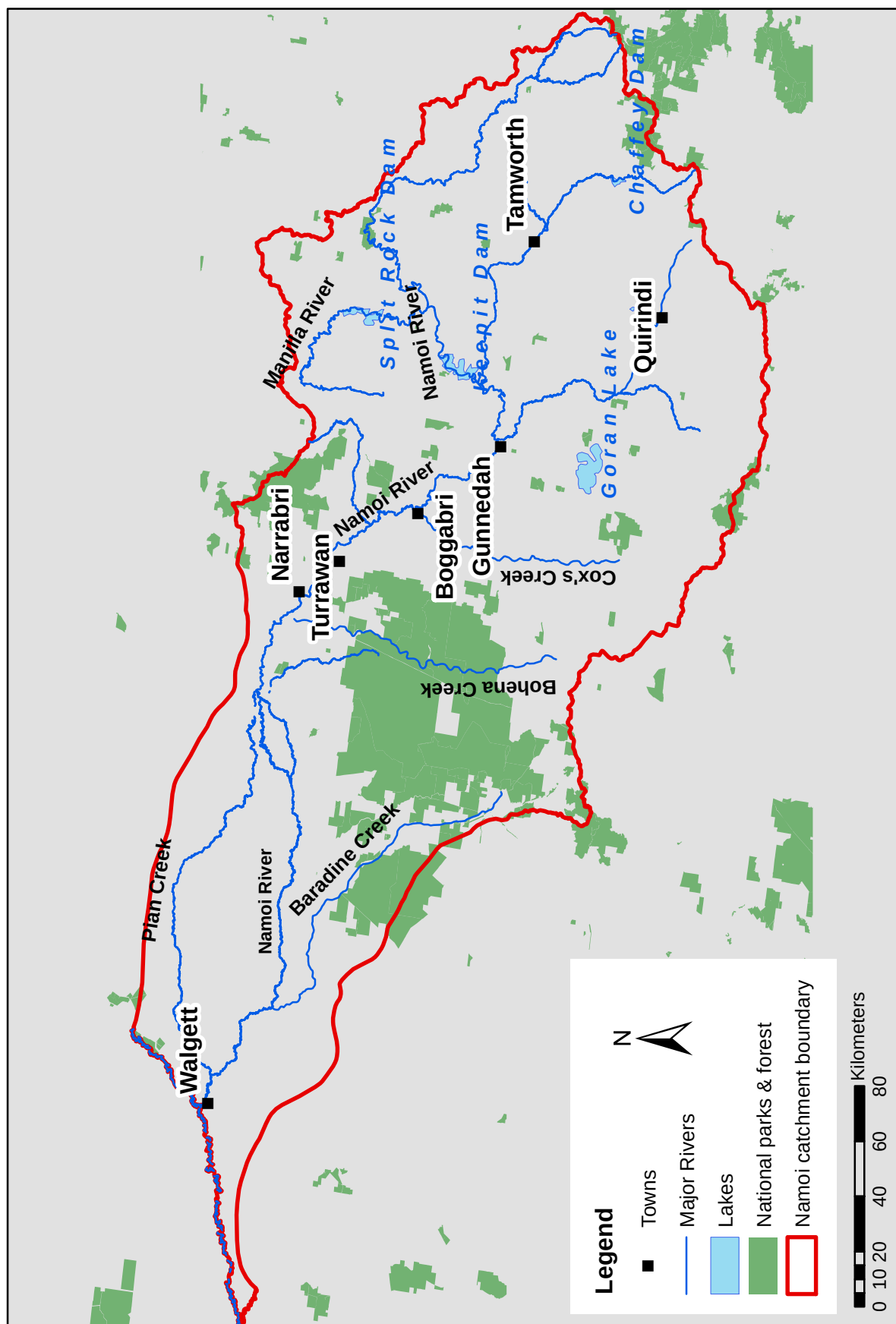
- Map the phases of the Study to show the progression from the commencement through to the conclusion of the Study and identify overlaps between phases;
- Show the key elements of the Program and Scope diagrammatically, including key tasks, milestones, and responsible personnel;
- Show and explain diagrammatically the interrelations between key tasks, key stakeholders, and also between tasks and stakeholders; and
- Identify governance processes that will be implemented during the Study or part thereof.

The flowchart will be developed in the form of both a Gantt chart for project management and scheduling purposes and diagrammatical form for consultative purposes.

1.3.3 Literature review

A Literature review of all currently available and accessible studies and reports will be undertaken. The objective of the literature review is to determine the social, geological, hydrological, and climatic character of the catchment whilst correlating existing data and gaining scientifically specific information of the catchment. The literature review is a significant first step in the process of catchment conceptualisation.

Figure 1.1 Location map for the Namoi catchment



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2 THE SCOPE OF WORK

2.1 Phase 1 scope discussion

The Scope of Work presented in this section has been designed to achieve the development of an integrated suite of models for the assessment of the nature and extent of potential effects from coal and gas developments on the water resources of the Namoi catchment. The Phase 1 scope items are discussed and the scope currently planned for Phase 2 to Phase 4 work is presented.

The Phase 1 scope includes a requirement to address the issues listed below and in the preceding section. However, at this stage (Phase 1 completion) only a review of the literature, preceding studies and the key issues has been completed and the process of acquiring and assembling the available data in a comprehensive hydrogeological conceptual model is only just commencing. This is the primary activity planned for Phase 2 and the early part of Phase 3. Prior to completion of conceptual model development it is not appropriate or possible to detail the configuration of the model or models, nor the assumptions, limitations and compromises that might be required. Therefore the discussion presented below is of a more general nature and includes:

- The high level technical parameters for the Study including the potential assumptions;
- A description of the areas of water resources to be prioritised;
- The spatial location/distribution of water resources and coal and gas resources;
- A current understanding of the nature, extent and condition of water, coal and gas resources in the catchment.

Aspects of the catchment hydrology and hydrogeology that will be addressed in Phases 2 and 3 of the Study will include:

- Geology of the catchment - considering the sub-catchments at the local scale, their architecture and geological setting, the different types of water source connectivity and recharge zones in those localised catchments, their geological proximity to coal and gas resources and prioritising for study those sub-catchments relevant to existing or planned coal and gas developments.
- Surface water – including flow conditions particularly during low flows, water quality, floods and flood-plain areas and impacts of potential mine-induced subsidence on overland water flows.
- Groundwater – including groundwater flow direction, level, yield and quality and current salinity levels.

The assessment of the relationship between the water resources and coal and gas resources will consider past, current and future coal and gas operations in the Namoi catchment including:

- Locations, depth, extent and areas of the coal and gas resources.
- Resource recovery practices and techniques used or to be used with respect to the profound differences between coal and gas development.
- A review of current monitoring programs including baseline, during operation, and post closure monitoring programs.
- Previous impact assessments undertaken by resource companies of surface and groundwater, water quality, subsidence, impact on aquatic, surface water and groundwater dependent and terrestrial ecology.
- Location of agricultural bores and their relation to existing and future coal and gas development.
- Likelihood of potential impacts of contamination, mobilisation and increasing salinity by coal and gas development.
- A general high level consideration of the potential for mine induced subsidence, recognising that subsidence can only be properly assessed in relation to specific mine plans which have not yet been developed for proposed future coal and gas development.
- A general consideration of the consumptive use of water by coal and gas development.

SWS will undertake the following investigations which will be combined to form the initial conceptual model of the groundwater and surface water systems for the whole of the Namoi catchment:

- Review of all relevant data and identification of key issues.
- Compiling and reviewing all relevant geological, geophysical, structural, hydrological and hydrogeological data available in the public domain.
- Obtaining all well records and historical abstraction from both groundwater and surface water, and documenting all relevant water features and potential impact receptors.
- Identification of sources of recharge to, and discharge from the groundwater system, including stream-aquifer interactions.
- Definition of all the principal hydrogeological units, including preliminary estimates of groundwater transmitting and storage properties.
- Estimates of groundwater elevations and groundwater flow directions.
- Definition of water chemistry, water types, potential evolution of water chemistry, regional and vertical variations in water quality, potential man-made influences on water chemistry.
- As appropriate, review the application of surface geophysics to help identify groundwater monitoring and investigation drilling targets.
- Preparation of sampling and analysis plans to ensure maximum value can be obtained from data collection in the future.

2.2 Priority water resource areas

The Namoi Catchment Water Study will have a priority focus on water resource areas most likely to be influenced by the development of coal and gas extractions. At this initial stage of the Study attention will be focused on the alluvial aquifers in close proximity to both potential and existing coal and gas operations and Gunnedah Basin sediments intersected by coal and gas operations. A high priority will also be placed on the investigation of the connectivity of the Gunnedah Basin sediments to the overlying and adjacent alluvial resource. The spatial relationship between coal exploration lease areas and main water resource areas is represented in Figure 2.1. The spatial relationship between petroleum exploration lease areas and main water resource areas is represented in Figure 2.2.

The scope of work for Phase 1 requires the spatial location/distribution of coal and gas resources and the extent of the nature and condition of these resources to be commented on. Adequate completion of this task requires the acquisition and assessment of data sets from the government and industry partners to the Study and until this data has been provided and reviewed, only a cursory assessment can be completed. This task will be addressed in more detail at the end of Phase 2 and during the conceptualisation process that will form the basis of Phase 3.

An initial review of resources, based on the exploration lease areas and currently licensed activities shows that:

- Current coal mining exploration and activity prospects are limited to a zone through the centre of the catchment which closely follows the location of the alluvial deposits upstream of Narrabri.
- No coal exploration leases are present in the areas downstream of Narrabri or within the Peel River catchment, although the potential for coal beds to underlie the fold belt within the Peel River catchment is currently being evaluated.
- Petroleum exploration leases cover the majority of the Namoi catchment, with the largest area of no coverage being located in the Peel River catchment area. Petroleum exploration licences are required to explore for coal seam gas.

In view of the above, during Phase 2 SWS intend to review all relevant and available data for the whole of the Namoi catchment.

2.3 Considerations for numerical model development

2.3.1 Background

Regional scale geological and numerical flow models provide an approximation of very large, heterogeneous and complex systems which are generally poorly defined in space and time. The combined effect of these factors is that many simplifications and assumptions are made about the systems in order to allow for the construction of numerical models.

The Namoi groundwater system has high data density (groundwater level, stratigraphic, hydrochemical observations) in certain areas (i.e. the alluvial plains) and very low data density in other areas (i.e. the Gunnedah Basin sediments). Similarly, the Namoi catchment surface water system has high data density (flow, aquifer connectivity, river bed elevation observations) in certain areas and low data density in other areas. This means that model predictions will be subject to more uncertainty in some areas than in other areas.

Until data collation, conceptualisation, model construction and calibration phases are complete it is not possible to detail the model (or models) assumptions and limitations. However, the following subsections highlight some general model-related considerations that are likely to be relevant to the Study.

2.3.2 Observational data

A significant amount of measured geological, hydrological and hydrogeological data will provide input to the Study. All measured data incorporate error. This error can come from a number of sources including (but not restricted to), measurement method, data collection, surveying accuracy, borehole completion and data handling and transfer.

The observational data used to construct and calibrate the geological and numerical models will be subject to a significant quality assurance exercise to ensure that only high-confidence data is used. The purpose of this audit will be to remove significantly erroneous information from the dataset, with the remaining data assumed to provide an accurate depiction of the groundwater and surface water systems.

2.3.3 Model spatial discretisation

In order to represent the geology and groundwater / surface water flow systems the area will be divided into a number of grid cells. The number of cells is a function of the spatial extent (domain) of the model and the size (dimensions) of each cell. These will depend on the size of the model and the simulation requirements (fundamental purpose) and complexity. Within each cell the properties of the cell such as elevation, hydraulic property, boundary condition, thickness, etc. are uniform. Inevitably, a compromise is required between the number of model cells and the time required for the model to complete a simulation, i.e. if the simulation time is too long then the value and benefit of the model as a predictive or management tool is significantly reduced.

2.3.4 Groundwater flow

A number of assumptions are required to reduce the complexity of groundwater flow to a level at which it can be simulated in a regional numerical model (i.e. with a set of simplifying equations). For the Namoi model these assumptions are likely to be:

- Darcy's law, which describes the flow of fluid through a porous medium, provides a valid simulation of groundwater flow at the regional scale of the model.
- Groundwater flow is laminar and streamlines are horizontal.
- Groundwater flow at any point is consistent for the full depth of the aquifer unit.
- Hydraulic properties are homogenous and isotropic for the area within a model cell.
- Fractured rock flow is equivalent to flow through a porous medium at a regional scale.
- The significance of variable density flow is assumed to be negligible and is not simulated.

2.3.5 Hydraulic properties

The hydraulic parameters assigned to the model will be derived from available data sources and as such assume that the methods used to attain those parameters were appropriate and that the results are representative. However, the hydraulic characteristics of individual hydrogeological units vary considerably and over very small distances. Laboratory tests of borehole core provide a very precise indication of the conditions at the borehole only. Long term (several months) and high volume pumping tests provide an indication of the (average) hydraulic characteristics of the material between the borehole and several hundreds of metres away. Alternative testing methods provide a scale of information between these two extremes and all are subject to a number of assumptions. This data will be used to divide the groundwater system into zones of similar hydraulic characteristics. There are likely to be significant areas within these zones where no testing data is available and the adopted hydraulic parameters will need to be extrapolated from tests many kilometres away. The model (and therefore model predictions) will be most uncertain in these areas.

2.3.6 Boundary conditions

The interaction between the simulated groundwater systems and surrounding units will be examined during the conceptualisation process. This will be used to determine boundary fluxes that can be applied to model grid cells. Where boundary flows exist, the volume of that flow will be estimated using Darcy's relationship.

A significant number of "internal" boundary conditions will be used to assign groundwater abstraction within the model domain. In many instances, due to the size of model grid cells, a number of individual abstractions may need to be amalgamated. The abstraction that is applied to the grid cell is divided evenly over that area and the model cannot therefore provide an estimate of the drawdown at the bore itself (even if only a single abstraction is present in the grid cell). All groundwater and surface water inputs / outputs within the model domain (rainfall, recharge, river interaction, boundary flow, etc.) are treated in this way.

2.3.7 Topography / natural surface

It is anticipated that the natural surface of the model will be constructed using New South Wales government Digital Elevation (Terrain) Model (DEM) where possible. The assumptions to be made from this data will be dependent on the scale and resolution of the available data. Where a DEM is not available land surface will be digitised from existing topographic mapping at a scale to be determined. All scale and resolution issues will be documented in an Assumptions and Limitation section of the appropriate report.

2.3.8 Model area

The model area will be defined through the development of a whole of catchment conceptual model. The conceptual model will take all available data on geology, water levels, water quality, abstraction, climate, etc., and combine it to generate as detailed an understanding as possible for as wide an area as possible. During conceptualisation areas of high quality spatial and temporal data will be identified. These areas will have fewer uncertainties than areas with very sparse data. This will translate across into a higher degree of confidence in numerical model results. Therefore, at the completion of the conceptualisation phase a numerical model area will be defined so that the Study objectives can be met with the lowest degree of uncertainty and the highest level of confidence.

At the present time no datasets have been analysed, but from the literature review it can be concluded that the majority of data will be focused along the main river valleys, within the Groundwater Management Areas, and within the areas of groundwater monitoring associated with the coal and gas operations. Specific areas which are likely to be a focus for current and historical data collection include:

- Upper Namoi River Alluvium
- Lower Namoi River Alluvium
- Peel River alluvium and fractured rock aquifers
- Active open cut coal mines
- Active underground mine at Narrabri
- Closed coal mines, including the Canyon Mine which was only closed in 2009
- Coal exploration areas at Carroona and Watermark
- Pilot CSG projects at Narrabri (ESG), and those currently being developed by Santos.

Some potentially large areas of the Namoi catchment, located away from the main agricultural and mining areas, are likely to fall within a category of low confidence data areas. These are likely to include areas such as the National Park areas, along the unregulated tributary streams, and the headwaters of the Namoi. The amount of data available in these areas will be identified further in the next phase of the project.

As the scope of this project is to look at the potential impacts of Coal and CSG extraction on the water resources the deeper borehole data that is available will be key to any understanding of the shallow-deep aquifer interactions.

The definition of a numerical model(s) area will depend on the following:

- The construction of the conceptual model.
- A review of the conceptual model to determine the areas which contain enough data to be meaningfully translated into a numerical model. At present these are likely to include, but not necessarily be restricted to:
 - The areas of alluvium along the main rivers which contain both the groundwater abstractions and coal mines regardless of whether they are directly underlain by potential CSG deposits;
 - The area of the catchment which is underlain by Gunnedah Basin formation, and which contains potential CSG sites, regardless of whether it is overlain by alluvium;
 - Any adjacent areas to those mentioned above which may be influenced by Coal or CSG extraction.
- The locations which are identified as being potentially impacted, and the scale at which numerical modelling would be possible, valuable and inline with Study goals. There may be more than one model area which is developed.

2.4 Current monitoring programs

Extensive water resources monitoring is undertaken throughout the Namoi Catchment by the New South Wales Department of Water. Data related to this monitoring is currently being sought from the department and will form the basis for water level, flow and quality information for the model. It is expected that this data will be obtained by late November 2010. Until this time, confirmation of existing monitoring programs is limited to publicly available data via the internet.

All coal and gas companies operating within the Namoi catchment have confirmed the existence of baseline monitoring programs for water resource management. Operating mines and gas extraction operations have also confirmed that monitoring is being undertaken and will continue. All companies contacted have indicated that they will provide the relevant information to SWS on the finalisation of data exchange agreements with the MOC. On the acquisition of the relevant data SWS will provide a discussion of the monitoring programs as a part of the model conceptualisation report scheduled for Phase 3.

2.5 Phase 2 - Data collation and analysis

2.5.1 Data collation

It is anticipated that the data collation phase will involve a high level of liaison with the study stakeholders and a visit to each of the data custodians may be required. SWS will undertake to collect and use of the most reliable and accurate data available at the highest resolution possible. However, data of lower resolution will have an effect on the overall resolution of the models and these will be identified and recommendations made for rectification.

SWS will liaise with the MOC, SAG, and all relevant stakeholders, including those listed in Appendix 3 of the Tender document, for the collection and collation of relevant data sets. Water extraction data will be collected from all available sources including agriculture, coal and gas activities, town, domestic, industry, and stock. Disparate datasets describing formation depths, hydraulic parameters, hydrochemical parameters are currently held by CSG companies, mining companies, external consultants and government departments.

In most cases these are held as datasets, not as functional databases since relational links and meta-data have not been fully established.

As part of the Study, it will be essential to compile a validated relational database, which includes the publicly available information, and any data which industrial companies are able to release for the purposes of the Study. To allow management of the basin as a whole, this database should be developed to the point where it is accepted by all stakeholders. In order to achieve this, a single, central, live database would be required which is accessible to the key stakeholders and which is regularly updated. This database would also have the capacity to maintain monitoring data collected during the study. All data sets will be presented spatially through the use of the Geographical Information System (GIS) software ArcGIS.

A large component of the data validation and management will include the installation of relational links, and the assessment of “orphaned data”. This process would be integrated with the construction of the geological model, and would use initial approximate contoured stratigraphic horizons to allocate hydraulic or hydrochemical data from unclassified wells to the most likely horizon.

The review and documentation of fundamental data and information, and the nature of coal seam hydrogeology will allow local and regional hydrogeological consequences of CSG extraction and mining activities to be better understood and monitored. SWS will design and develop a regional information system and data repository to support the development of a regional groundwater monitoring, impact modelling and cumulative impact monitoring regime. SWS will use this database to identify data gaps and to design further field investigations to fill these gaps.

Relevant data to be collated will include but not be limited to:

- Physical characterisation of the catchment;
 - Topography.
 - Surface drainage.
 - Regional geology.
 - Soils.
 - Vegetation coverage / land use.
- Climate;
 - Rainfall data.
 - Evaporation.
- Hydrogeological characterisation;
 - Groundwater monitoring data.
 - Hydraulic property data including pump tests, isotope testing results.
 - Aquifer extents.
 - Groundwater quality.
 - Geological logs.

- Groundwater management;
 - Groundwater monitoring data.
 - Current and historical groundwater allocations, extractions, and restrictions.
 - Historical and current groundwater allocation and management rules.
 - Historical and current groundwater management units.
- Surface water characterisation;
 - Surface water quality.
 - Stream and channel bed elevations.
 - Water supply infrastructure location and extents (including farm dams).
 - Rainfall / runoff data including Interception data.
- Surface water management;
 - Surface water monitoring data including flow, and stage heights.
 - Surface water allocations, extractions, and restrictions.
 - Historical and current surface water allocation and management rules.
 - Historical and current surface water management units.
 - Interaction between surface water and groundwater;
 - Baseflow data.
 - Stream bed and bank hydraulic characteristics.
 - Stream and channel leakage data including irrigation areas.
- Current and historical spatial data including;
 - Catchment and sub-catchment boundaries for surface water and groundwater.
 - Water management areas.
 - Urban areas.
 - Industrial areas including coal and gas extraction (historical, current, proposed and exploration areas).
 - Irrigation areas.
 - Agricultural extents including crop type, growing and irrigation cycles.
 - Rainfall zones.

2.5.2 Data analysis

The collated data will be analysed and presented through the use of GIS software such as ArcGIS, contouring packages such as Surfer, and the three dimensional geological modelling software platform of PETREL. The output from these packages will be presented in the form of maps at various scales. These may be of the

entire catchment when looking at the spatial extent of datasets etc, but can also be extracted for smaller areas when looking at issues such as complex geological layering in different regions.

The validated database would be used to construct a geological model of the study area. This model will include the position and extent of the main coal seams relevant to CSG production and mining activities, and all of the overlying and underlying horizons of relevance to the prediction of impacts. SWS would typically construct the geological model using PETREL, which is suitable to handle the volume of data and complexity of interpretations for the Namoi catchment units. The model would include:

- The top and base of each stratigraphic horizon within the catchment defined from drilling intercepts, outcrop mapping, interpretation of downhole geophysics, seismic interpretations.
- Structural features identified from seismic interpretation and drilling investigation.
- Formation properties derived from drill stem tests, pumping tests, injection tests, core analyses, downhole geophysics and records of flow rates from wells.
- Geochemistry of the formation materials derived from core analyses, hydrochemistry of formation waters defined by sampling and analyses and by downhole geophysics.
- Use of PETREL analyses to investigate alternative stratigraphic geometries and identify the most likely geometry and associated uncertainty.

The aim of the data analysis phase will be to gain a comprehensive understanding of the physical characteristics of the catchment, and the flow and quality characteristics of each water source. During this process a data gap analysis will be undertaken. All data gaps identified will be prioritised and the implications of those data gaps to the modelling process outlined and reported to the MOC and SAG.

Recommendations for the rectification of critical data gaps will also be presented. Subject to the level of data available from the database, the resulting uncertainties in the geological model, and the relative importance of the formation in terms of impacts, it may be necessary to collect additional data to support the ongoing activities. This may comprise requesting additional data from industry partners, or the design of a field program to collect additional data in key areas.

A draft Phase 2 Report will be submitted to the MOC and SAG one (1) week prior to the Phase 2 Completion Meeting. SWS will provide to the MOC with copies of all material including electronic data referenced in the Phase 2 Report. SWS will address all comments received at or before the Phase 2 Completion Meeting and finalise the Phase 2 Report within one (1) week of the Phase 2 Completion Meeting being held.

2.6 Phase 3 - Modelling

2.6.1 Scope

The aim of Phase 3 would be to develop tools and risk based methodology to provide ongoing assessment and monitoring of cumulative impacts of water extraction on surrounding and regional aquifer systems and surface water / groundwater interactions.

Impacts of water extraction may include depressurisation of stratigraphic horizons and consequent reduced levels in water supply bores, reductions in surface water stream flows, lowering of water levels in discharge areas, changes in groundwater quality, and subsidence. SWS would attempt to quantify these potential impacts using a combination of modelling packages (as appropriate), depending on their importance and the level of data available.

The geological model (partially developed as part of Phase 2 and hosted in PETREL), may be exported directly to the numerical modelling packages (e.g. MODFLOW, FEFLOW or ECLIPSE) to allow construction of the numerical model to simulate groundwater flow.

In each case, the models will simulate the production coal seams, and all of the relevant underlying and overlying aquifer systems. Although the database and geological model will provide significant data with which to populate the numerical models, some parameters such as leakage coefficients between units will be assigned from experience in comparable environments. The influence of these parameters will subsequently be assessed in sensitivity analyses.

The numerical models will be calibrated to observations available from the operating gas fields, mining operations and irrigation schemes. Predictive simulations will be undertaken with all possible abstraction operating to investigate potential cumulative impacts. The model will address the potential impacts on the coal formations and in the overlying and underlying units. It will provide an assessment of the area of influence of water production and how this area will change over time.

At the completion of conceptual modelling in Phase 3, SWS will present a rationale for the selection of the proposed suite of models. SWS will provide discussion on the logical selection of individual models, their anticipated mode of operation and their interaction to achieve the project outcomes.

The model rationale and design will be documented to outline of the proposed model architecture and clearly demonstrate how the model(s):

- Achieves the requirements of the study;
- Recognises the potential interconnection between surface water and groundwater aquifers, including coal seam water;
- Utilises parameters that reflect measurable physical characteristics of the catchment while justifying parameters derived from areas outside the catchment with references to published technical literature;
- Parameters will be incorporated to allow changes as further data becomes available;
- Discretisation will allow for a range of different spatial scales that reflect the important physical processes and availability of data on which to base parameter values and allow for the spatial scale within the model to be refined in areas of particular interest.
- Allows for rainfall and evaporation data to be derived from historical records or from synthetic datasets that can allow for the effects of climate change for the purpose of sensitivity analysis;
- Includes flexibility of time scales for modelling different physical processes;
- Includes the relevant flow and water quality aspects of:
 - Catchment runoff and baseflow inflows, or losses
 - Effects of different land uses on runoff and groundwater recharge;
 - Effects of wetlands, swamps, lakes, ponds, farm dams and major water storages;
 - Surface water and groundwater requirements for dependent ecosystems;
 - Water use and extraction (for surface water and groundwater) for urban water supply, irrigation, stock and domestic purposes, including potential changes in these uses over time;

- Interaction between different aquifers in multi-layered aquifer systems and the effects of extraction of groundwater for urban water supply, irrigation and stock and domestic purposes;
- Interactions between different aquifer systems and between aquifers and the surface water resources;
- Potential effects of mining including:
 - effects of both open-cut and underground mining;
 - connective cracking between different aquifer systems and between aquifers and surface water systems as a result of underground mining;
 - changes in surface flow patterns, runoff detention and flood storage as a result of changes in surface topography, and any consequential changes in water quality;
 - operational water requirements and effects of beneficial reuse and/or disposal of any excess mine water;
 - effects of changes in surface topography on groundwater recharge, and any consequential changes in water quality;
- Potential effects of gas extraction including:
 - effects of coal seam gas extraction processes, including drilling and hydraulic fracturing;
 - effects of coal seam water extraction;
 - effects on groundwater flows and water quality in multi-layered aquifer systems;
 - effects on groundwater recharge as a result of seam water extraction and any consequential changes in water quality;
 - operational water requirements and effects of beneficial reuse and/or disposal of any excess water;
- Is capable of being tested to demonstrate its sensitivity, accuracy, reliability, stability and ease of use;
- Considers population growth and regional development in the catchment;
- Enables incorporation of future data; and
- Takes into account NSW models and the Murray-Darling Basin Authority's Basin Plan models.

Details of all modelling assumptions will be clearly documented and reported and comprise:

- Details of each assumption;
- Demonstrate that each assumption is reasonable; and
- Identify the sensitivity to each assumption and any potential effects on the performance or outputs of the model.

2.6.2 Conceptual model report

SWS will undertake to present a conceptual model report which will include:

- The model rationale and design;
- The model assumptions; and
- An outline of the program for numerical model calibration, validation, sensitivity analysis and uncertainty analysis such as that set out in the Murray-Darling Basin Commission's (2001) Groundwater Flow Modelling Guideline.

SWS will submit the conceptual model report for review within the time frame agreed with the MOC. SWS will consider and respond to any comments that are provided by the MOC within two (2) weeks of receiving the report.

2.6.3 Model development

SWS will develop the model in accordance with the conceptual model report whilst responding to any comments or adjustments as reviewed by the MOC throughout the program.

A number of relevant scenarios for future mine or gas development will be developed by SWS and incorporated into a test plan outlining the details of the mine and gas development scenarios for the testing of the model. The test plan will be approved by the MOC prior to testing of the model.

While, recognising that future development plans are likely considered 'commercial in confidence' SWS would undertake to discuss realistic testing scenarios with stakeholders from the oil and gas industries.

2.6.4 Model testing

This activity will require analysis of the performance and outputs of the model for a range of simulated and/or existing coal and gas developments in areas of the catchment where water resources are vulnerable to the effects of coal and gas development. The model testing must clearly demonstrate that:

- A rigorous program of model calibration and verification will be undertaken;
- 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;
- For existing developments, the model produces outputs that closely reflect collected data and actual observations;
- For simulated coal and gas developments, the model produces outputs that closely align with expected outcomes, where there is a reasonable basis for an expectation;
- The model outputs are reproducible;
- The model is capable of enabling 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; and
- The model provides data output in the form of tables, graphs and maps that are easy to understand.

2.6.5 Model documentation

As a part of the Phase 3 deliverables SWS will develop model documentation. This documentation will consist of a Reference Manual and a User Manual. The manuals will be produced as standalone documents for ease of updating and amendment by the model(s) end user. The model documentation will consist of:

- A Reference Manual which will include full details of the model architecture, the justification and background (including published literature references) for all physical processes and the basis for selection of parameter values.
- A User Manual which will provide full details of how to operate the model including updating with additional improved data and the locations for mines or gas extraction developments.

The model, draft Reference Manual and draft User Manual will be submitted for review to the MOC on or before the date agreed with the MOC at the Phase 3 Commencement Meeting. SWS will consider and address any comments that are provided by the MOC within two (2) weeks of receiving the model and manuals.

2.6.6 Monitoring program

SWS will develop and document a monitoring program to provide data for maintenance and updating of the model. The monitoring program will be rigorous and defensible while prioritise the collection of surface water, groundwater, water quality and climate data.

SWS will include in the monitoring program recommendations outlining the scope for any separate follow on investigations to enhance the model as may become apparent during the course of the Study.

2.6.7 Phase 3 report

A draft Phase 3 Report will be submitted to the MOC and SAG one (1) week prior to the Phase 3 Completion Meeting. SWS will provide the MOC with copies of all material including electronic data referenced in the Phase 3 Report. SWS will address all comments received at or before the Phase 3 Completion Meeting and finalise the Phase 3 Report within one (1) week of the Phase 3 Completion Meeting being held.

2.7 Phase 4 - Reporting

Phase 4 of the Study will consist of the compilation, review and finalisation of the Study reporting. SWS will undertake to initially produce a report outline which will be followed by a Draft Study Report based on the review of the outline report. Ultimately, a Final Study Report will be delivered based on the review recommendations of the Draft Study Report.

An Outline Study Report will be produced as a precursor to the compilation of the final study reporting. The Outline Report will include:

- A table of contents; and
- A brief summary of the proposed contents of key sections of the report.

A draft Outline Study Report will be submitted to the MOC at a date negotiated at the Phase 4 Commencement Meeting. SWS will consider and address any comments received from the MOC within two weeks of receiving the comments.

SWS will provide an electronic version of the final Outline Study Report to the members of the MOC, SAG and community consultative committees, and also I & I NSW. The report will be in PDF file format and of a size suitable for downloading from the internet. Further, SWS will distribute one (1) bound hard copy of the Outline Study Report to each of the council offices and libraries listed in Appendix 4 within one (1) week of finalising the report.

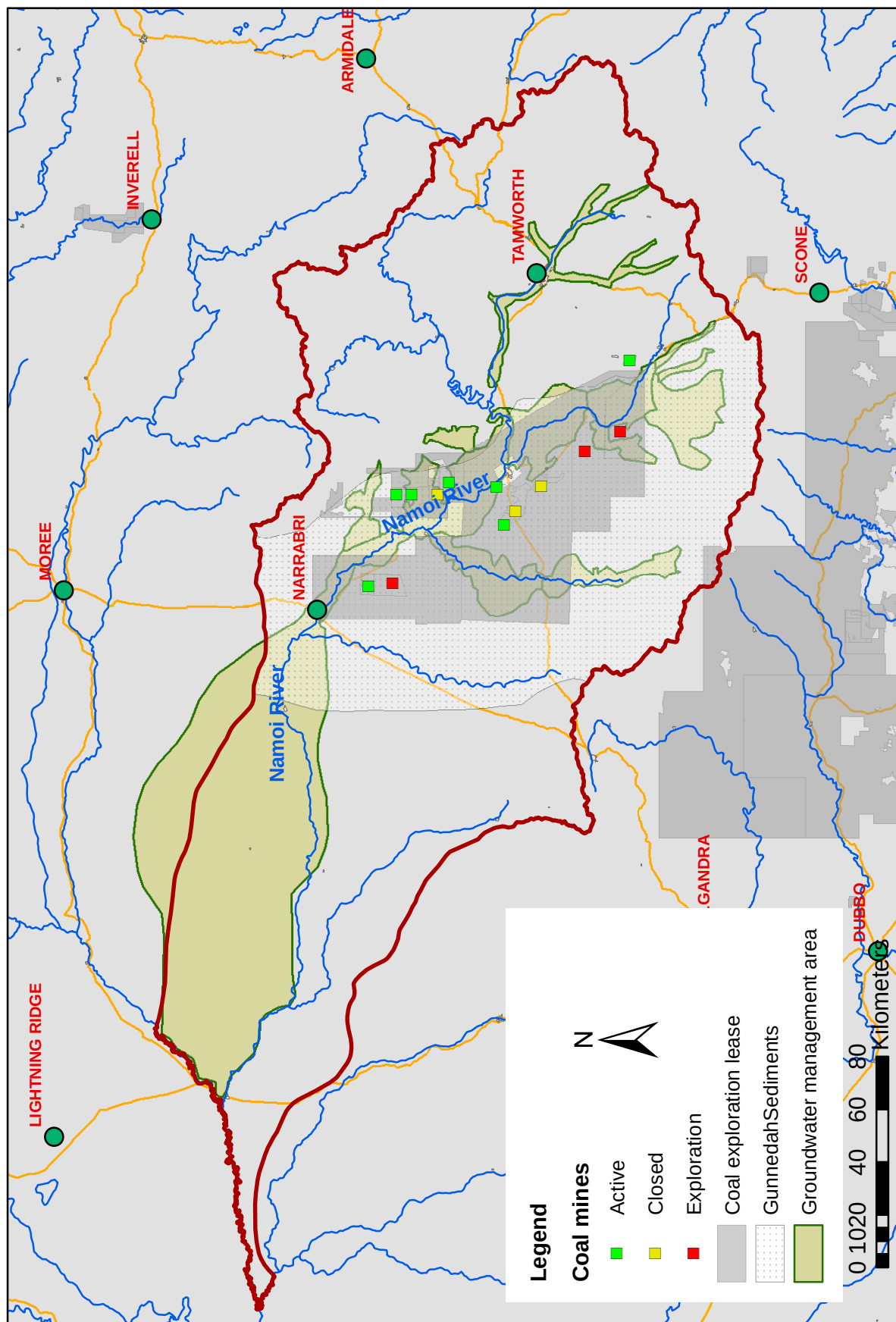
SWS will prepare a Draft Study Report, taking into account the Outline Study Report and comments received from the MOC. The Draft Study Report will include:

- An executive summary;
- The study background and problem definition;
- The Study requirements;
- A summary of the outcomes of the detailed scoping and literature search undertaken in Phase 1 of the Study;
- A summary of the results of the data collation and data analysis undertaken in Phase 2 of the Study;
- Details of the modelling undertaken in Phase 3 of the Study including details of the model rationale, model assumptions and model testing;
- Details of the recommended monitoring program and any recommended separate follow-on study to enhance the model;
- A conclusion that includes a demonstration of how the model achieves the Study requirements and a strategic assessment of the likelihood of potential effects posed by coal and gas development on the quantity and quality of surface water and groundwater resources in the catchment;
- Recommendations as to practical measures which could be considered by government agencies in mitigating or managing potential effects of coal and gas development on water resources in the catchment; and
- The final Reference Manual and User Manual for the model as attachments to the report.

SWS will submit the Draft Study Report to the MOC, SAG and community consultative committees for comment. SWS will consider and address any comments that are provided by the MOC, SAG or community consultative committees within four (4) weeks of receipt.

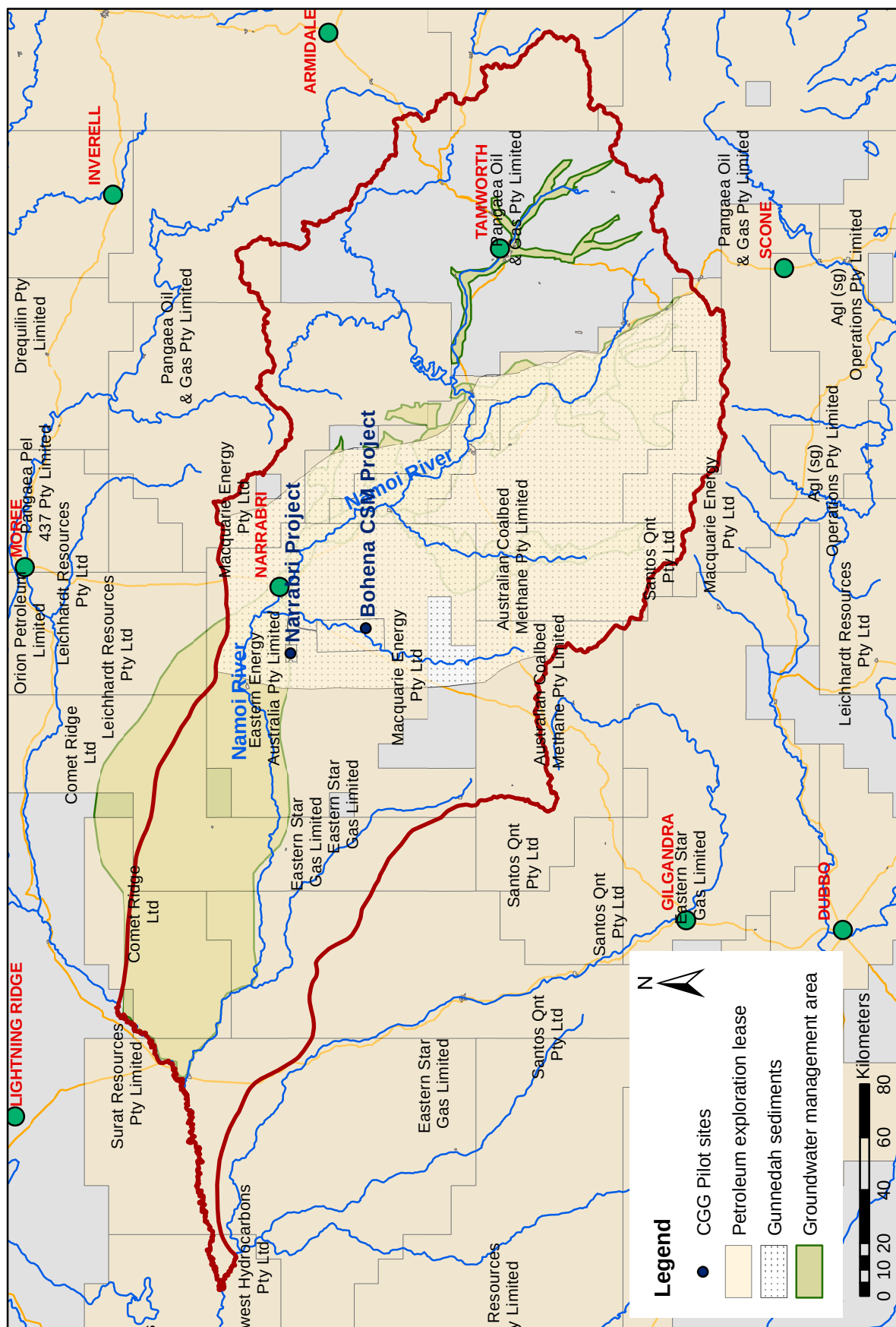
SWS will submit a Final Study Report that addresses comments made by the MOC, SAG and community consultative committees on the Draft Study Report.

SWS will provide an electronic version of the Final Study Report to the members of the MOC, SAG and community consultative committees, and also I & I NSW. The report will be in PDF file format and of a size suitable for downloading from the internet. Further, SWS will distribute one (1) bound hard copy of the Outline Study Report to each of the council offices and libraries listed in Appendix 4 within one (1) week of finalising the report.



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Figure 2.2 Petroleum exploration lease areas



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3 THE STUDY PLAN

3.1 Introduction

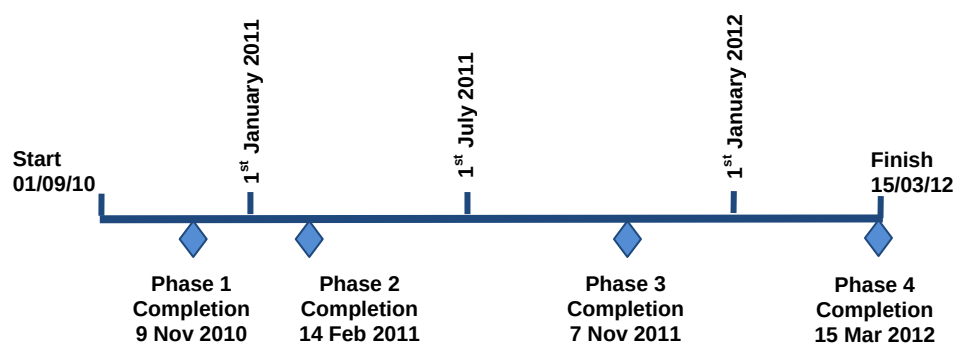
A Project Plan has been completed using the Microsoft Project software and is presented in the form of a Gantt chart as the Appendix to this document. The Project Plan includes the allocation of time and resources for the tracking of project progress, assists with project management and planning and demonstrates the target dates for key processes. The Project Plan presents a detailed schedule for the completion of the Study and includes the following key details:

- Start and end dates for each phase of the Study;
- Key tasks required to deliver the deliverables;
- Identification of key personnel involved in each task;
- Milestone dates for the deliverables;
- Tasks that are critical to the completion of the Study within 18 months of commencement;
- Identification of tasks that are critical to meeting the end dates of each Study phase; and
- Those tasks that require participation by the MOC and the SAG.

The Study flowchart has been updated and is provided as Figure 3.1. The flowchart:

- Maps the phases of the Study to show the progression from the commencement through to the conclusion and identifies overlaps between phases;
- Shows the key elements of the program and scope diagrammatically, including key tasks, milestones, and responsible personnel;
- Illustrates the interrelations between key tasks, key stakeholders, and also between tasks and stakeholders; and
- Identifies governance processes that will be implemented during the Study.

The following timeline is representative of the Project Plan and defines the key dates such as commencement and completion of each phase. Further detail is presented in the Project Plan.



3.2 Key tasks and dates

The following are the dates identified as key milestones to completion of the study within an 18 month time frame. The milestones and their expected completion dates have been presented for each of the four phases of the Study. All dates are subject to the assumption that study progress will be unimpeded by unavoidable delays, the availability and prompt delivery of data by Study partners and government departments, and assumes the full cooperation of the MOC and SAG.

Phase 1 Key Tasks	Date
Inception Meeting and Phase 1 Commencement Meeting	1st September 2010
Phase 1 Draft Report Submission	2nd November 2010
Phase 1 Completion Meeting / Phase 2 Commencement Meeting	9th November 2010
Public Presentations Gunnedah and Quirindi	10th November 2010
Final Phase 1 Report Submission and Distribution	19th November 2010
Phase 2 Key Tasks	Date
Phase 1 Completion Meeting / Phase 2 Commencement Meeting	9th November 2010
Phase 2 Draft Report Submission	4th February 2011
Phase 2 Completion Meeting	14th February 2011
Public Presentations Gunnedah and Quirindi	15th and 16th February 2011
Final Phase 2 Report Submission and Distribution	17th February 2011
Phase 3 Key Tasks	Date
Phase 3 Commencement Meeting	28th February 2011
Conceptual Model Report Submission	8th April 2011
Numerical Model Development	3rd June 2011
Model Test Plan Submission	15th July 2011
Model Testing	29th July 2011
Draft Reference Manual and User Manuals Submission	26th August 2011
Monitoring Program Development	23rd September 2011
Phase 3 Draft Report Submission	21st October 2011
Phase 3 Completion Meeting	7th November 2011
Public Presentations Gunnedah and Quirindi	8th and 9th November 2011
Final Phase 3 Report Submission and Distribution	14th November 2011

Phase 4 Key Tasks	Date
Phase 4 Commencement Meeting	21st November 2011
Outline Study Report Submission	2nd December 2011
Draft Study Report Submission	13th January 2012
Final Study Report Submission	17th February 2012
Handover of Data and Model	5th to 9th March 2012
Study Completion Meeting	12th March 2012
Public Presentations Gunnedah and Quirindi	13th and 14th March 2012
Final Report Distribution	15th March 2012

3.3 MOC and SAG participation

This section outlines the key activities requiring participation of the Ministerial Oversight Committee (MOC) and the Stakeholder Advisory Group (SAG).

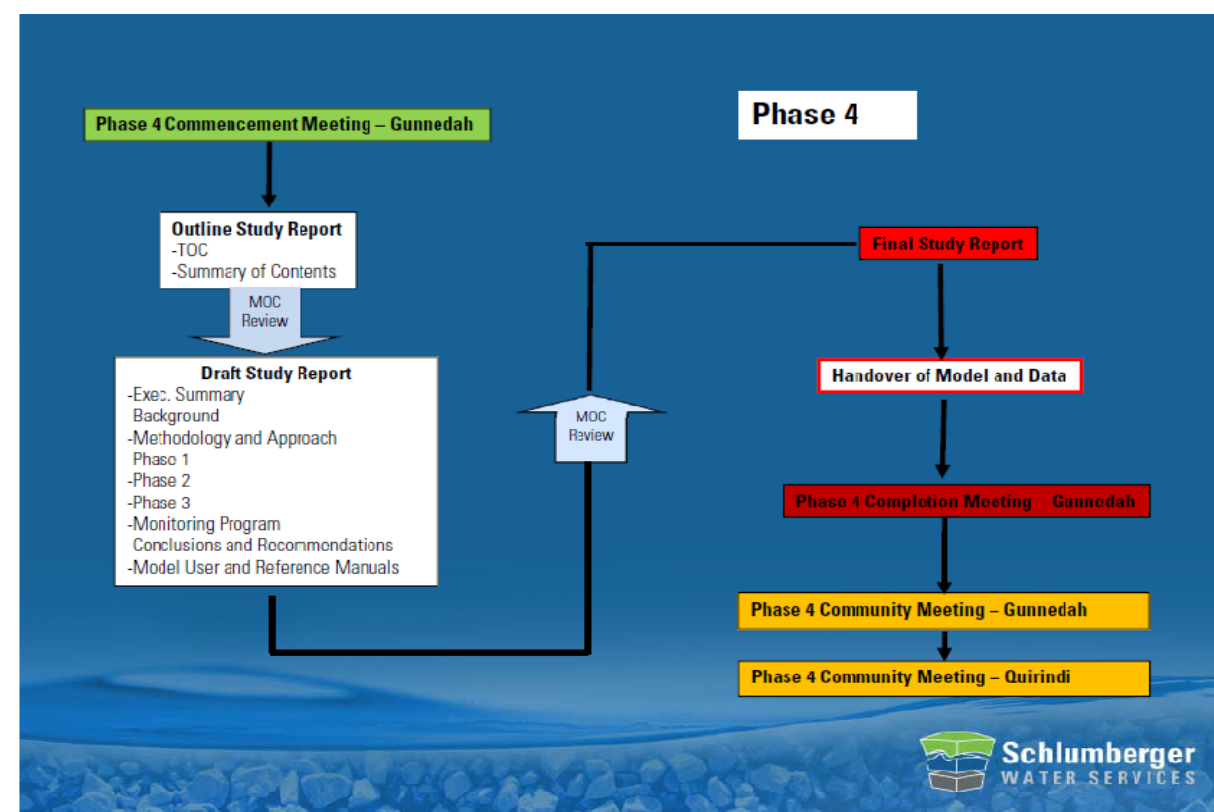
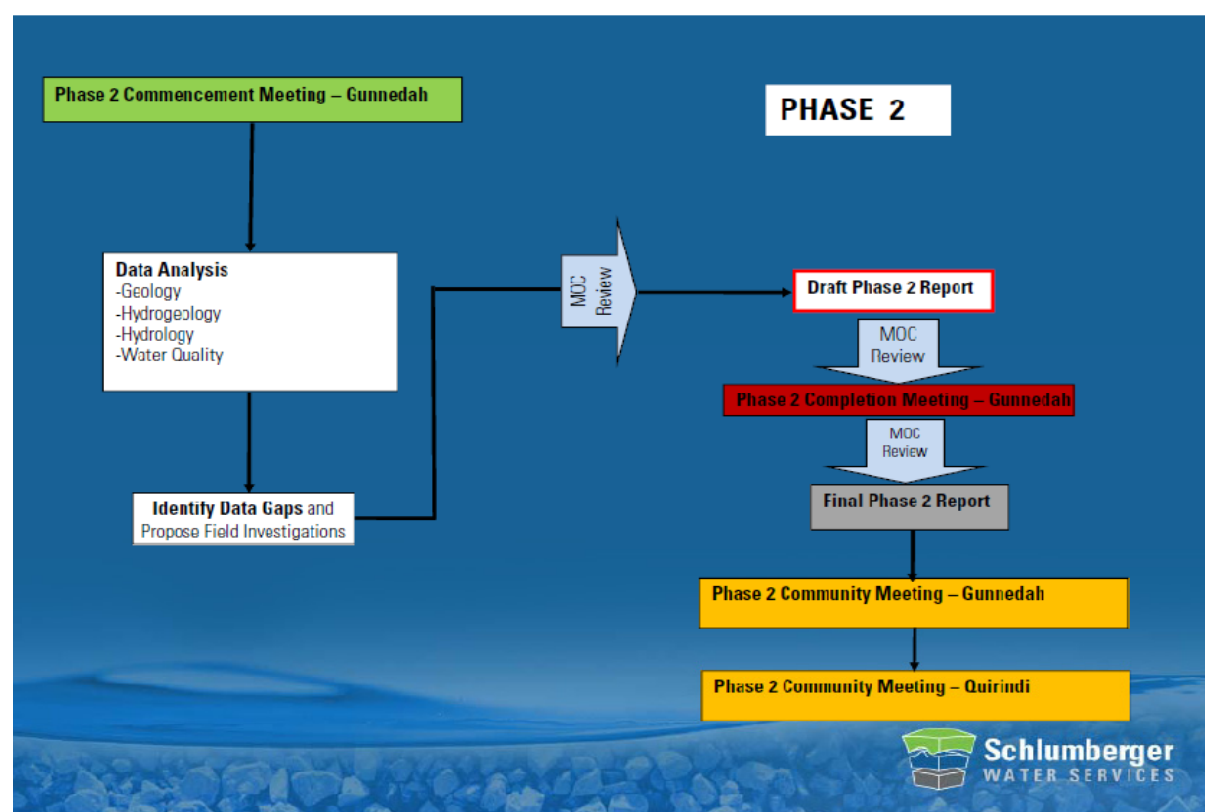
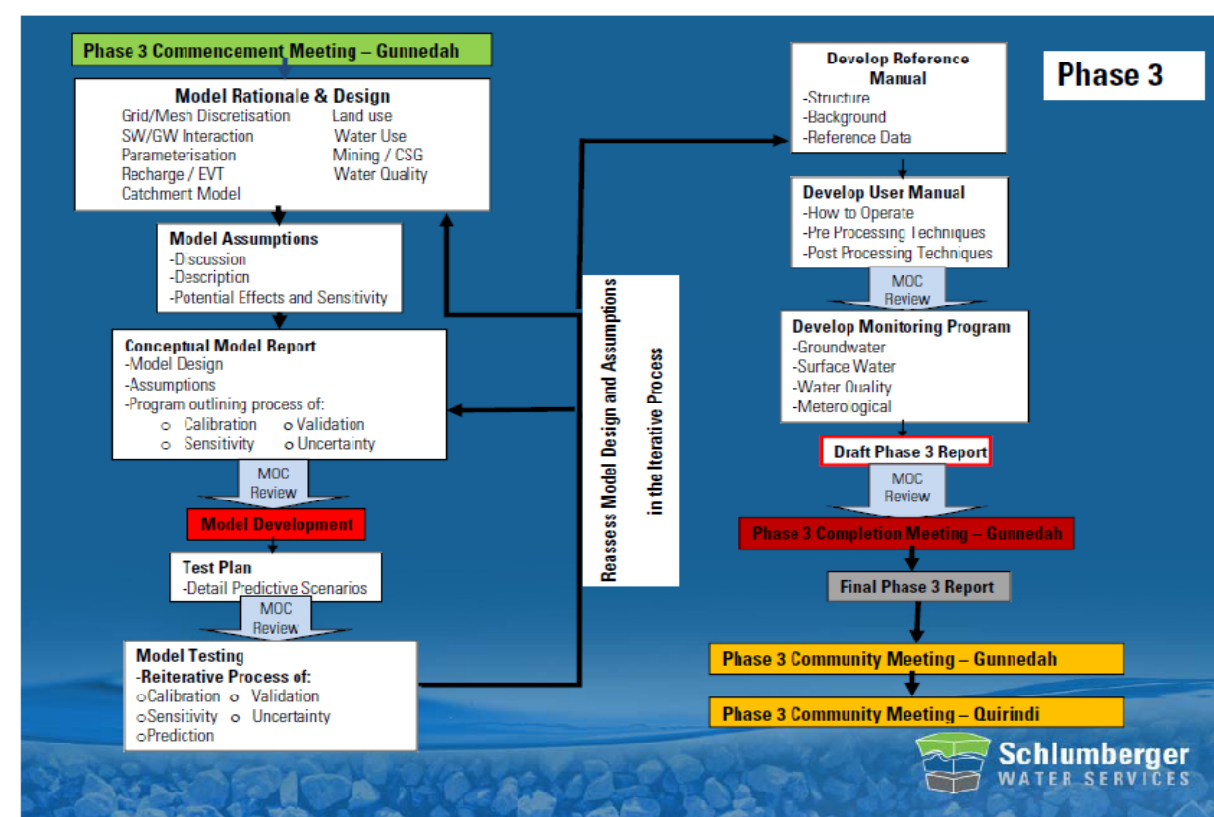
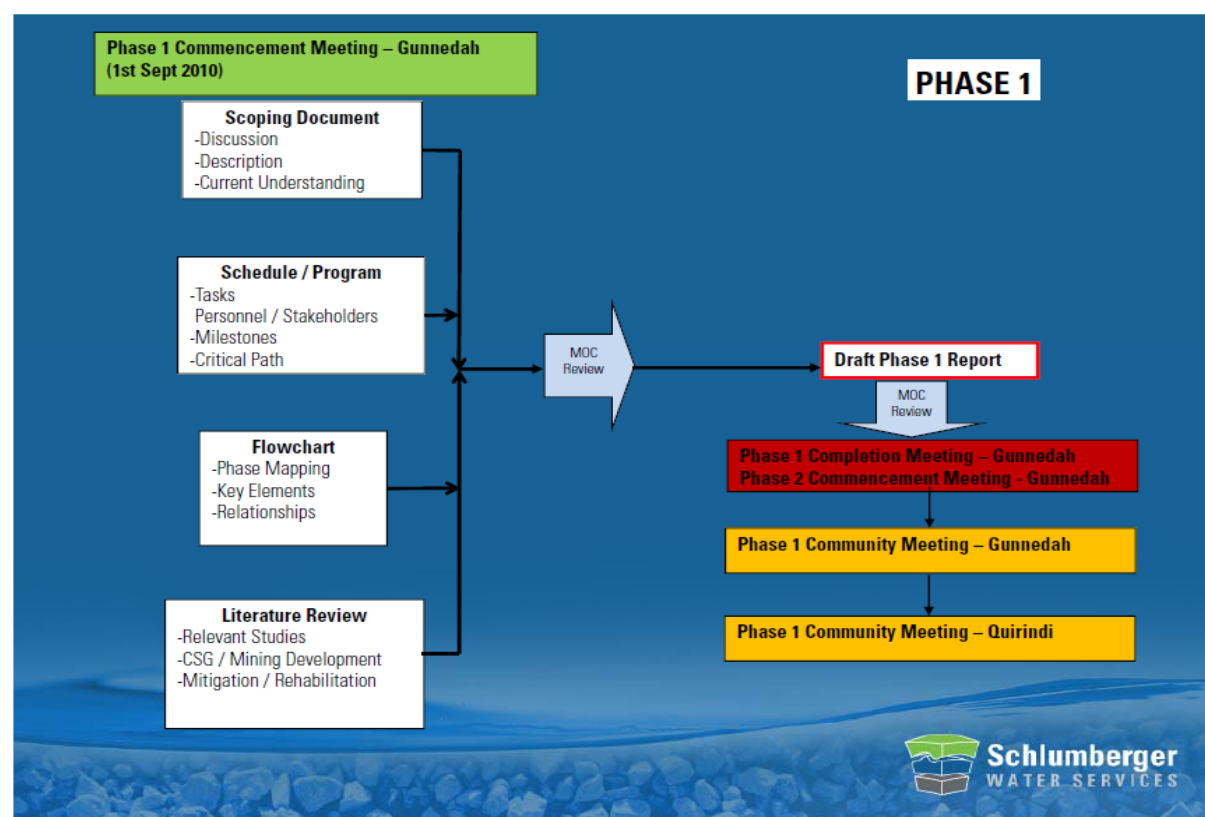
Prior to the commencement of each phase, SWS will attend a meeting convened by the Chair of the MOC and to which all members of the MOC and SAG are invited to attend. The Phase Commencement Meetings are required to ensure alignment between the Independent Expert, the Independent Advisor, the MOC and the SAG as to the requirements and the expectations of the following phase of work. A critical analysis of the expected work will be presented and advice and assistance sought, as required by the Independent Expert. The Phase Commencement Meetings are to be held in Gunnedah.

The purpose of the Phase Completion Meetings will be to present the findings of that phase of the Study, receive feedback and input from the MOC and SAG and address any concerns, questions or other issues as raised by the MOC and/or SAG. Phase Completion Meetings are also to be held in Gunnedah. The Phase 1 Completion Meeting and Phase 2 Commencement Meeting are to be held concurrently.

SWS will consider all comments received at or before the Phase Completion Meetings and finalise the Phase Report within one (1) week of the Phase Completion Meeting.

SWS will attend two (2) community information sessions organised by the MOC at the end of each phase of the Study. One Community Information Session will be held in Gunnedah and the other in Quirindi. At each Community Information Session the Independent Expert will present the findings of that phase of the Study in lay terms, and answer any community queries.

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4 LITERATURE REVIEW

4.1 Overview

The following literature review has been undertaken in fulfilment of the Phase 1 objectives of the Namoi Catchment Water Study. The literature review covers a wide range of topics and summarises relevant published literature which is readily available in the public domain. The review allows an initial interpretation of data, information and knowledge so that a targeted approach to data collection, model conceptualisation and modelling can be undertaken. Subsequent sections of this document list the references cited and also provide a bibliography of information reviewed but not referenced in this report.

4.2 Geological setting

The geology of the Namoi catchment is generally well understood with detailed discussions of the Mooki River catchment are presented by Gates (1980) and Lavitt (1999); of Cox's Creek catchment by Broughton (1994); and of the Lower Namoi catchment by Williams (1986) and McLean (2003). Details of the geology and hydrogeology of the eastern portion must exist in survey reports for the site selection and construction of Keepit, Split Rock, Quipolly and Chaffey dams in the eastern region (Kelly et al. 2007).

The majority of the alluvial aquifers in the Namoi catchment are underlain by the Permian to Tertiary sedimentary and volcanic rocks of the Gunnedah Basin, and by Jurassic and Cretaceous sandstones and siltstone sediments of the Great Artesian Basin (GAB) in the northwest (DPI Minerals, 2010).

Alluvial sediments of the Upper and Lower Namoi are usually subdivided into three formations. The uppermost formation is the Pleistocene to recent Narrabri Formation which predominantly consists of clays with minor sand and gravel beds. Underlying the Narrabri Formation is the Pliocene to early Pleistocene Gunnedah Formation, which consists predominantly of gravel and sand with minor clay beds and is the principal aquifer used for irrigation. At the base of the alluvial sequence in the Lower Namoi is the Cubbaroo Formation consisting of sand and gravel with interbedded brown to yellow and grey clay (Williams, 1986). Cubbaroo Formation sediments infill the pre-tertiary channel (Williams, 1986).

The Devonian to Carboniferous strata of the New England Fold Belt forms the eastern and south eastern margins of the catchment. The Gunnedah Basin is separated from the New England Fold Belt by the Hunter-Mooki Thrust. In the south the boundary between the Gunnedah Basin and the Sydney Basin is argued as being either the Mount Coricudgy Anticline or the Liverpool Range (DPI Minerals, 2006). In the southwest the drainage basin is bounded by the Liverpool Range volcanics.

The stratigraphic section for the Gunnedah Basin and the overlying Surat Basin is presented in Figure 4.1 (after Tadros, 1993).

4.2.1 Gunnedah Basin

Tadros (1993) describes the Gunnedah Basin as containing up to 1,200 metres of marine and non-marine Permian and Triassic sediments resting unconformably over Early Permian and possibly Late Carboniferous silicic and mafic volcanics, which form the basement to the east of Rocky Glen Ridge. Metavolcanics and metasediments and minor ignimbritic volcanics of the Lachlan Fold Belt form the majority of the basin to the western part of the Gunnedah basin (Rocky Glen Ridge and Gilandra Sub-basin). In the east, the silicic and mafic basement volcanics outcrop to form the eastern basin extent as the Boggabri Ridge, prominent between Gunnedah and Narrabri.

To the north of the Liverpool Range the Jurassic Sediments of the Surat Basin unconformably overlie the Gunnedah Basin Sediments. The Gunnedah Basin Sequence outcrops as a narrow north-north-west trending zone from the south of Quirindi to the North of Narrabri (Figure 4.2) (Tadros, 1993).

The Sydney-Gunnedah-Bowen Basin is a long composite structural basin separating and bounded by basement highs, the New England Fold Belt in the east and the older Lachlan Fold Belt (continental craton) in the west. The basin sediment is asymmetric in nature and is thickest in the east along the Mooki – Goondiwindi Faults in the Taroom Trough of the Bowen Basin and along the east dipping Hunter – Mooki Fault system in the south. The eastern extent of the basin is basically undefined being over thrust by the New England Fold Belt. The basin sediments thin to the west as it onlaps to the Lachlan Fold Belt.

Tadros (1993) notes that the structural highs within the Late Carboniferous to Early Permian volcanic units which form the effective basement for the Gunnedah Basin outline three north-north-westerly orientated sub-basins. The Boggabri Ridge in the east separates the Maules Creek Sub-basin from the Mullaley Sub-basin which is further separated from the western Gilgandra Sub-basin by the Rocky Glen Ridge. Russell (1981) and Hill (1986) after Tadros (1993) suggest that the Boggabri Ridge is continuous in the subsurface between outcrops extending from the south-east of Bellata to the south through the Deriah Forrest area to Baan Baa and through Boggabri to south-east of Gunnedah where it is truncated by the Mooki Fault system. It is thought probable that the ridge extends to the north past Moree.

The Rocky Glen Ridge is located in the Coonabarabran area as a subcrop of Ordovician – Carboniferous metasediments, Carboniferous granites and volcanics. Silicic volcanics consisting of ignimbrite and ashfall tuff, which correlate to the Boggabri Volcanics, form the eastern flank (Tadros, 1993).

The Maules Creek Sub-basin is bound by the Hunter-Mooki Fault system, to the east, and the Boggabri Ridge, to the west. It is a remnant basin. However the New England Fold belt is now thrust over the eastern margin of the basin (Tadros, 1993).

The Mullaley Sub-basin extends the entire length of the Gunnedah Basin from Moree, in the north, to Mount Coricudgy Anticline, in the south. It is divided by prominent transverse highs including the Walla Walla and Narrabri Highs. The most important troughs lie within the Pilliga region and include north-north westerly orientated Bellata, Bohena and Bando Troughs (Tadros, 1993).

The area to the west of the Rocky Glen Ridge has been defined by Tadros (1993) after Yoo (1988) as the Gilgandra Sub-basin. Consisting of Permian to Triassic sediments extending westward to the Mount Forster Structural Zone and northward to the Cobar – Inglewood Kink Zone the Gilgandra Basin is divided by a transverse basement high forming northern and southern troughs (Tadros, 1993).

The Mount Coricudgy Anticline is described by Tadros (1993) as a major transfer fault showing large movement between basin compartments. The spine of the anticline runs from the south of Rylstone to Muswellbrook and forms the structural boundary between the Sydney and Gunnedah Basins.

4.2.2 Gunnedah Basin sediments

The Permian section of the Gunnedah Basin consists of the Upper and Lower Coal Measures (Black Jack and Maules Creek Formations respectively), separated by the marine sediments of the Porcupine and Watermark Formations and underlain by the basal Goonbri and Leard Formations.

Goonbri and Leard Formations

The Goonbri and Leard Formations forming the basal units of the Gunnedah Basin receive little attention from Tadros (1993). They unconformably overlie the regional volcanic basement and consist of colluvial and lacustrine sediments, pelletoidal claystone and organic rich sequences of claystone to sandstone.

Maules Creek Formation

Tadros (1993) reports the Maules Creek Formation as up to 800 metres thick and consisting of lithic granule to pebble conglomerate, lithic and quartzose sandstone, siltstone, and claystone. The formation is described as containing numerous coal seams, some up to 8 metres thick and form a minable resource amenable to open cut or underground extraction. The coals are characterised as low ash, high energy, high volatile coal with low phosphorous suitable as thermal and soft coking coals (Tadros, 1993).

Porcupine and Watermark Formations

A Late Permian marine sequence, consisting of the Porcupine and Watermark Formations, conformably overlie the lower coal measures, the Maules Creek Formation. The upper part of the Watermark Formation consists of prodelta and delta front sediments forming the foundation for the major deltaic deposits in the lower part of the overlying Black Jack Formation (Tadros, 1993).

The Triassic section of the Gunnedah basin sequence, consisting of the Digby, Napperby and Deriah Formations, unconformably overlies the Black Jack Formation over much of the basin except on the eastern and western margins where it overlies the regional basement rocks.

Black Jack Formation

The Black Jack Formation is described by Tadros (1993) as Late Permian coal measures out cropping in a narrow north-northwest trending line of hills extending from Breeza in the southeast to Boggabri in the north. Tadros (1993) describes the Black Jack Formation as deltaic and fluvial deposits of up to 470 metres thick and consisting of lithic conglomerate and sandstone, quartzose sandstone, siltstone, claystone, tuff and numerous coal seams. The Hoskissons and Melvilles seams are the most significant. The seams contain medium to high ash thermal coals. Tadros (1993) reports that small quantities of low ash, low phosphorous, soft coking coal are produced from two small collieries near Gunnedah for blending.

The Digby Formation

The Digby Formation consists of a lower part of lithic conglomerate, a middle part of lithic and quartz lithic sandstones and an upper part of quartzose sandstone. The sequence is generally capped by a palaeosol horizon. (Tadros, 1993).

The Napperby Formation

Tadros (1993) reports the Napperby Formation as consisting of an upward coarsening sequence of dark grey claystone, interbedded siltstone and sandstone with common bioturbation and medium to coarse sandstone. The Napperby Formation forms the uppermost unit in the Gunnedah Basin Sequence except where the Deriah formation exists, and is marked by a regional unconformity between the Triassic and Jurassic sediments.

The Deriah Formation

The Deriah Formation is noted by Tadros (1993) as the upper limit of the Gunnedah Basin in the northern areas. The Deriah Formation consists of green lithic sandstone rich in volcanic fragments and mudclasts.

Many areas of the Gunnedah Basin contain basic intrusion of Mesozoic and Tertiary rocks associated with the massive extrusions of the Garwilla Volcanics complex and the Liverpool, Warrambungle and Nandewar Ranges in the central, south, southwest and northeast respectively. Mesozoic phonolite intrusions and

Tertiary igneous rocks consisting of basalt and dolerite plugs, sills, and diatremes, also occur in the south-westernmost part of the basin (Tadros, 1993 after Yoo, 1991).

4.2.3 The Surat Basin

The Jurassic age Surat Basin unconformably overlies the Permian to Triassic sediments of the Gunnedah Basin in the north and west. The Garrawilla Volcanics form the basal unit of the Surat Basin sequence and outcrop mainly in the central area of the Gunnedah Basin around Mullaley and Coonabarabran (Tadros, 1993). The sequence is described by Tadros, (1993) after Bean (1974) as up to 180 metres of alkali basaltic lava flows, pyroclastic units and subordinate intercalated claystones. Overlying the Garwilla Volcanics are the Early to Mid-Jurassic fluvial and lacustrine sediments of the Purlawaugh Formation consisting of up to 75 metres of thinly bedded carbonaceous mudstone, silty sandstone and subordinate coal (Tadros, 1993).

In the absence of the Garrawilla Volcanics the Purlawaugh Formation unconformably overlies the Gunnedah Basin. Conformably overlying the Purlawaugh Formation is the Middle to Late Jurassic Pillaga Sandstone. The Pillaga Sandstone consists of medium to coarse-grained fluvial quartzose sandstones which outcrop over much of the Gunnedah Basin area with Jurassic cover (Tadros, 1993 after Yoo, West, and Bradley, 1983).

4.3 Hydrology

The long term average annual runoff for the Namoi River is 770,000 ML at Gunnedah, which represents 6 % of the average annual catchment rainfall and is only 33 % of the New South Wales average rainfall-runoff. Most of the runoff is generated in the headwater regions of the catchment; 90 % of the total runoff comes from 40 % of the catchment area. The Cockburn, Peel and MacDonald catchments yield the greatest runoff per area of catchment (Table 4.1). Generally, annual flows increase with increasing catchment area, but downstream of Gunnedah annual flows decrease due to increasing evaporation, transmission losses and water use.

Table 4.1 Total annual flow statistics for the Namoi River (ML)

	Narrabri	Gunnedah	MacDonald	Peel	Cockburn	Mooki	Coxs
Median	403,500	415,200	242,600	130,300	58,500	36,700	24,500
Mean	629,000	734,000	381,600	196,700	81,400	92,500	77,300
Min	19,000	33,300	14,500	4,500	600	1000	500
Max	3,624,000	3,871,000	1,905,000	994,000	315,000	388,000	344,000
Area (km ²)	25,100	17,100	5,180	2,410	907	3,630	4,040
Yield	16	24	46	56	65	10	7

(Thoms et al. 1999)

Flow variability is a feature of the Namoi River. For example, long term variations in average annual flow for selected stations throughout the catchment range from 23 to 660 percent (Thoms et al., 1999). In general, discharges recorded at the main gauging stations are skewed, with a large proportion of average flows occurring in wet years and during major floods.

Flows in the Namoi catchment are regulated by three head water storages (Figure 1.1): Keepit Dam on the Namoi River upstream of the Peel River confluence; Chaffey Dam on the Peel River upstream of Tamworth; and Split Rock Dam on the Manilla River. Keepit Dam, constructed in 1960, has a storage capacity of 427,000 ML. Split Rock Dam was constructed in 1988 to augment the supply to Keepit Dam by an average of 53,000 ML per year. It also supplies water to users along the Manilla River. Split Rock has a maximum storage capacity of 397,000 ML. Chaffey Dam was constructed in 1979 and has a maximum storage capacity of 62,000 ML (Thoms et al. 1999).

A series of regulating weirs downstream of Keepit Dam are located at Mollee, Gunidgera and Weeta. The Mollee Weir (3,300 ML) was designed to regulate flows and improve the precision of supply. Gunidgera Weir has a storage capacity of 1,900 ML and is used to regulate and divert flows to Gunidgera and Pian Creeks. Weeta Weir has a storage capacity of 280 ML and provides storage for downstream irrigators (Thoms et al. 1999).

A number of works have been constructed on the Gunidgera-Pian Creek system to control flows. A regulator on Gunidgera Creek controls the rate of diversion from the Namoi River to the creek. Flows may then be diverted into Pian Creek via The Cutting (Knights Weir) or The Supplementary Pian Creek Channel, which was constructed to allow water transfer into Pian Creek and to prevent overbank flow. Four privately owned weirs owned by irrigators are also present in the Gunidgera-Pian Creek system, Knights, Hazeldean, Greylands and Dundee Weirs (Thoms et al. 1999).

4.4 River geomorphology

Thoms et al. (1999) observed that the geomorphology of the Namoi catchment has a significant influence on the hydrology and physical character of the river system. River channel planforms (styles) are largely controlled by the valley slopes and the width of the valley floor trough. In constrained valleys of the headwater regions, the presence of bedrock outcrops influences the slope and mobility of the river channel and its ability to respond to changing discharges. The geomorphology of the Namoi and its main tributary valleys are varied and some change markedly in a downstream direction (Thoms et al., 1999).

All the main rivers of the Namoi catchment were noted to have typical concave long profiles, although there is a wide variation between them (Thoms, 1999). The Namoi/MacDonald River headwaters are in the Great Dividing Range at an elevation of approximately 1,200 m above mean sea level (ASL). It flows to the west and drops quickly in elevation to 340 m near Manilla, some 200 river kilometres downstream. The river valley in this section has a high gradient as it is heavily constrained and has a small valley floor width. Downstream of Keepit Dam, the valley slope decreases with a 140 m decent to around 200 m (ASL) elevation at Narrabri, over a 200 km distance. The valley floor increases in the width to become a large floodplain and is essentially a flat featureless surface associated with an unconstrained valley downstream of Narrabri. Elevation is 120 m at the Namoi-Barwon confluence, some 710 km downstream from its headwaters. The extensive floodplain areas contain numerous billabongs, anabranches and effluent streams such as Pian and Gunidgera Creeks (Thoms et al., 1999).

Like the Namoi, the Cockburn River and Cox's Creek both drain areas of relatively high relief (960 m and 1,060 m respectively), while the Peel and Mooki Rivers drain areas of low to moderate relief (480 m and 500 m respectively) (Thoms et al., 1999).

Thoms et al. (1999) have identified seven river zones with unique physical characteristics within the Namoi catchment. The location of the zones reflects the variable control of the discharge of water and sediment in relation to catchment size and geological influences on the nature of the valley. Similarly, the extent of each zone varies according to the overall geomorphology of the region.

The anabranch zone is recognised by Thoms et al. (1999) as the dominant river zone, in terms of length, in the Namoi catchment. However, within the individual sub-catchments the dominance of individual zones varies. For example, the meander zone is dominant in the Mooki River and Cocks Creek, whilst the mobile zone is the dominant zone in the Cockburn River.

All of the rivers in the Namoi catchment have a variable form and character. Different river zones respond in a different manner to physical disturbances, whether they are natural or human induced. Hence, management activities should be conducive to the natural character and functioning of river systems. A description of the zones as defined by Thoms et al. (1999) is presented in Table 4.2 and locations are shown by Figure 4.3.

Table 4.2 Geomorphological zones of the Namoi catchment

River Zone	River	Character
Pool	MacDonald	Stable channel Deep pools are important habitat.
Constrained	MacDonald	Stable channel Sediment supply area. Plunge pools and runs are important habitat.
	Cockburn Peel	
	Mooki Coxs	
Armoured	MacDonald	Relatively stable channel but can become active and unstable.
	Cockburn Peel	Temporary sediment stores within the channel. The gravel bed/bars are important habitat.
Mobile	MacDonald	Very active channel and bed sediment – sediment transfer area with numerous temporary sediment stores. The sandy gravel deposits are important habitat.
	Cockburn Peel	
Meander	Namoi	Active channel in which bank erosion is common. Sediment transfer area with some sediment stores. Floodplain functioning increases in importance to the river system.
	Cockburn Peel	
	Mooki Coxs	
Anabranh	Namoi Peel	Main channel is relatively stable but can experience bank erosion. River system is multi-channelled during floods. Secondary channels may erode if they become the main flow path. Both the main and anabranh channels are important habitat. Floodplain functioning important to the river system.
	Mooki Coxs	
Distributary	Namoi	Multi channelled -secondary channels are the dominant habitat area. The condition of the floodplain vital to river functioning.

(Thoms et al. 1999)

4.5 Hydrogeology

4.5.1 Overview

Groundwater resources in areas of the Namoi catchment are the most intensively developed in New South Wales extraction occurs primarily from the alluvial aquifers associated with the main rivers and remnant stream channels. The majority of groundwater extraction is from the coarse-grained Gunnedah Formation in the eastern areas and from the Gunnedah Formation and the underlying Cubbaroo Formation in the central and western parts of the Namoi region. This central and western part is also underlain by the consolidated sandstones, shales and mudstones that form the multi-layered aquifers of the Gunnedah Basin, a part of the Great Artesian Basin (CSIRO, 2007).

The CSIRO Namoi Water Study (2007) did not consider the groundwater resources within the Gunnedah Basin aquifers except where intake beds outcrop within the region. The outcrop areas were considered only when potential connection to surface water systems and interaction with other aquifer systems such as those in the Lower Namoi was considered possible.

The Namoi region is usually subdivided into the two major areas of alluvium, the Upper and Lower Namoi Alluvium, with the remainder lying in the headwaters of the region further to the east. The aquifers of the headwaters areas consist largely of a variety of different fractured rock types of Palaeozoic and Mesozoic age. Rock types include sedimentary and metamorphic rocks, basalts and granites. Other important aquifers in the region include unconsolidated highland alluvium deposited in valley floors. Regional groundwater flows are from east to west. However, the groundwater flow systems within all of these aquifers are generally local to intermediate in scale (CSIRO, 2007). Figure 4.4 presents upper and lower alluvial areas and Groundwater Management Units.

Fractured rock and granite aquifers are recharged where soils are thin, on mid to upper slopes and discharge to adjacent streams, valley floors and at breaks in slope. The basalts are highly porous and well flushed.

Recharge to these aquifers occurs throughout the landscape. Alluvium deposited in valley floors is recharged throughout, depending upon the nature of soils and weathered rock above the water table and on the frequency of flooding (CSIRO, 2007).

Within the highland alluvial systems groundwater discharges typically to drainage lines, local changes in soil texture, around the break-of-slope and at the base of terraces. Salt storage in the finer grained units of these systems is high and groundwater salinity is variable from fresh to saline with lower salinity levels being characteristic of the coarser sediments. The response of these systems to a change in the water balance can be relatively fast (CSIRO, 2007).

Alluvial sediments of the Upper and Lower Namoi are usually subdivided into three formations. The uppermost formation is the Narrabri Formation which predominantly consists of clays with minor sand and gravel beds. The sediments date from the Pleistocene to recent. Underlying the Narrabri Formation is the Gunnedah Formation, which consists predominantly of gravel and sand with minor clay beds from the Pliocene to early Pleistocene (Kelly et al., 2007). This is the productive aquifer used for irrigation. At the base of the alluvial sequence in the Lower Namoi is the Cubbaroo Formation and it consists of sand and gravel with interbedded brown to yellow and grey clay (Williams, 1986). Cubbaroo Formation sediments infill the pre-Tertiary channel (Kelly et al., 2007).

Little information was found within available literature referring to the hydraulic parameters of the catchment aquifers. In their presentation of September 2009, Australian Groundwater and Environmental Consultants published the results of a pumping test undertaken at Bore C102 on the Caroon Coal Project site. The test indicated that there was little connection at that location between the alluvium and the Clift Coal Seam. The hydraulic conductivity of the gravel aquifer within the alluvium was reported as 1.6×10^{-3} m/s.

The hydraulic conductivities for encountered geological units were reported by Aquaterra (2009) in the Narrabri Coal Mine Stage 2 Longwall Project: Hydrological Assessment. Several zones of elevated hydraulic conductivity were observed in various formations. Hydraulic conductivities ranging up to 0.4 m/d were found in the Garrawilla Volcanics and the Pilliga Formation. Moderately high conductivity was also found in the Napperby Formation above the sill.

Aquaterra (2009) reported all other units as showing a wide range of conductivities, but generally quite low, ranging from 0.0005 to 0.03 m/d, with the higher conductivities generally in subcrop areas. This was noted as consistent with reports of significant inflows and more intense fracturing in some holes at shallower depths.

The mean hydraulic conductivity of the Purlawaugh Formation and Basalt Sill is an order of magnitude lower than the Pilliga and Garrawilla Formations, at 0.01 to 0.02 m/d. The geological units underlying the Basalt Sill are characterised by low inherent permeability. The hydraulic conductivity of the Napperby Formation (below the sill) and the Digby Formation range from 1×10^{-4} m/d to 8×10^{-5} m/d. These units are typically fine-grained, laminated and cemented with a clayey matrix. Limited groundwater intersections were noted during drilling. Aquaterra (2009) further noted that these low permeability units separate the overlying permeable Jurassic strata from the underlying Permian Black Jack Formation.

The geological units underlying the Basalt Sill are characterised by low inherent permeability. The hydraulic conductivity of the Napperby Formation (below the sill) and the Digby Formation range from 1×10^{-4} m/d to 8×10^{-5} m/d. These units are typically fine-grained, laminated and cemented with a clayey matrix. Limited groundwater intersections were noted during drilling (Aquaterra, 2009).

These low permeability units separate the overlying permeable Jurassic strata from the underlying Permian Black Jack Formation. The hydraulic conductivity of the Black Jack Group, comprising the Hoskissons Coal Seam, Arkarula Formation/Brigalow Formation and the Pamboola Formation, ranged from 2×10^{-3} to 3×10^{-2} m/d. Relatively high groundwater pressures were observed in the Black Jack Group indicating that these formations are confined by the overlying Digby Formation and Napperby Formation aquitards (Aquaterra, 2009). Hydraulic Conductivities adopted for the Narrabri Coal mine model are presented in Table 4.3.

Table 4.3 Hydrogeological units and parameters, Narrabri Mine model

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

(Aquaterra, 2009).

Upper Namoi Alluvium

The aquifer system of the Upper Namoi Alluvium comprises unconsolidated sediments associated with the Namoi and Mooki rivers and Coks Creek. The alluvial sediments consist mainly of sand, gravel and clay and their thickness is largely controlled by the bedrock topography. The total area of alluvium is in the order of 3,000 km² and is up to 130 m thick (DLWC, 2000). A palaeochannel runs through the central area of the valley and represents the deepest parts of the aquifer.

Good quality groundwater can be found in high yielding aquifers across wide areas of the alluvial plain. However, the most productive aquifer is in the main palaeochannel. The coarseness of the palaeochannel sediments allows for high groundwater extraction rates (DLWC, 2000).

Hydrographic evidence indicating rising groundwater levels in deep (50 to 80m depth) confined aquifers has been presented (Broughton 1994). Rises of up to 2.5 cm/year since the 1970's were documented. DLWC (1995) and subsequent status reports show that in some areas groundwater levels have continued to rise in confined aquifers, while in other areas, often where intense pumping of groundwater occurs, long-term groundwater level decline has been observed (Timms and Acworth, 2002).

Lower Namoi Alluvium

The aquifer system of the Lower Namoi Alluvium is made up of the unconsolidated sediments, namely inter-bedded clays, sands and gravels, associated with the Namoi River and its tributaries downstream of Boggabri. They accumulated over more than 15 million years within a broad valley of the old Namoi River, to a maximum depth of about 120 m and with an extent of about 5,100 km². To the northwest, the Lower Namoi Alluvium joins the alluvium associated with the Barwon and Gwydir rivers. In the northeast and south it is bounded by colluvium associated mostly with weathered GAB sediments and basalt flows. To the southwest the Namoi River alluvium joins the alluvium associated with the Barwon and Castlereagh rivers (DLWC, 2000).

In most areas of the Lower Namoi Alluvium there are two general aquifer systems identified, the shallow Narrabri Formation and the deeper Gunnedah Formation, with a third aquifer associated with the palaeochannel, the Cubbaroo Formation below the Gunnedah Formation (Kelly et al. 2007). In some areas to the east, there is no discernible difference between the identified aquifer systems and they may act as a single aquifer. The Gunnedah Formation (middle aquifer) is the most extensive over the area and generally occurs between 40 to 90 m depth. The Cubbaroo Formation (palaeochannel) occurs 90 m below the ground surface and is restricted to the main palaeochannel.

4.5.2 Surface water - groundwater connectivity and recharge

Within the highland areas of the region, recharge to the fractured rock systems flows through the fractures to discharge into adjacent streams and valley floors. The rivers of the highland valleys tend to be gaining in nature.

All streams in the western parts of the region on the alluvial plain run across the top of the Narrabri Formation. At the eastern margin of the plain, the rivers are in direct hydraulic contact with the water table. Further west, an unsaturated zone develops where the water table falls well below the streams and surface water leaks to the underlying aquifer whilst stream flow persists. At the far western edge of the alluvial plain, water tables are found closer to the surface and saturated conditions are re-established. The Gunnedah Formation is recharged via infiltration from the overlying Narrabri Formation. Recharge to the groundwater system on the alluvial plain is primarily from leakage from the stream channel under normal flows, leakage from overbank flooding, and infiltration from rainfall. In the eastern parts of the plain, there is a downward movement of groundwater from the Narrabri to the Gunnedah Formation, whilst at the western margin the direction is reversed.

The Peel River Alluvium is highly connected to the Peel River and more than 80 percent of the groundwater extracted is drawn ultimately from the river.

Kelly et al. (2007) emphasise that discussion of the alluvial sequences in the Namoi Catchment generally under represent the complexity of the alluvial sequence and the interplay between clay, sand and gravel beds. The dominant sediments are sometimes reversed with clays dominant in the Gunnedah Formation at some locations and sand and gravel dominant in the Narrabri Formation at others. This complexity of the alluvial deposits is to be expected and adds complexity to the conceptualisation of hydraulic parameters and flow pathways within the alluvial components.

Timms and Acworth (2006) indicate that the high yielding aquifers in the Liverpool Plains are found in sand and gravel lenses. The Gunnedah Formation is an unofficial geological title sometimes given to the deepest, thickest deposit of gravel and sand. There are substantial high yield/low salinity aquifers east of the Mooki River at 90m to 130m below the land surface. Recharge of these aquifers is from a combination of diffuse infiltration on the footslopes of the surrounding hills, infiltration from gravel outcrops in stream beds, and from leakage through the clay strata underlying the floodplain.

Groundwater flow in the Liverpool Plains is naturally to the north and west. In the area of alluvium east of Caroona, flow rates have been estimated to be of the order of 2 m to 10 m per annum. Flows are constricted at the Breeza gap, and the high levels of extraction between Breeza and Carroll/Gunnedah have resulted in a reversal of groundwater flow direction in the north of the area, such that groundwater is now believed to flow south from the Namoi. Groundwater age, measured by various isotopes, is of the order of tens of thousands of years. Falling groundwater levels are clearly seen at some sites in the area (Timms and Acworth, 2006).

Weathered basalt slopes and drainage channels are found near the Liverpool Ranges where most recharge occurs to the alluvial aquifers. Sandstone hill slopes found at Pine Ridge, Spring Ridge, and near Caroona are thought to not be as important to recharge. For example, at one sandstone hill slope, monitoring and investigation found that groundwater levels were lower under the ridge than on the plains and that almost no recharge occurred. Rainfall on the sandstone ridges appears to be lost mainly to evaporation with minor runoff. However, further investigation is needed to confirm this (Timms and Acworth, 2006).

Salt has been accumulated in the soil and clay aquitards over tens of thousands of years by wet and dry deposition. Deep clay cores have shown that only about 10% to 20% of total salt is stored in the upper 3 m to 6 m depth where it is detected by soil surveys. There is also evidence of saline playa lakes in the sediments, suggesting that Lake Goran may be the remnant of a larger salt lake system. Erosion of these sediments, or release of salts by drying and increased flushing, will have implications for achieving river salinity targets downstream. Proposed mining activity should therefore be planned to minimise or eliminate the release of additional salt to the surface drainage system (Timms and Acworth, 2006).

Recent work has caused a rethink of conceptual models describing groundwater flow and discharge in valleys south of Caroonna (Timms and Acworth, 2006). New data was used in a computer model of flow and contaminant transport to show that salt has diffused downwards through a 30 m thick aquitard over at least ten thousand years. The very low permeability of clay below the surface cracked and fractured zone, combined with almost no hydraulic gradient means that upward discharge of water is extremely slow with water possibly moving only about 5 m in 10,000 years. This means that the clays can effectively become barriers if used appropriately (Timms and Acworth, 2006).

Further Timms and Acworth (2006) found that the increased weight of moisture in the soil zone causes water pressure changes deep within the compressible clay even though no physical recharge occurred. A small increase of groundwater levels in the gravel aquifer at 50 m depth, confined by the clay aquitard was observed about 70 days after rainfall increased storage weight near the ground surface. Groundwater hydrographs need to be re-examined in the light of this finding because a rise in the hydrograph has previously been taken to imply direct downward movement of groundwater.

4.6 Water resources

4.6.1 Overview

Water resources within the catchment comprise both surface water and groundwater. Surface watercourses are present throughout the entire area, although the headwaters of many of the tributary streams are ephemeral and only flow after prolonged rainfall. There are over 9,500 km of watercourses within the Namoi catchment (Lampert & Short, 2004) and the main features are presented in Figure 4.5. Groundwater resources are principally located within the alluvium along the river valleys.

The water resources available in any given year are highly dependent on rainfall within the catchment. Average annual rainfall is 633 mm and average runoff has been calculated as 24 mm/yr (CSIRO, 2007). Average rainfall decreases from west to east, with 1200 mm/yr being recorded at the top of the Great Dividing Range, and 450 mm/yr being recorded around Walgett. Rainfall occurs in all months but on average 40% more rainfall occurs in the summer than the winter, leading to high intensity, short duration flood events. In addition to seasonal variations in rainfall there are also longer-term trends within the dataset, noted as comprising (Crapper *et al*, 1999):

- A period of above average rainfall at the turn of the last century
- Below average rainfall until 1945
- Above average rainfall to 1999.

This fits with the wider rainfall pattern for New South Wales

4.6.2 Location and distribution of surface water resources

The Namoi River is the principal river in the area and flows in a generally western direction over a distance of 350 km from its source in the Great Dividing Range to its confluence with the Barwon River near Walgett.

Significant tributary streams to the Namoi River include the Macdonald River, Peel River, Cockburn River and the Manilla River. Smaller tributaries of the Namoi River include the Cobrabald River, Coxs Creek, Maules Creek, Mooki River and Bundock Creek.

These can be split into five main sub-catchments as follows:

- Peel sub-catchment
- Mooki sub-catchment

- Macdonald/Manilla sub-catchment
- Middle Namoi sub-catchment
- Lower Namoi sub-catchment.

Three key water supply storage dams are present in the Namoi Catchment:

- Split Rock Dam on the Manilla River, built in 1988 and able to store 397,000 ML
- Keepit Dam on the Namoi River, built in 1960 and able to store 423,000 ML
- Chaffey Dam on the Peel River, built in 1979 and able to store 62,000 ML.

These regulate the flow of water in the catchment below these points. There are also several smaller on-river dams, and around 140,000 ML of off-river storage developed as on-farm dams and used for storing off-allocation water from tributaries, or water diverted from the main rivers during high flow events. There are also several public and private weirs along the Namoi which are used to divert and regulate river flows as necessary (Lampert *et al*, 2004).

Over 90% of the total runoff in the Namoi River catchment is generated in the upper 40% of the catchment. The average total surface water resource in the Namoi region is 965 GL/year and on average flow at Gunnedah is around 770,000 ML/yr. Flows in the majority of the Namoi River are regulated by the storage dams. Split Rock Dam regulates 93% of inflows, Keepit Dam regulates 77 % of inflows and Chaffey Dam regulates 41% of inflows (CSIRO, 2007). Although the streams are regulated the average flow is still highly dependent on annual rainfall.

The large water supply dams also trap sediment. This gradually infills the available storage area and also restricts the amount of material that can move downstream to replenish the streambed further down the system.

The Upper Namoi has historically fluctuated between being a gaining and losing stream. The reach above Boggabri is recognised historically as the main losing reach, with the area below Boggabri to the Lower Namoi historically classed as a gaining reach. The Lower Namoi has always historically been a gaining reach but the flow patterns have now reversed and water is lost to the aquifer. Under current abstraction regimes leakage into the aquifer from the river is estimated to peak at 99 GL/yr (CSIRO, 2007).

A study on the Maules Creek sub-catchment (Andersen & Acworth, 2009) has shown a correlation between shallow abstraction from the alluvial aquifer in the creek and a reduction in stream flow immediately downstream of the abstraction point. This creek is generally ephemeral in nature, and consequently flows are low enough that a change can be picked up. The study also looks at flow changes in the much larger Namoi River between Boggabri and Turrawan. Despite the river being regulated it was still possible to observe changes in flow along the reach of interest. In July 2005 there were significant gains in stream flow as a result of rainfall runoff events. Later there was a losing period, where it was assumed that water was lost to the aquifer. Over a two year period (Oct 2005 – Sept 2007) the loss was calculated as 68,000 ML. Only about 3.4% - 4.9 % of the loss could be attributed to surface water abstractions.

The vertical head gradients observed in the lower reaches of the Maules Creek catchment also suggest that surface water from this ephemeral sub-catchment recharges into the Namoi Valley alluvial sediments. This loss is believed to be exaggerated by drawdown due to abstraction within the Namoi Valley alluvial deposits at this location. It is not known at present how representative this is of the catchment as a whole.

Regulation of the system has increased the average period between floods from 3 months to 3.8 months and has reduced the average flooding volume by 150 GL (CSIRO, 2007).

4.6.3 Location and distribution of groundwater resources

Groundwater resources have primarily been developed within the alluvial deposits along the river valleys although there are also minor developments within the bedrock aquifers. The alluvial plains are extensively managed for agriculture. Historically, over-abstraction of water has led to falling groundwater levels in several areas of the catchment, with the aquifer becoming dewatered at the margins (e.g. near Wee Waa). In several areas drawdown has reached between 40% and 60% of the saturated aquifer thickness and the aquifer has become unconfined.

The alluvial aquifer consists of unconsolidated sediments lying unconformably on a pre-Tertiary erosional basement surface. The sediments are generally divided into three units:

- Narrabri Formation – 30 m thick clays with minor sands and gravels.
- Gunnedah Formation – (semi confined), fluvio-lacustrine sediments up to 70 m thick; predominantly gravel and sand with interbedded clay (productive aquifer unit).
- Cubbaroo Formation – (semi confined), sand and gravel with interbedded clay.

These alluvial groundwater resources areas are often split into the Lower Namoi and Upper Namoi groundwater catchments, and the Peel River groundwater unit (Figure 4.6).

The Upper Namoi groundwater catchment has been split into 12 different management units based on hydrogeological properties. The Lower Namoi catchment and the Peel River Alluvium remain as one unit each.

Around 75% of groundwater abstracted in the catchment comes from the Upper and Lower Namoi Alluvium. Extraction from the Lower Namoi GWMU exceeds the sustainable abstraction limit but there are measures in place to reduce abstraction to a sustainable level by 2015 through the reduction of supplemental licences. Extraction from the Upper Namoi GWMU is currently 95% of the sustainable yield. This is a very high level of development. The Peel River Alluvium and Barwon River catchment groundwater units are moderately and highly developed (respectively).

The Peel River Alluvium is highly connected to the river, with more than 80% of any abstracted water estimated to be sourced from the river, and therefore to reduce surface water flows. Abstraction also occurs from the fractured bedrock within the Peel catchment. This has also been shown to directly connect to the surface water and will also reduce stream flows in the short term (CSIRO, 2007).

Groundwater-surface water interaction decreases downstream in the Upper Namoi system as the overlying sediments become less permeable. The area of alluvium in the Upper Namoi catchment is about 3,000 km² (up to 170 m thick), while the Lower Namoi alluvium covers an area of about 5,100 km² (up to 120 m depth). The most productive abstraction areas are the main palaeochannels along the central valley.

The Department of Natural Resources maintains a network of 305 monitoring boreholes in the Upper Namoi and 258 monitoring boreholes in the Lower Namoi. Additional boreholes are also located in the Peel River catchment (Kelly *et al.*, 2007).

4.7 Water resource management

4.7.1 Regulatory framework

Water resource management within the Namoi catchment is controlled by the legislation and regulations of the NSW government and, as a part of the Murray Darling Basin, is also regulated by the Commonwealth. The following section is an overview of the relevant legalisation and a discussion of how that legislation affects water use within NSW and the Namoi. The section is a summarisation of the Water Regulatory Framework for Rural NSW as presented by the NSW Parliament (2010).

Water resource management - NSW

The *Water Management Act 2000* (NSW) repealed the *Water Act 1912* (NSW); however, the *Water Act 1912* (NSW) still applies in those areas of NSW not yet covered by a Water Sharing Plan. The *Water Management Act 2000* (NSW) abolished common law riparian rights and vested all water rights in the Crown. Water rights can now only be acquired through possession of an access licence, with the exception of some domestic and stock rights, harvestable rights and native title rights.

The *Water Management Act 2000* (NSW) was introduced to reflect the Commonwealth of Australian Government (COAG) goals for water reform and the principles of ecologically sustainable development. The *Water Management Act 2000* (NSW) repealed the *Water Act 1912* (NSW) in areas of NSW covered by a Water Sharing Plan. The *Water Act 1912* (NSW) still applies to areas outside of Water Sharing Plans. Water sharing plans in force for the Namoi catchment are listed in Table 4.4.

Table 4.4 Water sharing plans of the Namoi catchment

Water Sharing Plan	Status
Upper Namoi and Lower Namoi Regulated River	Commenced 01 July 2004 Amended 12 June 2009
Peel Valley Regulated, Unregulated, Alluvium and Fractured Rock Water Sources 2010	Commenced 01 July 2010
Phillips Creek, Mooki River, Quirindi Creek, and Warrah Creek Water Sources	Commenced 01 July 2004
Upper and Lower Namoi Groundwater	Commenced 01 November 2006
NSW Great Artesian Basin Groundwater Sources	Commenced 01 July 2008

(Department of Infrastructure, Planning and Natural Resources. 2004)

The *Water Management Act 2000* (NSW) made provision for a State Wide Management Outcomes Plan providing an over-arching policy context, targets and strategic outcomes for the management of the State's water sources. The first version ceased to be in force in December 2007 and a new plan has not been released as yet.

Under the *Water Management Act 2000* (NSW) several types of water management plans can be implemented although to date only Water Sharing Plans have been enacted. Water Sharing Plans apply to a specific water management area, establish environmental water rules, identify water requirements for all stakeholders, establish access licence rules and establish a bulk access regime for the extraction of water under access licences.

Water management plans have a lifespan of 10 years and must be audited at least every 5 years. Implementation programs set the framework through which the water management plan will be implemented.

Water access licences have two components. A share component gives entitlement to a specified share of available water within a water management area. An extraction component gives entitlement to take water at a specific time and rate, under specific circumstances and location. They do not give the right to take or use the water.

A water use approval designates the use of water for a purpose at a location. A water management work approval gives the right to construct and use a specified work at a specified location. An activity approval confers the right to carry out activities that will impact a groundwater source or that are located adjacent to a water source.

A number of water access categories and sub-categories are provided for within The Water Management Act 2000 (NSW) and Water Management (General) Regulation 2004 (NSW). These are:

- domestic and stock, local water utility and major utility access licences;
- regulated river (high security) access licences;
- supplementary water access licences, and
- all access licences other than those referred to above.

There are three types of water access licence tenures: continuing, specific purpose and supplementary. These are:

- Access licences with continuing tenure are issued in perpetuity, and are generally used for commercial purposes.
- Access licences with specific purpose tenure have higher priority than continuing tenure licences, e.g. town water or domestic and stock purposes.
- Access licences with supplementary tenure have the lowest priority and are only created when a Water Sharing Plan makes provision for them.

Water trading is provided for through two generic types of water dealings which are general water dealings and water allocation assignment dealings. General water dealings involve the permanent or temporary transfer of water or alteration to a share of water. Water allocation assignment dealing involves the sale of a volume of water. Water transfers require the consent of the responsible NSW Minister and the responsible Minister from the other State or Territory if across borders. The NSW Minister can impact upon access licences through the following means:

- temporary water restrictions;
- embargoes on applying for licences;
- cancellation and suspension of licences;
- acquisition of licences; and
- variation of the bulk access regime.

No compensation is payable under the first three categories. Compensation, as determined with reference to the current market value, is payable in the case of the fourth category. Payment of compensation in cases arising under the fifth category involves a complex set of rules.

Water management in rural NSW is under the control of several NSW administrative bodies. State Water is NSW's rural bulk water delivery corporation, delivering water in accordance with Water Sharing Plans to all users including the environment. The NSW Office of Water is responsible for the majority of water planning and management in NSW, and implements a number of policies including the Draft Floodplain Harvesting Policy 2010, Water Compliance Policy and Water Extraction Monitoring Policy. The prices charged by both of these bodies for their services are regulated by the Independent Pricing and Regulatory Tribunal.

Other bodies involved in water management include:

- the Department of the Environment, Climate Change and Water;
- NSW Government Land and Property Management Authority;
- Natural Resources Commission;

- Catchment Management Authorities; and
- the Dumaresq-Barwon Border Rivers Commission.

Water resource management – Commonwealth

State powers were referred to the Commonwealth by the *Water (Commonwealth Powers) Act 2008* (NSW) in order for the commonwealth to implement the *Water Act 2007* (Cth). This Act also amended the *Water Management Act 2000* (NSW) and repealed the *Murray-Darling Basin Act 1992* (NSW). Equivalent legislation was passed by the other Basin States. The *Water Act 2007* (Cth) is not intended to exclude or limit the concurrent operation of any State law.

The *Water Act 2007* (Cth) was designed to address the deteriorating environmental condition of the Murray-Darling Basin by enabling the Commonwealth, in conjunction with the Basin States, to manage the Basin water resources in the national interest. The Act also establishes two national level institutions for water management: the Commonwealth Environmental Water Holder manages all Commonwealth environmental water holdings; and the Bureau of Meteorology will create and manage a National Water Account.

The Murray-Darling Basin Authority is established by the *Water Act 2007* (Cth) to:

- prepare and implement the Basin Plan,
- advise the Commonwealth Minister for Climate Change, Energy Efficiency and Water on the accreditation of State water resource plans (NSW Water Sharing Plans),
- develop a water rights information service to facilitate water trade in the Basin and several other water management activities.

The Basin Plan will set diversion limits for the Basin and for each individual water management area, set water trading rules, and contain an Environmental Watering Plan and a Water Quality and Salinity Management Plan for the Basin. Water Sharing Plans in the Basin will need to become consistent with the Basin Plan once their current version expires.

The operation of water trading in the Murray-Darling Basin is also altered by the *Water Act 2007* (Cth). Risk allocation in relation to changes in water access entitlements corresponds with the *Water Management Act 2000* (NSW). However, water market and water charge rules may be made by the Commonwealth Minister for Climate Change, Energy Efficiency and Water.

Water resource management - Namoi

Management of water resources in the catchment is under constant review, with the latest water resources plan being agreed in 2008. Water resources in the catchment are managed through the use of groundwater and surface water licences, which are issued by the New South Wales Office of Water.

Ivkovic (2006) reports surface water and groundwater resources as historically over-allocated, and abstraction has exceeded sustainable levels of consumption. Groundwater users in particular have recently faced significant cuts in their allocation in order for the resource to be returned to a sustainable level of development as part of the water reform agenda (Ivkovic, 2006). Water use falls into three main categories:

- unregulated surface water;
- regulated surface water;
- groundwater.

The unregulated systems include the portions of the catchment above the major dams (Keepit, Split Rock and Chaffey) and the tributaries that flow into the Namoi River such as Cox's Creek, Mooki River, Maules Creek and Barradine Creek. The regulated systems comprise the main rivers below the dam storages.

In 'average' years there is an approximate 50:50 split between abstraction of surface water and groundwater. In drought years this changes to up to 78% groundwater use (CSIRO, 2007).

4.7.2 Surface water management

The surface water resources of the Namoi are considered to be fully committed for abstraction purposes. In addition to the licensed surface water abstractions it is estimated that up to 33% of the surface water used is obtained from off-allocation supplies from tributaries etc.

4.7.3 Groundwater management

There are 21 towns in the catchment which are reliant on groundwater for domestic supply. Groundwater is also used extensively for irrigation and stock supplies.

Groundwater allocations are managed based on management areas and zones developed by the Department of Natural Resources.

Lower Namoi groundwater resource management

The Lower Namoi Groundwater unit covers the all water in the alluvial sediments associated with the Namoi River and its tributaries below Narrabri. The lower boundary of the water resource is defined by the formations of the Great Artesian Basin.

In addition to stock and domestic water rights there are three categories of groundwater licence in the Lower Namoi GWMU. In the 2008-09 water year these broke down into the following (Smithson, 2009): aquifer access licences – 210 active, with a total of 81,593 units; supplementary water access licences – 130 active, with a total of 21,005 units; and local water utility access licences – 3 active, total of 4407 ML.

The value of each licence unit is set at the start of each water year depending on the predicted supply available. In 2007-08 this was 1ML/unit. If units are unused they can be rolled over into the next water year, up to a maximum of 2 ML/unit abstraction in most cases.

The maximum sustainable abstraction from the Lower Namoi GWU has been calculated at approximately 8,6000 ML/yr (Smithson, 2009). Current abstraction is above this limit, but under the current water management plan licensed water rights will be reduced to this sustainable level by the 2015-16 water year through the removal of supplemental water access licences. These are due to reduce by 0.1 ML per unit each year, from 0.9 ML/unit in 2006-07 to 0.1 ML/unit in 2014-25, after which they will cease to exist. During the 2006-07 water year groundwater use was 125.7 GL, and in 2007-08 year it was 102.4 GL. (Smithson, 2009).

Groundwater resources are monitored throughout the Lower Namoi GWU using a series of 560 piezometers at 240 monitoring locations plus 470 licensed bores on 175 properties which are metered to allow for calculation of water usage (Johnson, 2001).

Upper Namoi groundwater resource management

Assessment of the available Upper Namoi groundwater resources are more complex than the Lower Namoi as there are multiple groundwater units. Average groundwater use has been close to the sustainable calculated resource in several of the Upper Namoi groundwater units (CSIRO, 2007). In 2004/05 groundwater abstraction was 100,000 ML (National Water Commission website, 2010). The sustainable yield has been set as 122,100 ML/yr (CSIRO, 2007). This breaks down as shown in Table 4.5 for each unit (NSW Govt, 2008).

Table 4.5 Upper Namoi GMU sustainable yields

Groundwater Management Unit	Sustainable Yield
Zone 1	2,100 ML/yr
Zone 2	7,200 ML/yr
Zone 3	17,300 ML/yr
Zone 4	25,700 ML/yr
Zone 5	16,000 ML/yr
Zone 6	14,000 ML/yr
Zone 7	3,700 ML/yr
Zone 8	16,000 ML/yr
Zone 9	11,400 ML/yr
Zone 10	4,500 ML/yr
Zone 11	2,200 ML/yr
Zone 12	2,000 ML/yr

The groundwater resources allocation for each unit share is shown in Table 4.6. The data shows that aquifer access rights have been steady over the last few water years but that supplementary licences have been dropping, as seen in the Lower Namoi.

Table 4.6 Available water per unit in selected water years (ML/unit)

Zone	Supplementary water license				Aquifer access water license			
	2010/11	2009/10	2008/09	2007/08	2010/11	2009/10	2008/09	2007/08
Upper Namoi Zone 1 Borambil Creek	0.64	0.76	0.88	1	1.3	1	1	1
Upper Namoi Zone 2 Cox's Creek (Mullaley to Boggabri)	0.5	0.6	0.7	0.8	1	1	1	1
Upper Namoi Zone 3 Mooki Valley (Breeza to Gunnedah)	0.5	0.6	0.7	0.8	1	1	1	1
Upper Namoi Zone 4 Namoi Valley (Keepit dam to Gin's Leap)	0.5	0.6	0.7	0.8	1	1	1	1
Upper Namoi Zone 5 Namoi Valley (Gin's Leap to Narrabri)	0.84	1	1	1	1	1	1	1
Upper Namoi Zone 6 Tributaries of the Liverpool Range (South to Pine Ridge Road)	NA	NA	NA	NA	1	1	1	1
Upper Namoi Zone 7 Yarraman Creek (East of Lake Goran to Mooki River)	1	1	1	1	1	1	1	1
Upper Namoi Zone 8 Mooki Valley (Quirindi - Pine Ridge Road to Breeza)	0.5	0.6	0.7	0.8	1	1	1	1
Upper Namoi Zone 9 Cox's Creek (Up-stream Mullaley)	NA	NA	NA	NA	1	1	1	1
Upper Namoi Zone 10 Warrah Creek	NA	NA	NA	NA	1	1	1	1
Upper Namoi Zone 11 Maules Creek	0.84	1	1	1	1	1	1	1
Upper Namoi Zone 12 Kelvin Creek	0.84	1	1	1	1	1	1	1
Lower Namoi	0.5	0.6	0.7	0.8	1	1	1	1

Peel River groundwater resource

The long term average annual extraction limit for the Peel River Alluvium has been set as 9,344 ML/yr, and from the fractured rock aquifer as 71,218 ML (NSW Govt, 2010). In 2004/05 total groundwater abstraction for the Peel River alluvium was 9000 ML/yr, and 16,300 ML for the fractured rock aquifer (National Water Commission website).

4.8 Water quality

4.8.1 Surface water

A review of surface water quality issues in the Upper Namoi was conducted by Hyder Consulting as a part of the "State of Environment Report 2008 – 2009". Hyder Consulting (2009) stated that water quality is a strong indicator of catchment health particularly in terms of detecting impacts associated with current and future land management practices. Water quality within the Namoi region is influenced by a number of direct and indirect land use pressures, including urban and agricultural runoff, stormwater inflows, sewage discharges and the clearing of native vegetation.

Further, Hyder Consulting (2009) noted that high concentrations of nutrients are important triggers of algal blooms with other factors such as water temperature, turbidity and water turbulence also important determinants of bloom formation. Water quality is monitored at a number of locations throughout the Namoi region to assess impacts associated with land management practices, collect information to inform improved management of water resources and to monitor change over time.

Three water quality parameters were noted by Hyder Consulting (2009) as of concern: nutrients, salinity and turbidity. The parameters measured include pH, electrical conductivity, turbidity, dissolved oxygen, and total phosphorus.

Most water quality monitoring sites across the Namoi region were observed by Hyder Consulting (2009) to exceed Australian and New Zealand Environment and Conservation Council (ANZECC) water quality guidelines for total phosphorous (50 µg/L limit) most of the time for the period July 2005 to June 2008. A number of significant exceedances of ANZECC guidelines for total nitrogen (500 µg/L limit) were also recorded for the period July 2005 to June 2008. Only the Peel River was observed to have an acceptable level of total phosphorous, while total phosphorous at the Manilla River and Goonoo Goonoo Creek failed to comply with ANZECC trigger value. Total phosphorous was not recorded for other waterways.

Hyder Consulting (2009) stated that electrical conductivity readings over 650 µS/cm are considered to be of high salinity for irrigation water and can cause crop damage and/or soil salinity problems. They found that the major irrigation areas in the lower Namoi catchment have exceeded this level on occasions. Electrical conductivity results for samples from the Cockburn River, the Manilla River, Goonoo Goonoo Creek and Halls Creek exceeded the ANZECC trigger value during 2008/09, while only 33% of electrical conductivity recorded at Peel River complied. The rest of rivers and creeks sampled complied with the ANZECC trigger value for electrical conductivity (Hyder Consulting, 2009).

Based on Waterwatch data, Hyder Consulting (2009) noted that turbidity levels at sampled sites sampled mostly complied with the ANZECC guidelines for turbidity. Notable exceptions were the Cockburn River where no samples complied and Swamp Creek where only 50% of turbidity levels recorded complied with the ANZECC trigger value.

The pH levels in most of rivers and creeks in Namoi Region were within the ANZECC trigger values. Low pH values were detected at Manilla River and Peel River (Hyder Consulting, 2009). Data for dissolved oxygen was only available for the Cockburn River, Peel River and Goonoo Goonoo Creek. Dissolved oxygen in these waterways was found to be below the ANZECC trigger value (Hyder Consulting, 2009).

The major ion chemistry of the stream water within the Namoi catchment has been presented by NSW DNR (2005) as a piper diagram (Figure 4.7). Each river is represented as a distinct cluster, reflecting the unique geology, flow path and chemical evolution of the water in each catchment. This is particularly evident with samples from the Peel River and Cox's Creek which do not overlap, while further down the system where the waters have mixed in the Namoi River at Narrabri there is a larger degree of overlap. The report indicates that the major ion chemistry of the river water has remained reasonably static over the past two decades.

4.8.2 Groundwater

Kelly (2007) provides some insight into the condition of groundwater quality within the Namoi catchment. Such discussion is limited within available literature. Whilst, data is available from the relevant New South Wales government departments discussion on the actual quality and more importantly changes in quality is limited. This is best encapsulated by McLean (2003) supported in Kelly (2007) who states:

"Difficulties arise in the interpretation of historical chemical data due to infrequent sampling and lack of documentation pertaining to sampling methodologies and instrumentation. The absence of a regular sampling program and the transfer of data from original hard copies to electronic databases in central and regional offices combined with the exclusion of data from technical reports have resulted in a limited historical data set."

This is the same for all catchments of the Namoi. McLean did a preliminary analysis of changes in the water quality based on the electrical conductivity measurements collected in the mid 1980's to her sampling run in 1999. This work highlights the need to further understand the rate of change in water quality and if the rate of change is significant with respect to the use of the water.

McLean (2003) after Kelly (2007) concluded that the salinity of the water in the recharge zone had increased by 100 $\mu\text{S}/\text{cm}$ over the last 30 years, and in the western portion of the aquifer by several thousand $\mu\text{S}/\text{cm}$. The changes in water quality due to pumping show no general trends and are localised. The more significant change in electrical conductivity in the order of several thousand $\mu\text{S}/\text{cm}$ in the western part of the catchment is directly related to changes in direction of potential flow paths caused by pumping practices (Kelly, 2007).

Groundwater quality at the Carroona Coal Project site has been examined by AGE Consultants (2009). Data published in their public presentation of September 2009 indicates that samples from within the alluvial aquifer at the site had an electrical conductivity (EC) of between 710 and 2760 $\mu\text{S}/\text{cm}$ and pH values ranging from 7.2 to 8.7. Water samples from the Clift Seam had an EC of 5,890 and a pH of 8.6. Samples from the Hoskisson Seam were significantly more saline with an EC of 16,700 and pH of 7.0.

Aquaterra (2009) in the Hydrogeological Assessment Report for the Narrabri Coal Mine Stage 2 expansion noted that an overall evaluation of water quality results indicated that in general, the groundwater at the site is brackish, with salinity generally ranging from 5,000 to 15,000 mg/L TDS. Localised fresher zones predominate in areas where the Garrawilla Volcanics subcrop, and groundwater in the Black Jack Group formations is generally greater than 7,000 mg/L TDS (brackish). In areas where the Hoskissons Coal Seam is shallow and proximal to the Boggabri Ridge, groundwater is less saline.

4.9 Previous numerical modelling studies

A number of sub-catchment scale models have been constructed for the management of water resources within the Namoi Catchment by the New South Wales Government. A number of site specific groundwater modelling projects and assessments have also been undertaken by the coal and gas companies. Access to these models will be at the discretion of their individual owners. This section provides a brief overview of a number of the known models for the Namoi catchment and provides a short discussion of their areas of influence. Spatial locations of each model are shown in Figures 4.8 and 4.9 for groundwater and surface water models (respectively).

Lower Namoi model

Kelly et al. (2007) report a mature groundwater flow model exists for the saturated aquifer system of the Lower Namoi catchment. The model has been through various stages of development and recalibration since initially constructed by Dr. Noel Merrick in 1982 as a resource management tool. The revisions have included changes in conceptualisation and computer software and hardware. The most recent model is the Narrabri to Cryon model developed by Dr. Noel Merrick using PMWin software in 2001. The calibration period for this model is from 1980 to 1998 and it comprises a 30 x 50 cell grid with a 2.5 km cell spacing. The various model generations are presented in Table 4.7.

Table 4.7 Lower Namoi groundwater models

Model	Area	Calibration	Developed	Software	Author
Lower Namoi	Narrabri to Merah North	1969-1981	1982	WRC	Merrick/Williams
Lower Namoi	Narrabri to Cryon	1969-1982	1984	WRC	(Undoc)
Lower Namoi	Narrabri to Cryon	1981-1986	1989	Modflow	Merrick
Lower Namoi	Narrabri to Cryon	1987-1994	1995	PMWin/Modflow	Merrick
Lower Namoi	Narrabri to Cryon	1980-1994	1998	PMWin/Modflow	Merrick
Lower Namoi	Narrabri to Cryon	1980-1998	1999	PMWin/Modflow	Merrick

(Kelly et al. 2007)

Upper Namoi model

Kelly et al. (2007) reported that a groundwater flow model for the saturated aquifer system of the Upper Namoi catchments was nearing completion at the time of their 2007 report "Groundwater Knowledge and Gaps in the Namoi Catchment Management Area". It is assumed that this model has been completed and is a functioning water management tool for the area. The model was being developed by the Department of Natural Resources at Parramatta. The model encompasses alluvial Zones 2, 3, 4, 5, 11 and 12 of the Upper Namoi Groundwater Management Area 004, as shown in Figure 4.10.

The model was developed with MODFLOW-96 software using the Visual Modflow Version 3.1 graphic user interface. Calibration extended from 1985 to 2001, using one-month stress periods. The discretisation is a uniform grid with cell size 1000 m x 1000 m, extending from Breeza to Narrabri. The model consists of two layers corresponding to the Narrabri and Gunnedah Formations, and has 106 rows and 82 columns. It covers an area of 82 km east-west by 106 km north-south, as shown in Figure 4.8. The model includes rainfall infiltration, floods, side-slope runoff, leakage from ephemeral streams, irrigation returns, stream-aquifer interaction, lateral groundwater inflow and outflow, and groundwater pumping (Kelly et al., 2007).

The model is calibrated to groundwater observations from 356 multi level monitoring bores. Calibration was preformed manually rather than by an automated method. During the last month of calibration, the RMS error was reported as 2.2% (mean residual 1.9m). Modelling reportedly indicates that the Upper Namoi aquifers rely mainly on rainfall infiltration at approximately 3% of rainfall less evaporation. Occasional flood recharge also appears important. In places, side-slope runoff and ephemeral leakage from ponds are also significant.

In Zones 2, 3 and 5 the second largest recharge component was found to be deep drainage. In zones 4 and 11 it is river leakage. During the 16 years of the calibration period flood recharge was found to be about 2 GL/year on average. By contrast, natural recharge from rainfall, ponds and side-slope runoff was about 30 GL/year on average, and irrigation deep drainage was estimated to be 17 GL/year. Groundwater extraction over the calibration period averaged 58 GL/year. The total recharge to the model area was calculated as approximately 54 GL/year.

Efforts to reconcile simulated river leakage with IQQM losses were unsuccessful. As a result Kelly et al. (2007) have recommended the utilisation of coupled river-aquifer modelling to ensure simulation of the two water systems is consistent.

The Upper Namoi model is the latest in a series of models which have been constructed using various software and hardware since 1989. This model has been constructed using data from the earlier models which were overlapping and were possible could provide boundary conditions and parameters. A chronology of the Upper Namoi models is presented in the Table 4.8.

Table 4.8 Upper Namoi groundwater models

Model	Area	Calibration	Developed	Software	Author
Upper Namoi	Carroll Gap to Narrabri	1981 - 1986	1989	Sam 3	Carr
Upper Namoi	Carroll to Gunnedah	1981 - 1986	1996	VM/Modflow	Paul et al.
Borambil Creek	Zone 1	1979 - 1996	1997	VM/Modflow	Salotti
Liverpool Plains	Liverpool Range to Quirindi	1969-1984	1998	MIKE-SHE	Carr
Upper Namoi	Breeza to Gunnedah	1980 - 1996	1999	PMWin/Modflow	(Undoc)
Mooki	Quirindi to Breeza	1980 - 1996	1999	PMWin/Modflow	Kalf
Mooki	Quirindi to Breeza	1979 - 2000	2001	PMWin/Modflow	Merrick

(Kelly et al. 2007)

Maules Creek model

This is a small model constructed by the University of New South Wales in 2009 (Giambastini *et al.*, 2009). The model was built to provide a better understanding of dynamics of the alluvial aquifer in the Maules Creek catchment. It was constructed using the FEFLOW 5.4 finite element code, and represents the alluvial material using 9 model layers. The bedrock aquifer is assumed to be impermeable.

Model inputs represented diffuse recharge, irrigation return, stream-aquifer interaction, lateral groundwater inflow/outflow, and groundwater pumping. The model runs from 1978 to 2007.

To assess the effects of groundwater abstraction on stream-aquifer interaction the model was run with and without abstraction. Approximately 20% less groundwater was discharged into the river when abstraction was occurring. The river changes from gaining to losing in both scenarios, either through natural seasonal variation, or as a result of irrigation cycles.

Cox's Creek model

This model was developed by Ivkovic (2006) to look at the surface water - groundwater interaction within the Cox's Creek sub-catchment, and the effect of abstractions on stream flow at the outflow to the catchment. The model uses a spatially lumped rainfall-runoff model combined with a groundwater bucket model to create a continuous water balance model called IHACRES_GW. The model looked at historical impacts of abstraction of river flows between 1988 and 2003 by comparing scenarios with and without groundwater abstraction.

Great Artesian Basin

The transient groundwater flow model of the Great Artesian Basin (GAB) was constructed by the Bureau of Rural Sciences (Welsh, 2006) and runs under MODFLOW-2000 (Harbaugh, et al. 2000). The model is built on the GABFLOW steady state model (Welsh 2000). It is a single confined layer model with 5 km x 5 km north-south oriented cells, calibrated over the period 1965-1999 inclusive with 1-year stress periods. The shallowest artesian (Cadnaowie – Hooray) aquifer is modelled over the entire on-shore extent of the Basin south of the Gilbert River in north Queensland.

Conceptually, water within the model is treated as predominantly meteoric origin entering the aquifer where it is shallow or exposed around the elevated basin margin and travels down slope through the aquifer from which it may exit via a bore or a natural spring. The groundwater is pressurised and leaks vertically from higher-pressure to lower-pressure aquifers. Because deeper aquifers are recharged from higher on the western side of the Great Dividing Range (the main recharge area) than shallower aquifers, leakage is dominantly upwards (Welsh, 2006).

The GAB transient model is not likely to assist in the construction of a Namoi catchment model but may give some indication of Gunnedah Basin outflows to the greater GAB. Further investigation will be required.

Surface water models (IQQM)

The New South Wales government has two existing IQQM models in this area, comprising the Peel River sub-catchment, and the remainder of the Namoi River valley (Figure 4.9). The models are summarised in Table 4.9. The models simulate irrigation practices and water diversions within the regulated parts of the valleys. For unregulated sections, Sacramento rainfall-runoff models are used to extend the historical record of flow at gauging stations. Inflows from major tributaries are represented as nodal daily volumes in the model (Kelly et al., 2007).

Table 4.9 Integrated quantity and quality models (IQQM)

Model	Area	Calibration	Developed	Software	Author
Peel River	Peel River catchment	1975-2000	2006	IQQM	Department of Infrastructure, Planning and Natural Resources
Namoi River	Regulated Namoi catchment	1975-2000	2005	IQQM	Department of Infrastructure, Planning and Natural Resources

(NSW DWE, 2008)

Further, Kelly et al (2007) report that groundwater volumes are included only for those irrigators who had conjunctive licences prior to 2000. From the year 2000 with the abolishment of conjunctive licences, a regression analysis based on pre-2000 behaviour is used to estimate annual whole-of-valley groundwater use by river pumpers. The regression equation reportedly gives errors of about 40%. Water pumped by groundwater-only licensees is not simulated by the IQQM model, but is handled within MODFLOW models for the catchment. The IQQM Namoi model calibrates against measured water losses between gauging stations for 17 reaches, with unexplained losses attributed to net groundwater exchange with the river or to flow measurement errors. IQQM is also calibrated against event hydrographs, diversion records, planted crop areas, and storage volumes (Kelly et al., 2007).

Kelly et al. (2007) note that salinity modelling in IQQM is quite crude, being based on the correlation between salinity and flow, rather than on salt-producing processes. IQQM does not aim to track salt movement across the landscape in response to land use. That task is left for catchment scale models such as 2CSALT (Stenson et al., 2005). IQQM's objective is to predict end-of-catchment salinity levels by routing salt down a stream. Kelly et al. (2007) further suggest that the model has accuracy in the order of 20% for salt load and 10% for salinity prediction. Loss functions in IQQM do not take adequate account of groundwater interactions which are better determined by coupled river-aquifer models such as MODHMS or GSFLOW.

MIKE-SHE

A MIKE-SHE model was constructed as part of a comparative study of modelling codes and examined three separate sub-catchments in the Liverpool Plains area. The Model by Carr (1998) is discussed by Kelly (2007) but little definitive information is currently available and further research will be undertaken.

SIMHYD

It is noted that a SIMHYD model has been produced to model runoff within the Namoi catchment though little is actually known of the extent, scale and intent of the model at this time. It is believed to be a part of the greater Murray Darling Basin modelling project being undertaken by CSIRO. Further research will be undertaken to determine the model outcomes and how they may relate to the Namoi Catchment Water Study.

4.10 Location and distribution of coal resources

The Gunnedah Basin has a history of coal mining, with coal first being discovered in the 1870's. Estimated recoverable reserves in the Gunnedah Coalfield are 1.48 billion tonnes. Inferred but unproven reserves may increase this up to 30 billion tonnes (NSW DI&I, 2010b) over an area of approximately 8,000 km². The coal is contained in multiple seams of variable thickness which are interbedded with conglomerates, siltstones and sandstones. Raw production in the Gunnedah coalfield was 4.3 Mt in 2007-08. Production from the Whitehaven mines is understood to have increased to around 6 Mtpa at the present time (Whitehaven Coal, 2010). Historically mining operations have generally been on the small to medium scale using a mixture of open cut and underground techniques. Mines that have been active and are now closed include Gunnedah Colliery, Preston Colliery and Canyon Mine.

Figure 4.11 shows the location of large closed mines, active mines, and current exploration areas. These exploration licences are restricted to exploration for Group 9 minerals (Coal and Shale) and not for any other purpose such as exploration for coal seam gas. Authorisations are primarily located in areas where the coal bearing formations are at surface or only covered by thin alluvium.

The main active coal mines in the Namoi catchment are presented in Table 4.10.

Table 4.10 Active coal mines - Namoi catchment

Site	Operator	Location	Production rate
Tarrawonga*	Whitehaven	16 km E of Boggabri	1.5 Mtpa
Werris Creek	Whitehaven	4 km S of Werris Creek	1.5 Mtpa
Rocglen	Whitehaven	28 km N of Gunnedah	1.5 Mtpa
Sunnyside	Whitehaven	15 km W of Gunnedah	1 Mtpa
Narrabri	Whitehaven /Idemitsu	28 km S of Narrabri	0.7 Mtpa to 5.3 Mtpa once phase two production starts
Boggabri	Idemitsu	15 km NE of Boggabri	1.4 Mtpa saleable coal, 2008 1.55 Mtpa coal exported, 2009

* Previously known as East Boggabri

All but Narrabri are open cut mines. The depths of the coal seams being extracted by open cut techniques vary from 20 m to 180 m below ground level. Data on groundwater inflows to the mines has yet to be provided but initial anecdotal information suggest inflow rates on the order of 1 ML/d.

Narrabri will initially be mined as a continuous miner operation and then convert to a longwall mining technique. Depths of coal being mined through the longwall phase are from 160 m below surface to 380 m below surface. Groundwater inflows are predicted to vary from 0.2 ML/d to 3.9 ML/d as the mine expands (Narrabri Coal Operations, 2009).

Two groundwater systems have been identified for the Narrabri mine by Aquaterra (2009): a shallow groundwater system within the Permo-Triassic sequence which is recharged by infiltration of rainfall through the shallow alluvial deposits; and a deeper aquifer system with predominantly fracture flow patterns which includes the coal seams. There are only a limited number of bores within the deeper system. These bores generally have high salinity and low yields.

The act of longwall mining creates subsidence in the overlying beds which can lead to subsurface fracturing and allow for vertical groundwater flow across previously confining units. This could potentially influence groundwater systems by creating cross connections. However, the degree of connection is expected to be low, with the majority of groundwater intercepted within the mine most likely being sourced from lateral flow within the coal seams rather than induced leakage from above (Narrabri Coal Operations, 2009). A groundwater model for the Narrabri operation has predicted minimal impact on water resources at shallow depth, including the Namoi Alluvium, due to the presence of low permeability material within the system (Narrabri Coal Operations, 2009).

For the Narrabri mine, risks from the potential impacts on groundwater from mining activities have been summarised in the Environmental Assessment report (Narrabri Coal Operations, 2009) and are provided below:

- Groundwater pollution from a leakage or spill (low-moderate risk)
- Drawdown of groundwater resulting in reduced water levels in various aquifer units (moderate – high risk)
- Reduction in yield/saturated thickness of groundwater bores (moderate – high risk)
- Impacts on groundwater dependent terrestrial ecosystems (high risk.)

Coal from the Tarrawonga, Rocglen, and Sunnyside mines is taken to the Gunnedah Coal Handling and Preparation Plant (CHPP) for processing before being taken away by rail to the Port of Newcastle.

There are also several areas in the catchment currently undergoing exploration activities. These are concentrated into two areas of the catchment, to the east of Boggabri and to the SE of Gunnedah, and are summarised in Table 4.11.

Table 4.11 Current coal exploration areas

Site	EL area	Operator	Location	Estimated reserves
Caroona Coal	EL6505	BHP Billiton	25km SE of Gunnedah	500 Mt
Watermark Coal	EL7223	Shenhua Energy	35km SE of Gunnedah	1 billion tonnes
Maules Creek	EL	Aston Resources	20km NE of Boggabri	356 Mt
Vickery South	EL7407	Coalworks Pty	15km SE of Boggabri	42 Mt
Goonbri	EL7435	Bloomfield Collieries	18km ENE of Boggabri	Unknown

Concern has been raised by stakeholders on the Liverpool Plains in relation to the impacts of the proposed Caroona Coal and Watermark projects on shallow water resources within the overlying alluvial aquifer. These are similar concerns to those raised by the Narrabri underground mine.

BHP Billiton, who holds the Caroona Coal licence, is currently conducting a hydrogeological investigation to look at the connection of the alluvial aquifers and the underlying coal seams. As part of this a monitoring program has been set up which allows water quality and pressures to be recorded at different depths within the system to look for any cross connections. Permeability testing is also being completed on these holes to determine the physical properties of the rock strata (BHP, 2008). This type of data will be valuable to the current study as it will provide test data that can be used to build up a conceptual model of the intermediate depth system. BHP Billiton has adjusted the timescale for future development to account for any findings from this Study.

Each coal mining application has to submit an Environmental Impact Assessment (EIA) and Site Water Management Plan prior to gaining a licence. The EIA deals with all environmental issues that may arise during and after the life of the mine and also contains plans of how these issues will be minimised and mitigated. Monitoring data is usually collected from the local area and including surface and groundwater levels and quality. Predictions of how the mining may affect the local groundwater environment are often undertaken by creating a groundwater model of the area around the proposed development. The raw monitoring data and information from the groundwater models will be collated and utilised in future phases of this project to obtain initial values for hydraulic properties and localised issues.

4.11 Potential hydrological effects of coal mining

Potential hydrological effects of coal mining (open-cut and underground) to be considered in the Study include the following;

- connective cracking between different aquifer systems and between aquifers and surface water systems as a result of underground mining;
- enhanced permeability and increased groundwater flow due to lithostatic unloading during open cut mining;
- changes in surface flow patterns, runoff detention and flood storage as a result of changes in surface topography, and any consequential changes in water quality;

- operational water requirements and effects of beneficial reuse and/or disposal of any excess mine water;
- effects of changes in surface topography on groundwater recharge, and any consequential changes in water quality.

Subsidence can be a problem with underground coal mining, caused by the extraction of coal at depth and the failure of overlying rock mass. Failures in the overlying strata have the potential to increase groundwater inflows into the underground workings. Shallow surface cracking and discontinuous subsurface cracking may impact on shallow groundwater such as at the base of the weathered zone within the subsidence zone.

Mine operations generally aspire to improved water management strategies, aiming to reduce demand through efficiency, technology and the use of lower quality and recycled water. Water pollution is generally controlled by separating the water runoff from undisturbed areas from water in contact with mine working that can contain sediments, salts and acids. Clean runoff can be discharged into surrounding water courses, while other water is treated and can be reused such as for dust suppression and in coal preparation plants.

Acid mine drainage (AMD) can be a challenge at coal mining operations. AMD is metal-rich water formed from the chemical reaction between water and rocks containing sulphur-bearing minerals. The runoff formed is usually acidic and frequently comes from areas where ore or coal mining activities have exposed rocks containing pyrite. However, metal-rich drainage can also occur in mineralised areas that have not been mined. AMD is formed when the pyrite reacts with air and water to form sulphuric acid and dissolved iron. This acid run-off dissolves heavy metals such as copper, lead and mercury into ground and surface water. There are mine management methods that can minimise the problem of AMD, and effective mine design can keep water away from acid generating materials and help prevent AMD occurring. AMD can be treated actively or passively.

4.12 Location and distribution of oil and gas resources

Oil and gas resources within the basin comprise both conventional natural gas and also coal seam gas. Conventional gas reserves are currently being extracted from a small area near Coonarah to the west of Narrabri. Whilst exploration for conventional oil and gas may have been completed in other areas there is limited documentation of the work undertaken and no other areas appear to have been developed into commercial extraction sites. This suggests that there is limited potential for development of this resource at this time.

Coal seam gas (CSG) is a potentially significant resource in the Gunnedah Basin. Coal seam gas is extracted from coal seams at depth by dewatering the coal bearing formations to reduce groundwater pressure and allow gases, principally methane trapped within the coal seams, to be released. The drier the coal seam the higher efficiency is the process as the gas can move more freely. The volume and quality of the water removed during the dewatering process varies between areas. The volume of water extracted from the seams through time will decrease as the system moves into equilibrium. A number of alternatives are possible for management of the extracted groundwater including treatment as necessary at surface prior to being release.

Coal bearing formations that have the potential for coal seam gas generation underlie large areas of the Namoi catchment. Correspondingly, petroleum exploration, assessment and production licences (PEL, PAL, PPL) have been assigned which cover large areas of the catchment.

The two main parties involved in exploration for coal seam gas within the Gunnedah Basin are Santos (since 2007), and Eastern Star Gas (since 2002). Lease areas are also held by several other companies including Macquarie Energy Pty Ltd, Apollo Gas, and Australian Coal Bed Methane Pty Ltd. Joint agreements are in place in several of the exploration areas which allows part-ownership of the PEL to be earned in exchange for running exploration activities. Santos and Eastern Star Gas are heavily involved with these joint agreements. Tenements held by Santos and Eastern Star Gas are shown in Figure 4.12.

Petroleum exploration licences owned by Santos cover a total area of around 22,000 sq km. Santos is also involved with joint ventures with Eastern Star Gas, bringing their total exploration area up to 45,000 km². Santos is installing pilot wells in areas PEL 1 and PALA 5 and remains in the exploration phase in the other areas of interest (Santos, 2010a).

Eastern Star Gas has already developed pilot CSG extraction plants at Bohema and Bibblewindi in PEL 238. These are part of the wider Narrabri Coal Seam Gas Project. The pilot sites extract using both vertical wells and lateral wells which follow the coal seams to achieve maximum connection between the wells and the coal seam. Gas from the schemes is piped to the Wilga Park Power Station, which historically ran solely on natural gas piped from the Coonarah gasfield (PPL3). The natural gas is obtained from the Maules Creek Sandstone Formation which is the lowest of the coal bearing formations. Eastern Star Gas is also developing two pilot CSG plants at Dewhurst and Tintfield. Coal seam depths in the Bohema CSG projects are typically more than 600 m below ground level. There are an estimated 11.3 PJ of proved and probable CSG reserves in the Narrabri area. Within the wider Gunnedah Basin there are potential recoverable gas resources of 146 billion m³ (NSW DI&I, 2010b).

4.13 Potential hydrological effects of CSG extraction

Within the communities in the Namoi catchment there are concerns relating to the environmental impacts of CSG extraction on water resources. Whilst these cannot be addressed specifically at the present stage of the study the generic water related issues related to concerns with coal seam gas projects can be identified. An overview of some of these issues is presented below.

Impacts on existing deep bores

Extraction is most likely to directly impact users who have existing bores which intersect the same deep aquifer units as the CSG producers. The impacts are likely to be in the form of a reduction in yield / decreased water pressures rather than a change in water quality. It is expected that most of the bores which intersect the coal bearing formations will be located in areas where the coal seams are shallower, rather than in the deep areas which are preferred for CSG exploration, and there is not likely to be a great deal of overlap between the agriculture and CSG sectors.

Impact on shallow groundwater resources

The impact of CSG on shallow water resources is highly dependent on the vertical connections between the shallow and deep aquifer units. Prior to any development activities monitoring networks are put in place throughout the shallow and deep aquifer units around the CSG development areas to enable any changes to be observed quickly and assessed before any significant impacts can occur. Impacts could be related to:

- Vertical downwards leakage of shallow groundwater to the deeper aquifer in response to lowering the pressure at depth. Existing underground and open cut coal mining within the Namoi catchment has shown there to be relatively low volumes of water inflows into the mines as there are numerous low permeability layers within the system that restrict the flow of groundwater. This would also be expected to be the case with the deeper coal seams.
- Contamination of the shallow aquifers with gas or other material such as 'fracking' fluids. This would most likely occur rapidly if the CSG boreholes are not constructed properly. It is currently understood that fracking has not been required at the Narrabri pilot CSG sites. Leakage of small amounts of gas into higher layers may occur if there are gaps in the low permeability material which confines the coal layers. However, pressures above the dewatered layer would still be expected to be relatively high which should help to contain any migration.

At the end of CSG extraction re-pressurisation of the coal units is usually a long term process due to the limited connections to the surrounding rock units. If there have been any changes observed there is therefore likely to be a prolonged period of time before the system can restore itself to natural conditions.

Disposal of water removed from the coal seams

Coal seam gas extraction requires dewatering of deep aquifers which usually contain moderate - high salinity, sodium enriched groundwater. The volume of water produced varies spatially within the aquifer and also temporally. The TDS (total dissolved solids) of extracted groundwater is often in the range of 1,000 – 6,000 mg/L, although values of 200 - 10,000 mg/L have been recorded in some areas. This water has the potential to be a very different chemistry to existing shallow water resources and must therefore be kept separate to avoid changing the local water environment. Large quantities of the 'produced' or 'associated' CSG water are sometimes disposed of in evaporation ponds that may be up to 100 ha in size. Concerns relating to these ponds include:

- Leakage of water from the ponds into the shallow groundwater;
- Long term management of the salts left after evaporation has occurred;
- Non-beneficial use of a medium quality water resource.

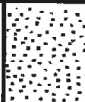
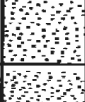
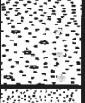
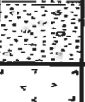
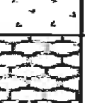
Alternative methods of disposal of CSG water include:

- To re-inject the water into other formations near to where it originated.
- To treat the water to an acceptable level using technology such as reverse osmosis plants then dispose of it into surface water. This can cause problems if it is sent to small streams where it is a large proportion of the total flow, or disposed of into streams which are naturally ephemeral as the flow regime will be changed to continuous flow below the discharge point.
- To treat the water to an acceptable level and use it for beneficial uses such as irrigation or water supply for towns or industry. This is acceptable practice in some areas but concerns may remain over disposal of the high salinity concentrate (reject stream) from the reverse osmosis procedure.

The production rate of the CSG water is also likely to be highly variable through time, with an initially higher flow rate at the start of dewatering and a gradual tapering off as dewatering becomes more established. This may restrict its value as a reliable supply of water over long periods of time, as may be required from third parties users.

The CSG pilot plants near Narrabri currently operate with a combination of evaporation pond storage and reverse osmosis technology. Concentrates are sent to a dedicated evaporation pond at Bibblewindi (Eastern Star Gas, 2006).

Figure 4.1 Stratigraphic section - Gunnedah Basin and Surat Basin

PERIOD		FORMATION	LITHOLOGY	
JURASSIC	EARLY – MIDDLE - LATE	ORALLO FORMATION		Clayey to quartzose sandstone, subordinate siltstone and conglomerate
		PILLIGA SANDSTONE		Fluvial, medium to coarse-grained quartzose sandstone
		PURLAWAUGH FORMATION		Carbonaceous claystone siltstone sandstone and subordinate coal
		GARRAWILLA VOLCANICS		Alkali basalt, trachyte, hawallite, pyroclastics and subordinate sediments
TRIASSIC	EARLY – MIDDLE	DERIAH FORMATION		Green lithic sandstone rich in volcanic fragments and mud clasts
		NAPPERBY FORMATION		Thinly bedded claystone, siltstone and sandstone; common bioturbation and burrows.
		DIGBY FORMATION		Lithic and quartz conglomerates, sandstone and minor finer grained sediments.
		BLACK JACK FORMATION		Dominantly fluvial and lacustrine sediments; lithic and quartz sandstones and conglomerates, siltstone, clay tuff and coal.
PERMIAN	LATE	WATERMARK FORMATION		Regressive marine sediments; sandy siltstone sandstone, common bioturbation, sporadic erratics and secondary calcite "cone-in-cone" replacements
		PORCUPINE FORMATION		Marine shelf sediments; lithic sandstone and conglomerate and bioturbated mudstone
		MAULES CREEK FORMATION		Fluvial; dominantly lithic and subordinate quartz-rich sandstone and conglomerate
	EARLY	GOONBRI & LEARD FORMATIONS		Colluvial and lacustrine sediments; pelletal claystone and upward – coarsening sequences of organic – rich claystone to sandstone
		Boggabri Volcanics, Werrie Basalt And Lachlan fold Belt rock		Mainly rhyolite flows and pyroclastic; minor sediments, basalt, subordinate tuffs and andesite lavas
PRE – PERMIAN				Metavolcanics and metasediments

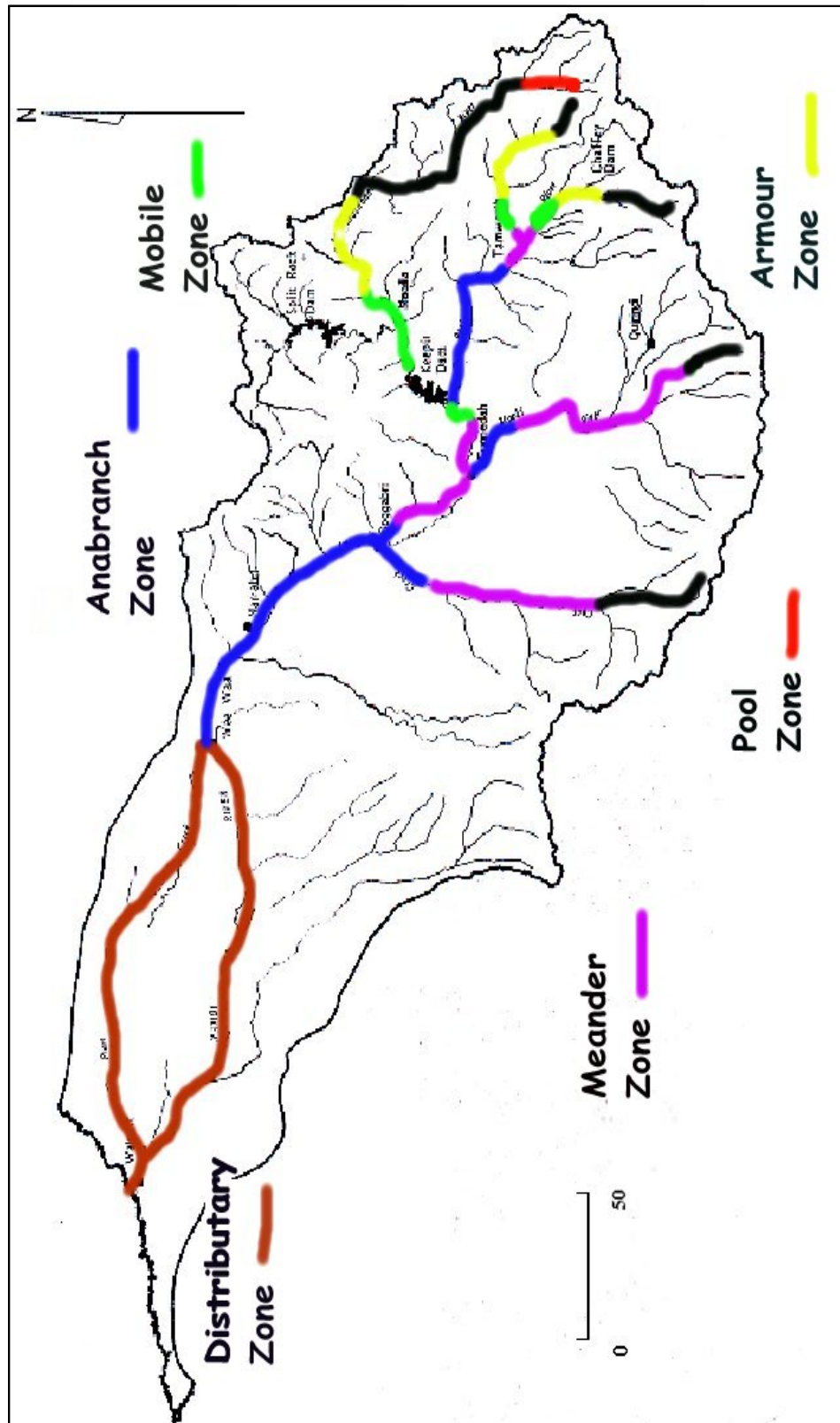
(After Tadros, 1993)

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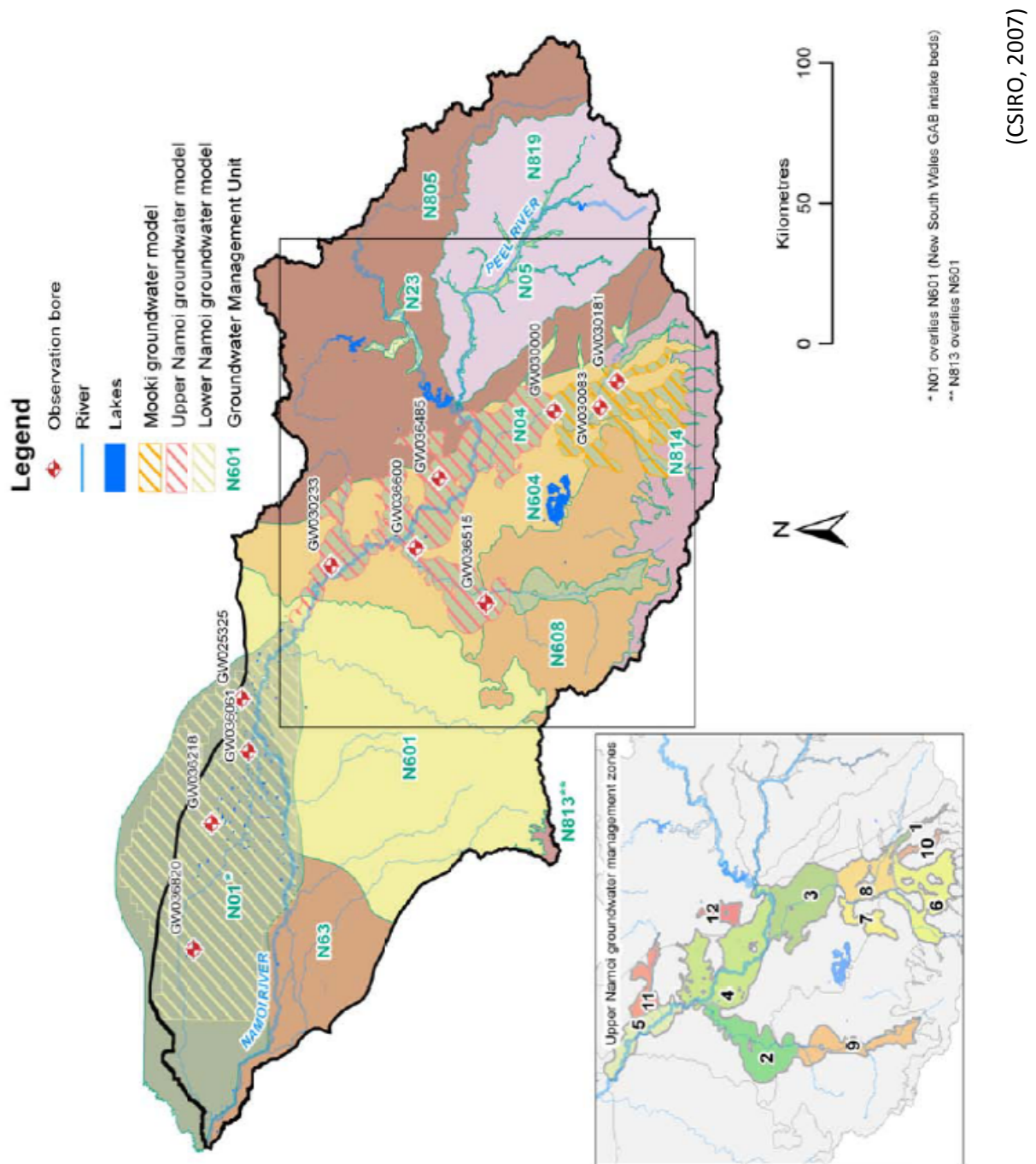
Figure 4.3 River zones in the Namoi catchment



(Thoms et al. 1999)

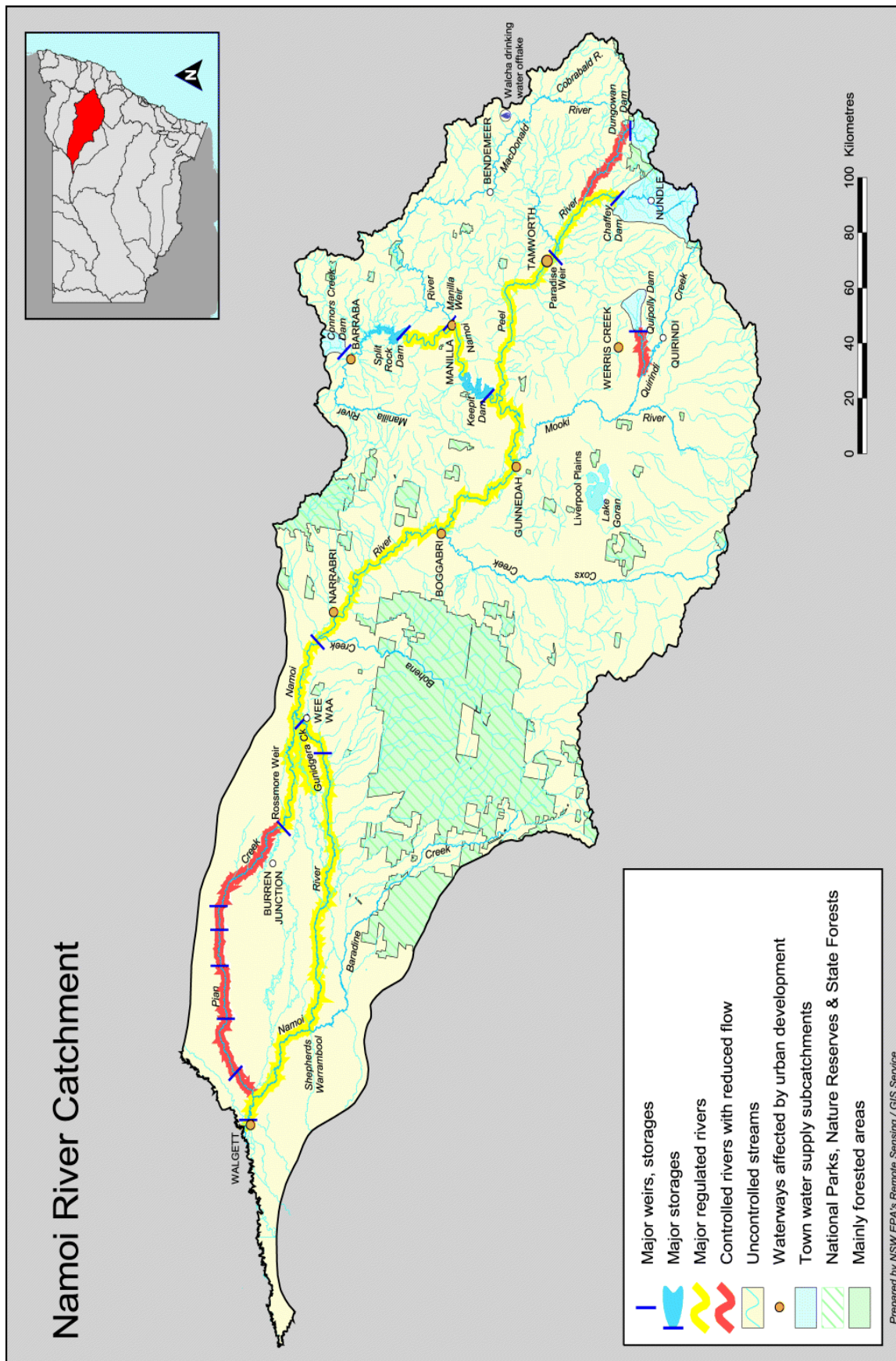
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Figure 4.4 Groundwater Management Units - Namoi catchment



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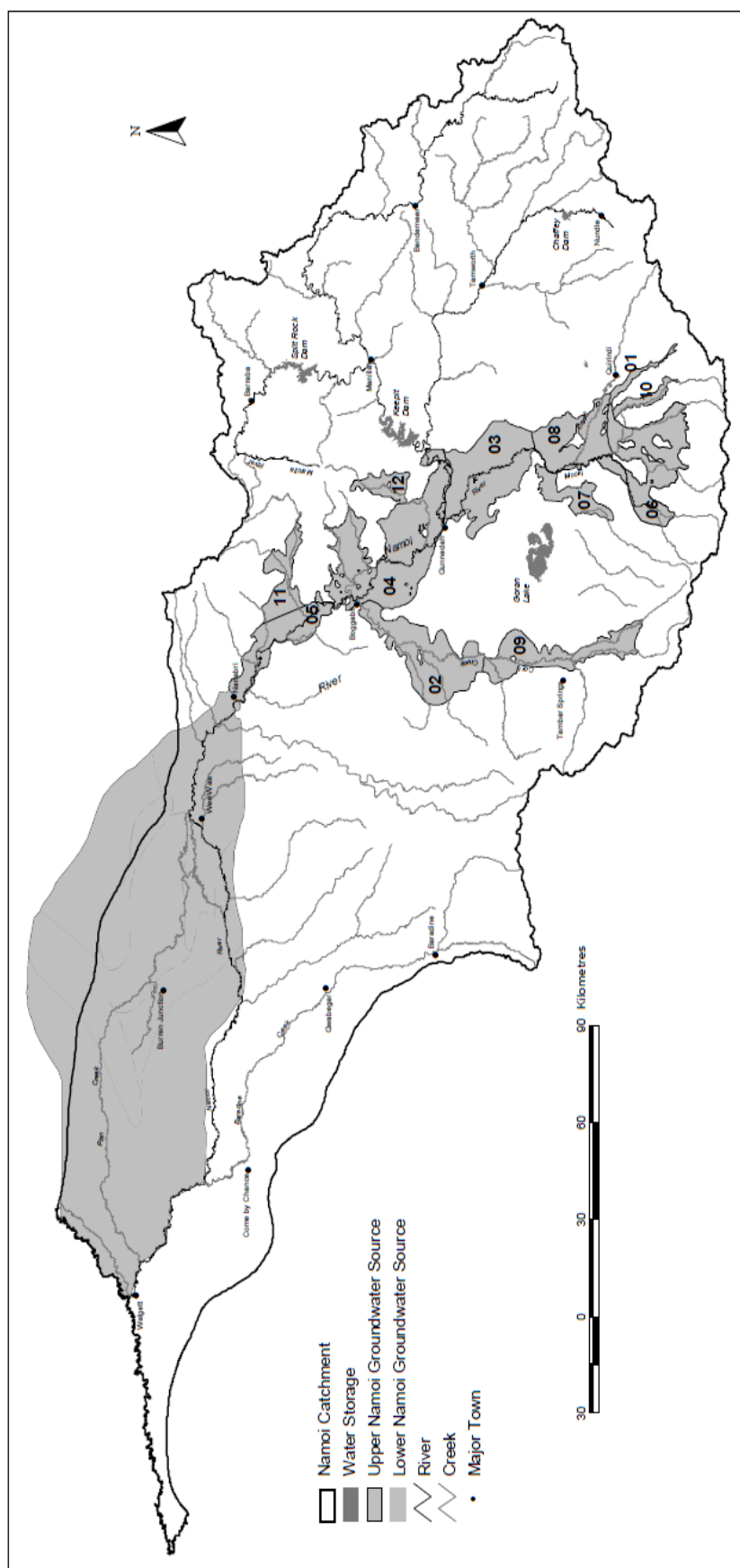
Figure 4.5 Namoi river catchment



(NSW Dept of Environment Climate Change and Water, 2010)

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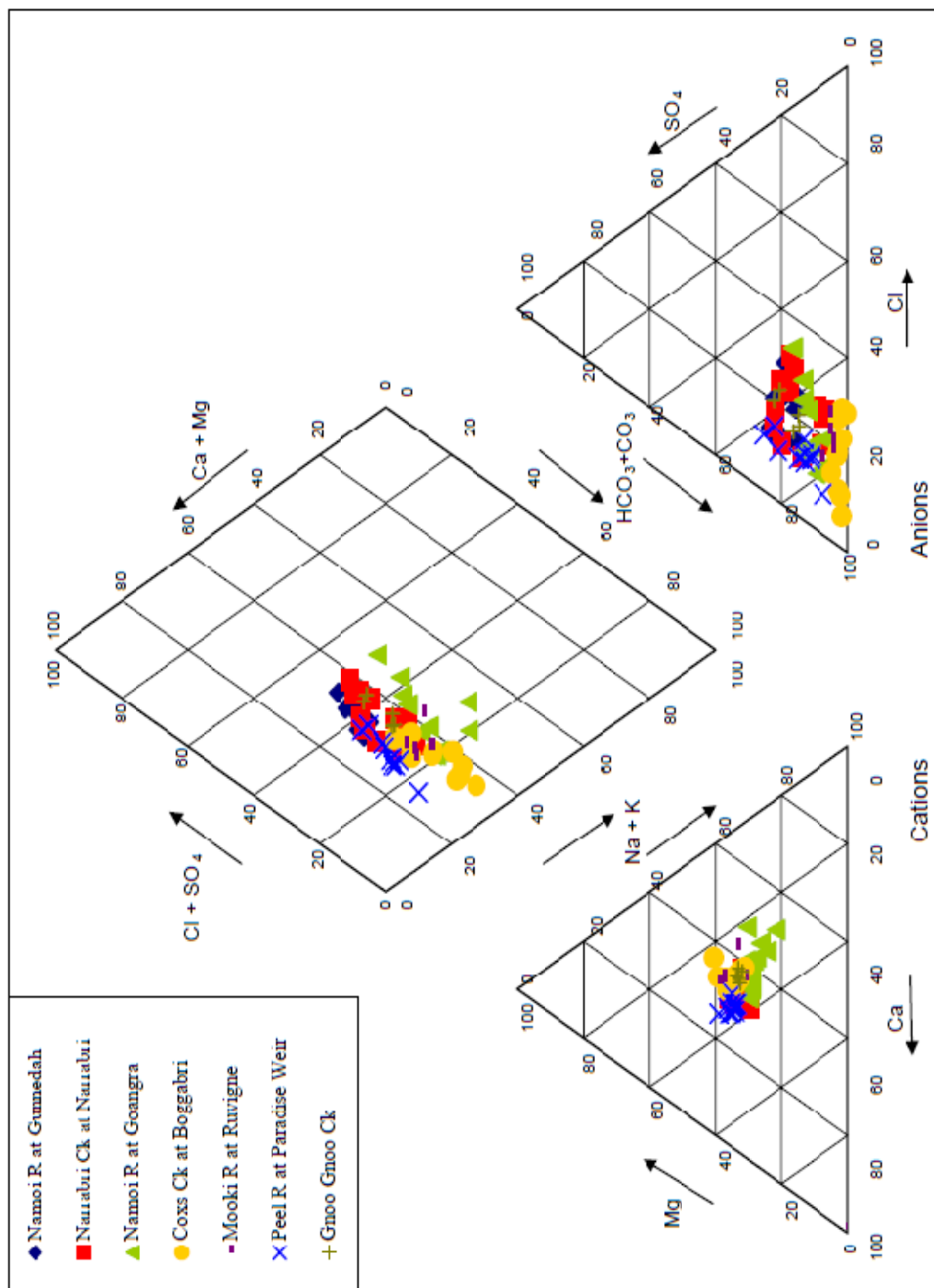
Figure 4.6 Major groundwater resources - Namoi catchment



(CMA, 2010)

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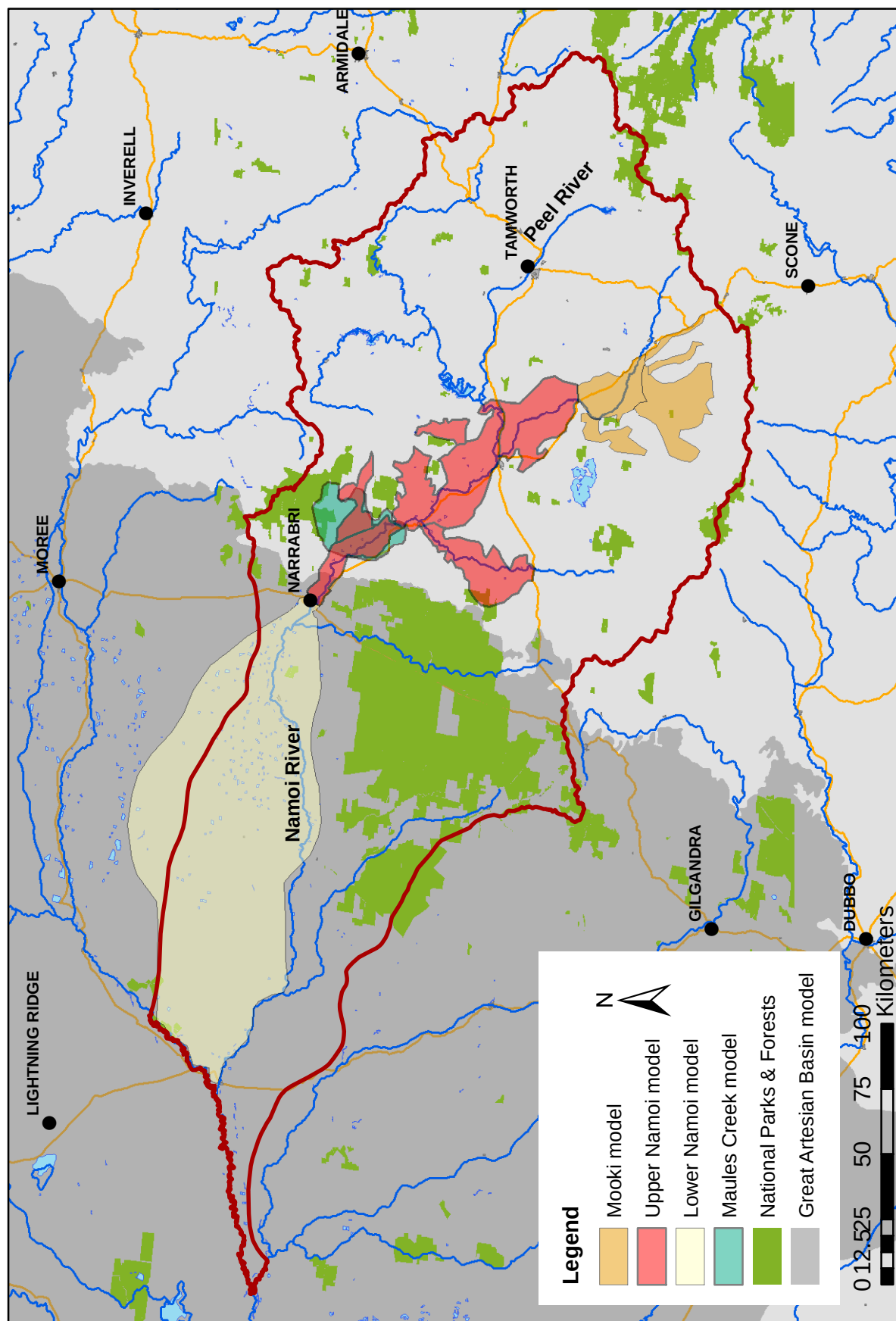
Figure 4.7 Piper diagram of major ions - Namoi catchment



(NSW DNR, 2005)

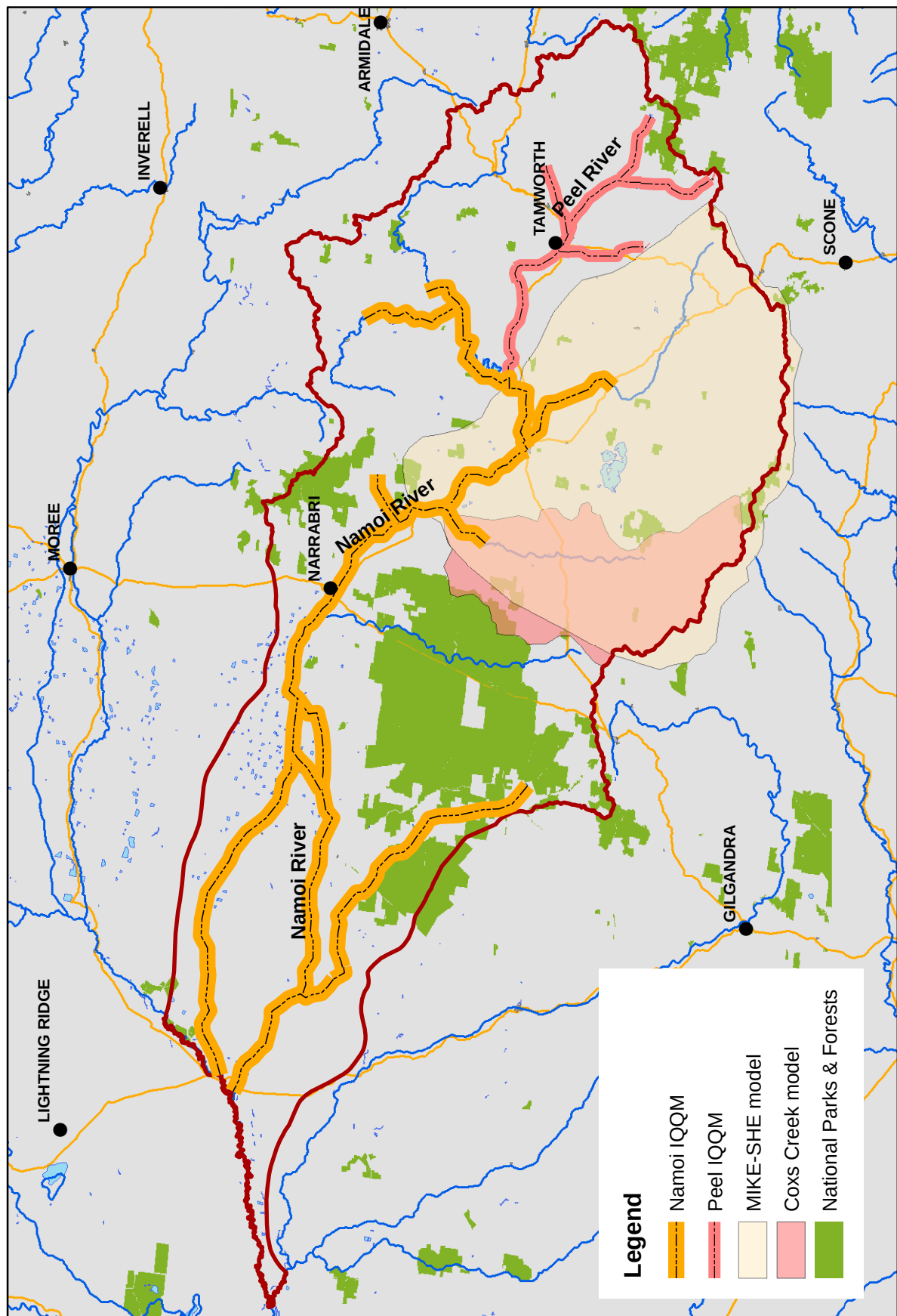
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Figure 4.8 Existing groundwater models in the Namoi catchment



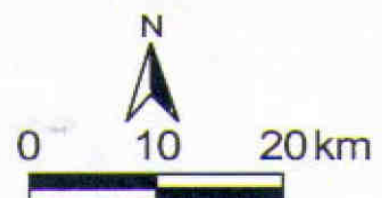
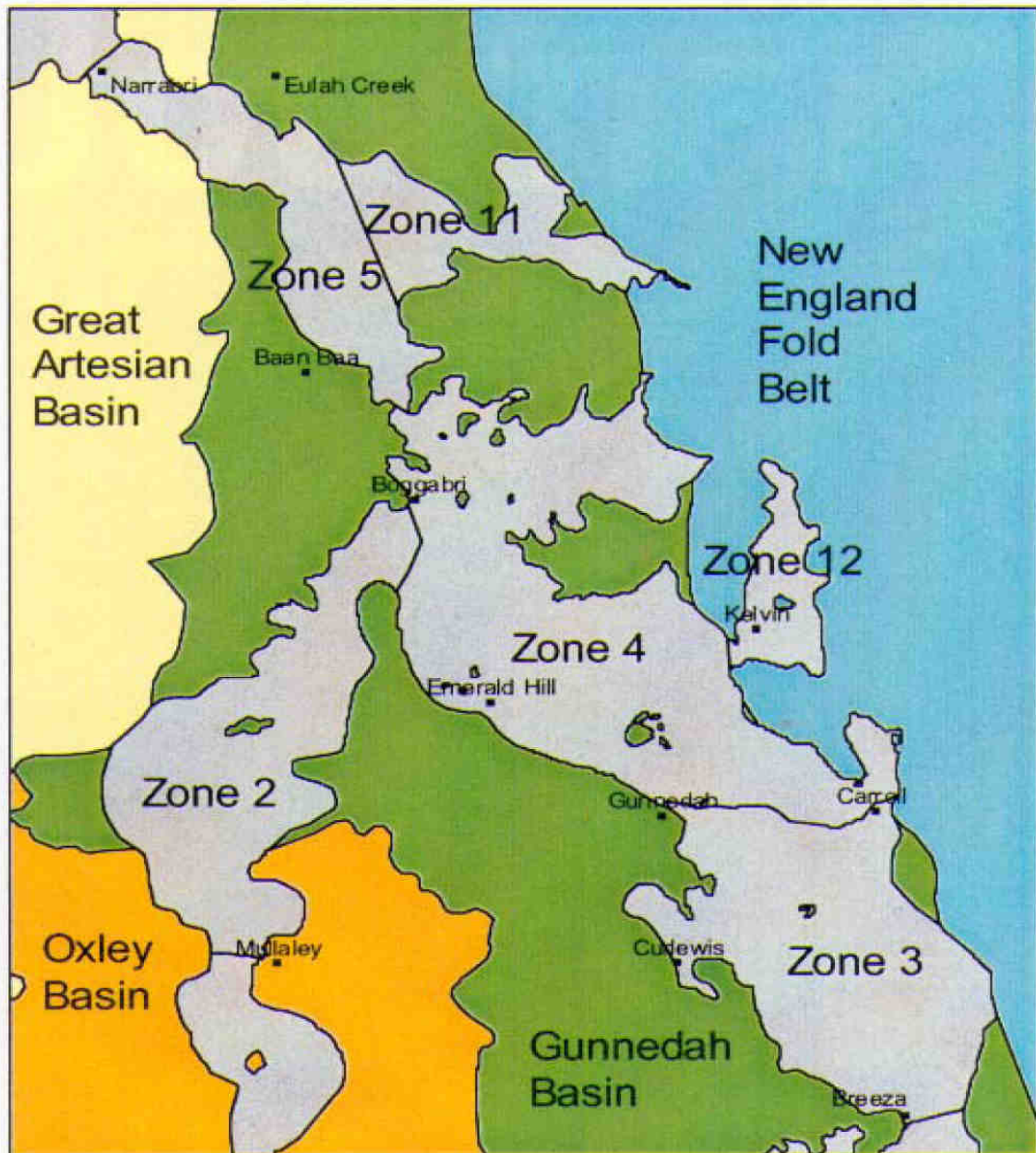
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Figure 4.9 Existing surface water models in the Namoi catchment



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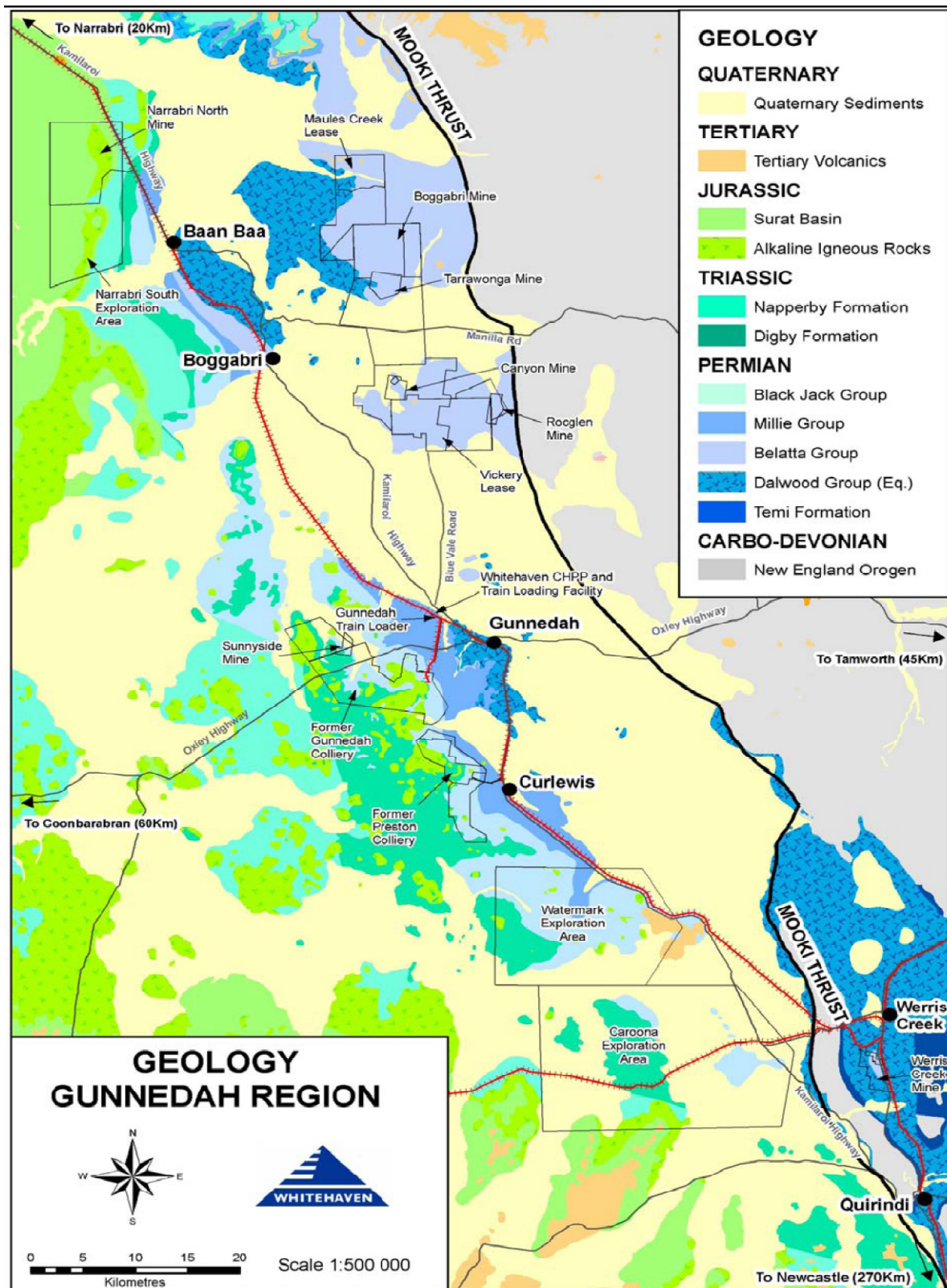
Figure 4.10 Upper Namoi groundwater model zones



(Kelly et al., 2007)

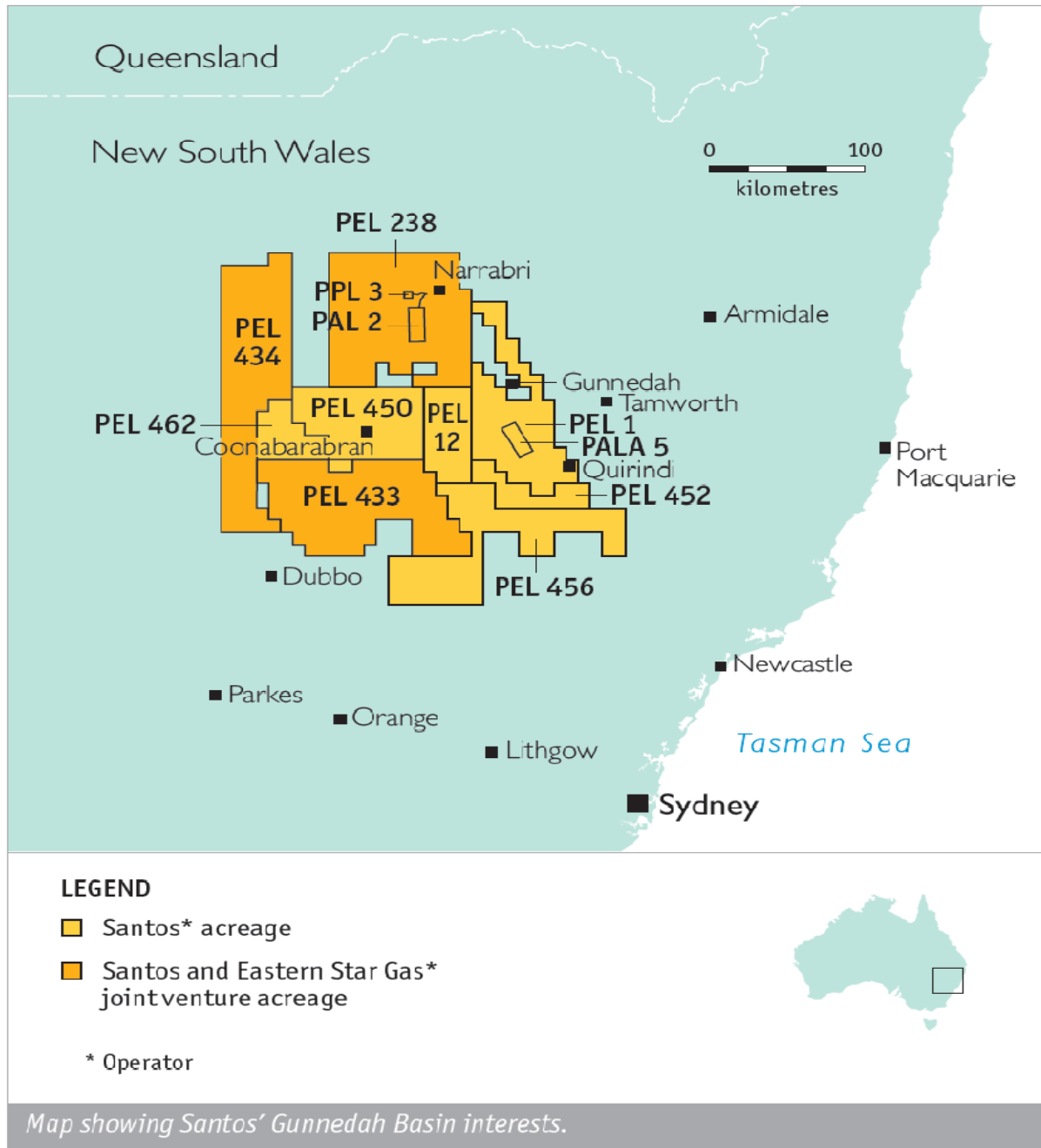
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Figure 4.11 Location of large closed mines, active mines, and current exploration lease areas



(Aquaterra, 2009)

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(Santos, 2010b)

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APPENDIX Project Plan

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Namoi Water Catchment Study																							
ID	Task Name	Duration	Start	Finish				1st Half			1st Half			1st Half									
					3rd Quarter			1st Quarter			3rd Quarter			1st Quarter			3rd Quarter			1st Quarter			
					Jul	Sep	Nov	Jan	Mar	May	Jul	Sep	Nov	Jan	Mar	May	Jul	Sep	Nov	Jan	Mar		
0	Namoi Project Plan Final 2	396 days	Wed 1/09/10	Thu 15/03/12																			
1	Inception Meeting	1 day	Wed 1/09/10	Wed 1/09/10	1/09																		
2	Phase 1: Scoping and Literature Review	55 days	Mon 6/09/10	Fri 19/11/10																			
3	Scope	10 days	Mon 6/09/10	Fri 17/09/10																			
4	Tech parameters and assumptions	2 days	Mon 6/09/10	Tue 7/09/10	Sean Murphy																		
5	Priority water resource areas	2 days	Wed 8/09/10	Thu 9/09/10	Sean Murphy,Jon Satchwell,Laura Bellas																		
6	Spatial relationships of water oil and gas	2 days	Fri 10/09/10	Mon 13/09/10	Sean Murphy,Jon Satchwell,Laura Bellas																		
7	Current understanding of water coal and csg	2 days	Tue 14/09/10	Wed 15/09/10	Sean Murphy,Jon Satchwell,Laura Bellas,David Jackson																		
8	Current Monitoring programmes coal and CSG	2 days	Thu 16/09/10	Fri 17/09/10	Sean Murphy,Jon Satchwell,Laura Bellas,David Jackson																		
9	Programme	5 days	Mon 20/09/10	Fri 24/09/10																			
10	Key dates	1 day	Mon 20/09/10	Mon 20/09/10	Sean Murphy																		
11	Key Tasks	1 day	Tue 21/09/10	Tue 21/09/10	Sean Murphy																		
12	Key Personnel	1 day	Wed 22/09/10	Wed 22/09/10	Sean Murphy																		
13	Critical Path Analysis	1 day	Thu 23/09/10	Thu 23/09/10	Sean Murphy																		
14	MOC and SAG participation	1 day	Fri 24/09/10	Fri 24/09/10	Sean Murphy																		
15	Study Plan Flowchart	3 days	Mon 27/09/10	Wed 29/09/10																			
16	Map timeline and ID overlaps	1 day	Mon 27/09/10	Mon 27/09/10	Sean Murphy																		
17	Create diagram of study programme and tasks	0.5 days	Tue 28/09/10	Tue 28/09/10	Sean Murphy																		
18	Diagramme of tasks / stakeholders	1 day	Wed 29/09/10	Wed 29/09/10	Sean Murphy																		
19	Develop Governance processes	0.5 days	Tue 28/09/10	Tue 28/09/10	Sean Murphy																		
20	Literature Review	2 wks	Mon 11/10/10	Fri 22/10/10	Sean Murphy,Jon Satchwell,David Jackson,Laura Bellas																		
21	Phase 1 Draft Report	1 wk	Mon 25/10/10	Fri 29/10/10	Sean Murphy,Jon Satchwell[50%],Laura Bellas[50%],David Jackson[50%],Mark Anderson[10%],Gareth Price[10%]																		
22	Phase 1 Draft Report Submission	0 days	Fri 29/10/10	Fri 29/10/10	29/10																		
23	Phase 1 Draft Report Review	5 days	Mon 1/11/10	Fri 5/11/10	Ministerial Oversight Committee																		
24	Phase 1 Completion / Phase 2 Commencement Meeting	1 day	Tue 9/11/10	Tue 9/11/10	9/11																		
25	Public Inforamation Gunnedah	1 day	Wed 10/11/10	Wed 10/11/10	Ministerial Oversight Committee,Mark Anderson,Sean Murphy,Gareth Price																		
26	Public Inforamation Quirindi	1 day	Wed 10/11/10	Wed 10/11/10	Ministerial Oversight Committee,Mark Anderson,Sean Murphy,Gareth Price																		
27	Phase 1 Report Distribution	1 day	Fri 19/11/10	Fri 19/11/10																			
28	Phase 2: Data Collation and Analysis	57 days	Mon 29/11/10	Fri 18/02/11																			
29	Collation of Data	10 days	Mon 29/11/10	Fri 10/12/10																			
30	Access Gov data Sydney	2 days	Mon 29/11/10	Tue 30/11/10																			
31	Water data	2 days	Mon 29/11/10	Tue 30/11/10	Sean Murphy,David Jackson,Jon Satchwell																		
Project: Namoi Project Plan Final Date: Thu 18/11/10		Task		Project Summary		Inactive Milestone		Manual Summary Rollup		Deadline													
		Split		External Tasks		Inactive Summary		Manual Summary		Progress													
		Milestone		External Milestone		Manual Task		Start-only															
		Summary		Inactive Task		Duration-only		Finish-only															

Namoi Water Catchment Study																								
ID	Task Name	Duration	Start	Finish				1st Half						1st Half						1st Half				
					3rd Quarter			1st Quarter			3rd Quarter			1st Quarter			3rd Quarter			1st Quarter				
					Jul	Sep	Nov	Jan	Mar	May	Jul	Sep	Nov	Jan	Mar	May	Jul	Sep	Nov	Jan	Mar			
32	IQQM Model	2 days	Mon 29/11/10	Tue 30/11/10				Sean Murphy,David Jackson,Jon Satchwell																
33	Climate Data	2 days	Mon 29/11/10	Tue 30/11/10				Sean Murphy,David Jackson,Jon Satchwell																
34	Landuse Data	2 days	Mon 29/11/10	Tue 30/11/10				Sean Murphy,David Jackson,Jon Satchwell																
35	Geo Data	2 days	Mon 29/11/10	Tue 30/11/10				Sean Murphy,David Jackson,Jon Satchwell																
36	Soil data	2 days	Mon 29/11/10	Tue 30/11/10				Sean Murphy,David Jackson,Jon Satchwell																
37	Access Santos Data	2 days	Wed 1/12/10	Thu 2/12/10				Sean Murphy,David Jackson,Jon Satchwell																
38	Access BMA Data	2 days	Fri 3/12/10	Mon 6/12/10				Sean Murphy,David Jackson,Jon Satchwell																
39	Access Watermark Data	2 days	Tue 7/12/10	Wed 8/12/10				Sean Murphy,David Jackson,Jon Satchwell																
40	Access CMA and Namoi Water Data	2 days	Thu 9/12/10	Fri 10/12/10				Sean Murphy,David Jackson,Jon Satchwell																
41	Data Analysis	3.6 wks	Mon 13/12/10	Fri 7/01/11	Sean Murphy,Jon Satchwell,Laura Bellas,Daniel Barclay																			
42	Phase 2 Draft Report	3.8 wks	Mon 10/01/11	Fri 4/02/11	Sean Murphy,Jon Satchwell,Laura Bellas,Mark Anderson[10%]																			
43	Phase 2 Draft Report Submission	0 days	Fri 4/02/11	Fri 4/02/11	4/02																			
44	Phase 2 Draft Report Review	5 days	Mon 7/02/11	Fri 11/02/11	Ministerial Oversight Committee																			
45	Phase 2 Completion Meeting	1 day	Mon 14/02/11	Mon 14/02/11	14/02																			
46	Public Inforamation Gunnedah	1 day	Tue 15/02/11	Tue 15/02/11	Mark Anderson,Sean Murphy,Gareth Price																			
47	Public Inforamation Quirindi	1 day	Wed 16/02/11	Wed 16/02/11	Mark Anderson,Sean Murphy,Gareth Price																			
48	Report Distribution	1 day	Thu 17/02/11	Thu 17/02/11																				
49	Phase 3: Modelling	191 days	Mon 21/02/11	Mon 14/11/11																				
50	Phase 3 Commencement Meeting	1 day	Mon 28/02/11	Mon 28/02/11	28/02																			
51	Model Rational and Design	3 wks	Mon 28/02/11	Fri 18/03/11	Sean Murphy,Gareth Price,Adrian Werner,Jon Satchwell,Laura Bellas,Daniel Barclay																			
52	Model Assumptions	3 wks	Mon 21/03/11	Fri 8/04/11	Gareth Price,Sean Murphy,Jon Satchwell,Laura Bellas,Daniel Barclay																			
53	Conceptual Model Report	6 wks	Mon 28/02/11	Fri 8/04/11	Sean Murphy,Jon Satchwell,Laura Bellas,David Jackson,Daniel Barclay,Mark Anderson[10%]																			
54	Conceptual Model Report Submission	0 days	Fri 8/04/11	Fri 8/04/11	8/04																			
55	Geological Model Construction	20 days	Mon 11/04/11	Fri 6/05/11	Gareth Price,Jon Satchwell,Laura Bellas																			
56	Hydrological Model Construction	20 days	Mon 9/05/11	Fri 3/06/11	Gareth Price,Jon Satchwell,Laura Bellas,Mark Anderson[10%],Adrian Werner[10%]																			
57	Stream Aquifer Interaction Model Construction	20 days	Mon 9/05/11	Fri 3/06/11	Adrian Werner[10%],Gareth Price[10%],Angelo Papaioannou																			
58	Calibration	5 days	Mon 6/06/11	Fri 10/06/11	Gareth Price,Laura Bellas,Adrian Werner[10%]																			
59	Verification	5 days	Mon 13/06/11	Fri 17/06/11	Gareth Price,Laura Bellas,Adrian Werner[10%]																			
60	Uncertainty analysis	5 days	Mon 20/06/11	Fri 24/06/11	Gareth Price,Laura Bellas,Adrian Werner[10%]																			
61	Test Plan Development	3 wks	Mon 27/06/11	Fri 15/07/11	Ministerial Oversight Committee,Mark Anderson,Sean Murphy,Gareth Price,Jon Satchwell,Laura Bellas																			
62	Test Plan Submission	0 days	Fri 15/07/11	Fri 15/07/11	15/07																			
63	MOC Review	5 days	Mon 18/07/11	Fri 22/07/11	Ministerial Oversight Committee																			
Project: Namoi Project Plan Final Date: Thu 18/11/10		Task		Project Summary		Inactive Milestone		Manual Summary Rollup		Deadline														
		Split		External Tasks		Inactive Summary		Manual Summary		Progress														
		Milestone		External Milestone		Manual Task		Start-only																
		Summary		Inactive Task		Duration-only		Finish-only																

Namoi Water Catchment Study																								
ID	Task Name	Duration	Start	Finish	3rd Quarter			1st Half			3rd Quarter			1st Half			3rd Quarter			1st Half				
					3rd Quarter			1st Quarter			3rd Quarter			1st Quarter			3rd Quarter			1st Quarter				
					Jul	Sep	Nov	Jan	Mar	May	Jul	Sep	Nov	Jan	Mar	May	Jul	Sep	Nov	Jan	Mar			
64	Scenario Runs (Model Testing)	5 days	Mon 25/07/11	Fri 29/07/11					Gareth Price,Laura Bellas,Jon Satchwell,Adrian Werner[10%]															
65	Model Documentation	4 wks	Mon 1/08/11	Fri 26/08/11					Gareth Price,Laura Bellas,Jon Satchwell,Sean Murphy,Mark Anderson[10%]															
66	Submission of Manuals	0 days	Fri 26/08/11	Fri 26/08/11				26/08																
67	Develop Monitoring Programme	4 wks	Mon 29/08/11	Fri 23/09/11					Sean Murphy,Jon Satchwell,Laura Bellas,Adrian Werner[10%],Mark Anderson[10%]															
68	Phase 3 Draft Report	4 wks	Mon 26/09/11	Fri 21/10/11					Gareth Price,Laura Bellas,Jon Satchwell,Sean Murphy,Mark Anderson[10%]															
69	Phase 3 Draft Report Submission	0 days	Fri 21/10/11	Fri 21/10/11				21/10																
70	Phase 3 Draft Report Reveiw	5 days	Mon 24/10/11	Fri 28/10/11					Ministerial Oversight Committee															
71	Phase 3 Completion Meeting	1 day	Mon 7/11/11	Mon 7/11/11				7/11																
72	Public Information Gunnedah	1 day	Tue 8/11/11	Tue 8/11/11					Mark Anderson,Sean Murphy,Gareth Price,Jon Satchwell,Laura Bellas															
73	Public Information Quirindi	1 day	Wed 9/11/11	Wed 9/11/11					Mark Anderson,Gareth Price,Sean Murphy,Jon Satchwell,Laura Bellas															
74	Phase 3 Report Submission and Distribution	0 days	Mon 14/11/11	Mon 14/11/11				14/11																
75	Phase 4: Reporting	80 days	Mon 21/11/11	Wed 14/03/12																				
76	Phase 4 Commencement Meeting	1 day	Mon 21/11/11	Mon 21/11/11					Ministerial Oversight Committee,Mark Anderson,Sean Murphy,Gareth Price															
77	Outline Study Report	2 wks	Mon 21/11/11	Fri 2/12/11					Sean Murphy,Gareth Price,Mark Anderson[10%]															
78	Outline Report Review	1 wk	Mon 5/12/11	Fri 9/12/11					Ministerial Oversight Committee															
79	Draft Study Report	4 wks	Wed 14/12/11	Fri 13/01/12					Sean Murphy,Gareth Price,Jon Satchwell,Laura Bellas,Mark Anderson															
80	Draft Report Reveiw	1 wk	Mon 16/01/12	Fri 20/01/12					Ministerial Oversight Committee															
81	Final Sudy Report	4 wks	Mon 23/01/12	Fri 17/02/12					Sean Murphy,Gareth Price,Jon Satchwell,Laura Bellas,Mark Anderson															
82	Final Study Report Review	1 wk	Mon 20/02/12	Fri 24/02/12					Ministerial Oversight Committee															
83	Final Report Amendments	1 wk	Mon 27/02/12	Fri 2/03/12					Sean Murphy,Gareth Price,Jon Satchwell,Laura Bellas,Mark Anderson															
84	Model Hand Over	1 wk	Mon 5/03/12	Fri 9/03/12					Gareth Price,Jon Satchwell,Laura Bellas,Sean Murphy,Mark Anderson															
85	Phase 4 Completion Meeting	1 day	Mon 12/03/12	Mon 12/03/12				12/03																
86	Public Inforamation Gunnedah	1 day	Tue 13/03/12	Tue 13/03/12				13/03																
87	Public Inforamation Quirindi	1 day	Wed 14/03/12	Wed 14/03/12				14/03																
88	Final Report Distribution	1 day	Thu 15/03/12	Thu 15/03/12		Sean Murphy																		
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		Split		External Tasks		Inactive Summary		Manual Summary		Progress														
		Milestone		External Milestone		Manual Task		Start-only																
		Summary		Inactive Task		Duration-only		Finish-only																

NAMOI CATCHMENT WATER STUDY

INDEPENDENT EXPERT

PHASE 2 REPORT



I/NSW09/19
50371/P2-R1



NAMOI CATCHMENT WATER STUDY

INDEPENDENT EXPERT

PHASE 2 REPORT

August 2011

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REPORT REVIEW SHEET

NAMOI CATCHMENT WATER STUDY - INDEPENDENT EXPERT PHASE 2 REPORT			
Report no:	50371/P2-R1		
Client name:	Department of Trade and Industry, Regional Infrastructure and Services, New South Wales, (DTIRIS NSW)		
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Disclaimer

Schlumberger Water Services Australia Pty Ltd (SWS) has prepared this report for the Namoi Catchment Water Study using data compiled from a large number of sources. Whilst SWS has exercised due care and attention in using the information to prepare this report, the data received from third parties has not been independently verified and SWS cannot guarantee its accuracy or completeness.

The report findings and recommendations are based on the information available to SWS at the time of writing. In many instances the data has been analysed by SWS or by the third parties to form interpretations of the nature and behaviour of the geological and water systems within the Namoi catchment. Future specific investigations may alter some of these interpretations.

The report should be read in full and has been provided for the express purpose of the Namoi Catchment Water Study and SWS accepts no responsibility for conclusions drawn by third parties who may use this document for other purposes.

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APPENDICES

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B	Land Use Data
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EXECUTIVE SUMMARY

Schlumberger Water Services (Australia) Pty Ltd has been appointed as the Independent Expert for the Namoi Catchment Water Study and has been charged with the development of an integrated suite of models for the assessment of the nature and extent of potential effects from coal and gas developments on the water resources of the catchment. The purpose of the Study is to collate and analyse available and relevant data to assist in identifying and quantifying risks associated with the coal mining and coal seam gas developments on catchment water resources.

The models will have the capability to represent past, current and future water use scenarios at spatial and temporal scales that realistically represent those processes and account for coal and gas developments, their spatial relationship to water resources and the potential effects of those developments.

The Study is to be conducted in four phases:

- Phase 1: Scoping and literature review;
- Phase 2: Data collation and analysis;
- Phase 3: Modelling; and
- Phase 4: Reporting.

Phase 1 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, as well as a comprehensive Literature Review. Phase 2 of the Study was initially due for completion in February 2011, but during the course of Phase 2 the schedule was revised to merge 'Phase 2 Data Collation and Analysis' with the initial stage of Phase 3 - 'Model Conceptualisation'. The Phase 2 - *Data Collation and Analysis Report* and the Phase 3 - *Conceptual Model Report*, have been combined as a single project deliverable (this document) for the end of Phase 2.5 (i.e. revised Phase 2). This has delayed completion of Phase 2 by approximately 6 months, while concurrently advancing Phase 3 activities. Despite the delays it is not anticipated that the final study completion date of March 2012 will be affected.

Due to the New South Wales (NSW) Government restructuring during the course of Phase 2, the Client for the Study has changed from the Department of Industry and Investment, NSW, to the Department of Trade and Investment, Regional Infrastructure and Services (DTIRIS), NSW.

Activities undertaken and reported in this document include the requirements of Section G.3.6 and Sections G.3.7.1 a, b and c of the Request for Tender. These have included:

- Data collation;
- Data analysis;
- Data Gap Analysis;
- Model Rationale and Design;
- Model Assumptions;
- Model Concept Report.

Data collation was initiated from the inception of the Study in September 2010 and an integral and fundamental component has been the construction of a validated relational database which includes all publicly available information and Industry Partner data. In order to achieve this, a single, central and live database has been developed which has the capability of being maintained and enhanced with any new data that may be made available during the course of the Study or post-Study. An ESRI ArcSDE GeoDatabase is used to store all geospatial map data and security levels are defined in the database to enable protection of confidential datasets, ensure base data is maintained, and subsequent iterations of datasets are uniquely identified. Geographic Information System (GIS) software ArcMap, ArcCatalog and Global Mapper were used to process and manipulate geospatial data.

The datasets received from the various NSW Government Departments and Industry Partners represent the most comprehensive and spatially extensive datasets available for the catchment. The collation of the datasets represents a significant achievement for the Study and should become a significant resource in its own right. The data includes:

- A total of 22.8 million records for stream discharge, levels, temperature and turbidity.
- In excess of 25,800 records of catchment water bores, including 21,518 government and 4,347 private bores. In total 328,469 groundwater head observations are available.
- Geology datasets comprising 172,000 facies interpretations, 22,804 stratigraphic log records, and stratigraphic surface interpretations, provided by the Industry Partners, containing in excess of 1.1 million records.
- Climate data containing 6.5 million daily rainfall records for the 412 rainfall stations within the catchment.

Analysis of the different datasets within the catchment has been undertaken and is briefly summarised below under relevant headings.

Physical and geological setting

The Namoi catchment has a population of approximately 90,000 people with major urban centres of Tamworth, Gunnedah, Boggabri, Narrabri, Quirindi, Wee Waa and Walgett supported by agriculture and coal mining industries. Agricultural interests include grazing and cropping with cotton, grain and cereals, orchards and forestry as major crops. Extensive irrigation areas are located in the western catchment.

The catchment has three distinct topographic regions; the highlands to the east, a central region with extensive alluvial plains bounded by low hills, known as the Upper Namoi catchment, and to the west of Narrabri extensive and extremely flat flood plains terminating at the Barwon River near Walgett known as the Lower Namoi catchment.

Climate is characterised by summer dominated rainfall with warm summers and cool to mild winters. The average annual precipitation rate is between 1,300 mm/yr in the east and 480 mm/yr in the west with a catchment average of approximately 690 mm/yr.

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 in the centre and the Surat Basin in the west. The geological basement to the Gunnedah and Surat Basins comprises volcanic deposits of the Lachlan Fold Belt. The New England Fold Belt comprises Devonian to Carboniferous strata and has had a complex structural history involving large-scale faulting and folding. It is faulted against and thrust over the eastern part of the Sydney-Gunnedah-Bowen Basin along the Hunter-Mooki Thrust Fault System, which is aligned in a south-southeast to north-northwest direction.

The Gunnedah Basin consists of up to 1,200 metres of marine and non-marine Permian and Triassic sediments. Within these sedimentary sequences both the Maules Creek Formation and the Black Jack Group contain coal seams which are prospective targets for coal mining and coal seam gas extraction. These units each contain numerous coal seams, some of which present a significant thickness. Net coal thickness can reach 50 - 60 metres adjacent to the Hunter-Mooki Fault System. The Hoskissons seam of the Black Jack Group averages greater than 16 metres in the southeast of the basin.

The Jurassic to Cretaceous age Surat Basin (a sector of the Great Artesian Basin) unconformably overlies the Gunnedah Basin in the north and west. Where these units outcrop they represent the southern recharge zone of the Great Artesian Basin. The Garrawilla Volcanics form the basal unit of the Surat Basin sequence and outcrop mainly in the central area of the Gunnedah Basin around the towns of Mullaley and Coonabarabran.

Alluvial deposits of Neogene to Quaternary age are found associated with the stream systems of the Upper and Lower Namoi and are particularly prominent as large outwash sequences in the Lower Namoi. The alluvial areas represent the major water resource areas within the catchment.

Digital geological model

The data collated for the Study has enabled the construction of a three dimensional digital geological model of the catchment using the Petrel software package. The model provides the basis for understanding the spatial relationship between the occurrence of coal suitable for mining and gas extraction and water resources in the catchment. The digital model forms a major component of system conceptualisation and is an essential precursor to any numerical modelling of the groundwater system at the required scale. Geological model inputs and algorithms have not been 'hard wired' and the model will be continuously audited and updated as the Study progresses as new data and interpretations are acquired.

The geological model comprises 19 layers that represent the distinct geological units present in the subsurface of the Namoi catchment. Input data has been sourced from both public and Industry Partner data and includes data from water bore logs, coal and gas exploration bores, geological maps and cross sections, geological reports and derived geological surfaces. The three dimensional model covers the entire catchment area (42,000 km²) from ground surface to a depth of -2,000 mAHD. The model therefore encompasses a volume of about 100,000 km³.

The model includes a representation of the Hunter-Mooki Fault System and the major formations west of the fault which include those that host the coal seams. Fourteen distinct geological layers, not including alluvium or the 'weathered zone', are included in this area of the model, from the Great Artesian Basin layer at the top, to the Goonbri / Leard Formations at the base. The Black Jack Group has been divided into 5 layers, allowing the Hoskissons seam and Melvilles seam to be modelled as individual layers.

The alluvial deposits have been represented as Narrabri Formation, Gunnedah Formation and Lower Namoi Alluvium. To the east of the Hunter-Mooki Fault System a 'fractured rock aquifer' has been included and a weathered zone has been modelled over the entire catchment. No coal resources are believed to exist east of the fault.

Coal mining and coal seam gas development areas

To effectively understand the potential effects on the water resources a thorough review of current and future coal and coal seam gas industries in the catchment has been undertaken. The coal mining industry has been active in the Namoi catchment since the 1890's, but only recently has a coal seam gas industry developed. The coal seams within both the Black Jack Group and Maules Creek Formation present the economical resources.

There are currently six active coal mines in the catchment with a further three major projects in exploration phase. Both open-cut and underground mining is currently undertaken, with both forms likely to be adopted for future mining ventures. These methods target coal at up to about 300 metres below ground level. The mines can produce more water than they use in wet periods with the greatest component of use usually for dust suppression. Most of this water is derived from surface water runoff and groundwater inflows to the pits. The mining process may directly impact the flow and quality of both surface water and groundwater. Underground mining may also cause subsidence of the ground surface affecting runoff or surface water flow dynamics.

To date, a relatively small number of boreholes have been installed by the coal seam gas industry in the catchment. Both vertical and lateral wells have been trialled to target coal seams at depths of up to 1 km below ground surface. In order to produce gas from these wells, groundwater pressure must first be reduced allowing the release of gas from the seam. In this process groundwater is removed from the coal seams and brought to the surface, becoming 'produced' or 'associated' water and depressurising the seams.

The direct impacts of coal seam gas extraction on the water resources are the depressurisation of the coal seams and the migration of reduced pressures into neighbouring and connected geological units, resulting in changes to groundwater flow. Wells can be stimulated by enhancement processes such as hydraulic fracturing, which may be used to increase the seam permeability and therefore flow. Management of the produced water may also be required as it is often more saline than surface waters. Dependent on the quality of the produced water and the location of the site, management options may include evaporation, treatment and beneficial reuse, release to streams or reinjection to the subsurface.

Groundwater

The principal aquifers of the catchment are the Upper Namoi and Lower Namoi alluvium. These systems have historically been heavily utilised for water supplies as yields are high and the water quality is good, although there can be significant variation of water quality vertically within them. Water supplies are also obtained from hard rock aquifers surrounding the main alluvial areas although yields are lower and water quality is often more brackish. The alluvial aquifers are complex multi layered systems. Historical over abstraction of the deeper alluvial units in several areas has led to falling water levels.

Several numerical models exist that examine the groundwater flow characteristics within the alluvial aquifers. The hydraulic properties of the alluvial units are therefore relatively well constrained. Models for the Upper Namoi region assumed that there is no hydraulic connection between the alluvium and underlying hard rock aquifers. The Lower Namoi model includes an inflow from the underlying Great Artesian Basin.

There is currently little catchment specific information available defining the hydraulic properties of the hard rock aquifers. The majority of work completed for the Gunnedah Basin units to date has been undertaken by the coal mining and coal seam gas companies and is therefore restricted to the areas of interest for these projects. Further work is currently being undertaken and will be included in the Study as it becomes available. There have been no comprehensive studies to the east of the Hunter-Mooki Fault System to date.

Monitoring of groundwater levels and quality is generally focused on the areas of high use groundwater resources within the catchment. A significant number of time variant groundwater level monitoring bores are located within the alluvial aquifers. Monitoring of groundwater within the remainder of the catchment is minimal due to low current levels of use and overall volume of the resource. Currently proposed developments are likely to see an increase in monitoring and data collection within the catchment.

Water level contours constructed with current groundwater monitoring data reflect the topography of the catchment on a regional scale. Groundwater flow directions in the upper reaches of the catchment are generally down-slope to the sub-catchment alluvial areas before discharging into the river network. Water quality data has been collected for the alluvium and shallow hard rock aquifers, with a focus on areas of high agricultural water use and monitoring of groundwater salinity increases (salinisation). This is also expected to change with an increased focus on the deeper formations and coal seams.

The majority of groundwater resources used within the catchment are sourced directly from the alluvial aquifers associated with the various streams within the catchment. An estimated annual allocation of 132.7 GL/yr is attributed to the alluvium of the Upper Namoi and tributary alluviums with a further 94.4 GL/yr from the Lower Namoi alluvium.

Surface water

The Namoi surface water catchment is a westerly draining system with headwaters on the western flank of the Great Dividing Range. 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.

River channel geomorphology on a sub-catchment scale is controlled by the valley slopes and valley floor width. In the headwaters, the river channel is constrained, has a steep gradient, and is bounded by gorges. Where the river enters the alluvial plains the channel is unconstrained, very shallow sloping and featureless. Towards the west the valley floor increases in width to become a large floodplain and is essentially a flat featureless surface.

Flows in the Namoi catchment are regulated by three head water storages: Keepit Dam on the Namoi River upstream of the Peel River confluence; Chaffey Dam on the Peel River upstream of Tamworth; and Split Rock Dam on the Manilla River.

Flow variability is a feature of the Namoi River. In general, discharges recorded at the main gauging stations are skewed, with a large proportion of average flows occurring in wet years and during major floods. Peak flows dominate in the calculation of mean flows in each system. There are substantially reduced flows present in each channel outside major rainfall events. The presence of significant flows outside rainfall events is therefore highly dependent on baseflow from groundwater inflows to the channel.

Major flood events occur approximately every 10 years on average. However, catchment development has seen the maximum period between flooding increase by around 50% on the regulated stretches of rivers, with the size and the average annual flood volume decreasing. Floods are a significant source of aquifer recharge. The aquifers undergo consistent depletion in between flood events and it is typically only during flooding that recharge exceeds extractions.

In terms of surface water/groundwater interaction, a general pattern of gaining streams exists in the upland incised valleys with losing (connected or disconnected) stretches in the flatter alluvial systems. Surface water quality threats include potential for increased salinisation, agrochemical runoff (both chemical and sediments), potential discharges from coal mines and coal seam gas derived waters.

A total of 379 GL/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 253.5 GL. The Upper Namoi accounts for 9.7 GL/yr while the Peel catchment has 48.3 GL/yr of water allocation. Currently 115 GL/yr is allocated as supplementary water allowances. These supplementary allowances however will be reduced to zero over the next 10 year period.

Rainfall, runoff and recharge processes for the catchment have been examined. The degree of rainfall recharge is observed to be highly dependent on sub-catchment geomorphology. The fate of rainfall falling directly onto the alluvial plains is generally controlled by the evapotranspiration potential of the soils. The predominant recharge mechanism to groundwater in these regions is likely to be diffuse. The fate of rainfall in the ridge systems is controlled primarily by the slope of the ground surface, the thickness and properties of the weathered zone and the underlying geology. Rainfall falling in the ridge systems may also provide a significant recharge of the groundwater system in certain areas.

Data gaps

A number of data gaps have been identified as a result of the data compilation and analysis. Each is described and their significance in terms of the Study goals and methodologies for addressing the gaps are presented. The data gaps of greatest importance to the Study can be grouped and summarised as:

- The spatial arrangement and density of information and the bias to the shallow alluvial systems west of the Hunter-Mooki Fault System;
- The type of hydrogeological data available and in particular the absence of test data on the interconnection of hydrostratigraphic units within the 'hard rock' system.

These gaps do not prevent the construction of numerical models using the data available, but they will result in instances where the parameters used will be generic or estimated at this stage of the Study. This is not unusual in numerical modelling studies, especially with initial phase models. Indeed the ability of models to explore and clearly focus on where high value can be derived from subsequent detailed site investigations is one of their primary functions and value. It will, therefore, be important that the models undergo appropriate sensitivity and uncertainty analyses and are amenable to updating when additional catchment specific data becomes available. The amount of catchment specific data available will increase as more exploration work is completed by both the coal mining and coal seam gas companies.

Modelling plan

A plan for numerical modelling has been developed to fulfil the goals and requirements of the Study. The model rationale and design recommends a suite of tools for the assessment of the effects of coal seam gas developments and for the assessment of the effects of coal mining on catchment water resources. This distinction is made based on the conceptualisation of the system, specifically the impact pathways, scale and spatial relationship of potential receptors and coal seams. The modelling plan also considers data gaps, uncertainty, technology and model value and utility.

Development of the coal seam gas impact assessment tool will involve two distinct stages comprising:

- Creation of a GIS / spreadsheet based assessment tool to map the risk of impacts on water resources, specifically groundwater (primary impact receptor), combined with simple analytical methods to determine worst case impacts.
- Development of a three-dimensional numerical groundwater model of the entire hydrogeological system west of the Hunter-Mooki Fault System (the Coal Seam Gas Model). This will include numerous model layers to allow the Hoskissons and Melvilles seams, the abstraction of groundwater from the seams, and their relationship with surrounding layers to be simulated. The model will be calibrated to a 'steady state' set of groundwater levels. The model will be subject to sensitivity analysis and / or predictive uncertainty analysis and predictive output will likely take the form of groundwater level and drawdown contours in the alluvium and other key units and groundwater hydrographs at selected locations.

The proposed plan for modelling coal mining impacts comprises a staged methodology with each stage requiring more data and being more complex than the previous one. The analyses will be undertaken following the principle that if impacts are shown to be insignificant during one stage, the development of more complex methods will not be warranted. The three-stages of the coal mining impact assessment tool will comprise:

- Development of a GIS or spreadsheet based runoff / recharge model. This will be used to give a first pass sensitivity and worst case analysis of the potential for coal mines to impact the recharge of groundwater in the alluvium and runoff to the stream systems. This will provide a simple risk mapping tool and will be combined with an assessment of the proximity of mining to water resources to determine whether one, or both, of the stages below is required.
- Development of a lumped parameter runoff / recharge model to better evaluate the key processes of recharge and runoff and, therefore, more accurately determine the impact that mining will have on these processes (the Hydrologic Model). The main aim of this stage is to determine the proportion of rainfall falling on the 'ridge' systems adjacent to the alluvial plains that ultimately recharges the alluvial aquifer and what proportion of this would be removed if mining proceeds. A predictive output therefore includes the change in recharge through time. The model can be calibrated against runoff estimates.

- Development of a sub-catchment scale three dimensional numerical groundwater model of the shallow (upper 300 m or so) system hydrogeology (the Coal Mine Model). Particular processes shown to be significant (i.e. stream / aquifer interaction, unsaturated flow, etc.) will be simulated at the appropriate level of detail; if shown not to be significant then they will be simplified. The primary aim of this model is to determine / quantify if and how open-cut or underground mining has the potential to impact the groundwater resource directly and how this may then impact the surface water system. An input to this model may be the refined recharge and runoff estimates from the Hydrologic Model and modified boundary conditions taking into account the results from the Coal Seam Gas Model. The model may be calibrated against groundwater levels and stream flow.

The models described, in particular the more complex examples, will be subject to differing degrees of uncertainty. A list of assumptions associated with the numerical models is discussed. These are associated with both the data on which the model is based and the necessity of system simplification for numerical representation. They will have varying affects on the accuracy of model outputs but are not considered significant enough to negate the usefulness of the catchment model.

The current phase of the Study terminated with the Phase Completion Meeting, held in Gunnedah on 30 June 2011. The Phase 3 Commencement Meeting was held on the same day, followed by Community Information Sessions on 1 July 2011 in Gunnedah and Quirindi. Following the Community Information Sessions an additional meeting was scheduled with the MOC and SAG on 27 July 2011 to enable SAG comments on the Draft Phase 2 report to be addressed and any feedback to then be added to the Final Phase 2 report. Phase 3 modelling is already in progress concurrent with ongoing data acquisition and analyses, and database and geological model updating as a part of the iterative modelling process. This iterative process will endeavour to reduce the impact of any identified data gaps through the inclusion of any new catchment specific datasets, such as freshly published research reports or additional exploration work completed by Industry Partners, which may become available during Phase 3.

1 INTRODUCTION

1.1 Background

1.1.1 *Study structure*

Schlumberger Water Services (Australia) Pty Ltd (SWS) has been appointed as the Independent Expert for the Namoi Catchment Water Study (the Study) and has been charged with the development of an integrated suite of models for the assessment of the nature and extent of potential effects from coal and gas developments on the water resources of the catchment. The purpose of the Study is to collate and analyse quality data to assist in identifying and quantifying risks associated with the coal mining and coal seam gas (CSG) developments on water resources. The scope of the Study is to include the whole of the Namoi catchment and the project will be conducted in four phases.

Delays associated with the acquisition of data and widespread recognition of the value of facilitating discussion of the conceptual modelling prior to the numerical model construction has led to the reorganisation of the Study structure. The conceptualisation tasks from Phase 3 have been added to Phase 2 of the Study. The following structure has been adopted for the completion of the Study:

- 1) Phase 1: Scoping and literature review;
- 2) Phase 2: Data collation, analysis, and conceptualisation;
- 3) Phase 3: Modelling; and
- 4) Phase 4: Reporting.

The Phase 1 report was finalised and widely distributed in November 2010. This document presents the Phase 2 report by the Independent Expert (aka the Phase 2.5 report). The report includes an extensive list of references and a glossary of terms and abbreviations. These are located at the end of the report, prior to the appendices that provide supporting information.

1.1.2 *Setting and context*

The Namoi catchment is an irrigation and agricultural area of significance in New South Wales (NSW) and Australia. Covering an area of approximately 42,000 km², the catchment has a variety of land uses including natural vegetation, grazing, cropping, forestry, nature conservation, water, urban and irrigated pastures. The Namoi River flows in a generally westerly direction over a distance of 659 km from its source in the southeast margin of the catchment to its confluence with the Barwon River near Walgett (Figure 1.1).

The Namoi catchment is a part of the Murray Darling Basin (MDB) covering approximately 3.8% of the total basin area (CSIRO, 2007). Significant tributary streams to the Namoi River include the Macdonald River, Peel River, Cockburn River and the Manilla River. Smaller tributaries of the Namoi River include the Cobrabald River, Cox's Creek, Maules Creek, Mooki River and Bundock Creek. Three key water supply storages are present in the Namoi catchment; the Split Rock Dam on the Manilla River (397,000 ML), the Keepit Dam on the Namoi River (423,000 ML) and the Chaffey Dam on the Peel River (62,000 ML) (Green et al., 2011).

The river plain merges with the Gwydir, Castlereagh, and Barwon River flood plains near Walgett. A number of wetlands are situated southeast of Gunnedah, the largest being Lake Goran with some small lagoons and billabongs on the river flood plain.

The catchment is reportedly one of the most intensively developed groundwater resources in NSW. Groundwater is a significant resource in the Namoi catchment and has been extensively developed with the highest rate of groundwater extraction in NSW (NSW Government, 2010a).

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

The Study requires the development of a model or models (to be determined in the course of the Study, and hereafter known as “the model”) to facilitate assessment of the potential effects from coal and gas developments on catchment water resources. The model will therefore have the capability to account for coal and gas developments, their spatial relationship to water resources and the potential effects of those developments.

The model will be whole of catchment in order to account for all sectors of the community including agriculture, industry, resources and the broader community. It is further acknowledged that the completed model or models will be:

- 1) Designed to be transferred to a third party at the conclusion of the Study;
- 2) Capable of taking no more than one day to execute a model run;
- 3) Designed to allow ongoing operation and maintenance in a reliable and efficient manner;
- 4) Suitable for incorporation of future data (post-Study);
- 5) Capable of the management and display of spatial data.

1.2 Study Scope of Work

The Scope of Work presented in this Section has been designed to achieve the development of an integrated suite of models for the assessment of the nature and extent of potential effects from coal and gas developments on the water resources of the Namoi catchment. Phase 1 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, as well as a comprehensive Literature Review.

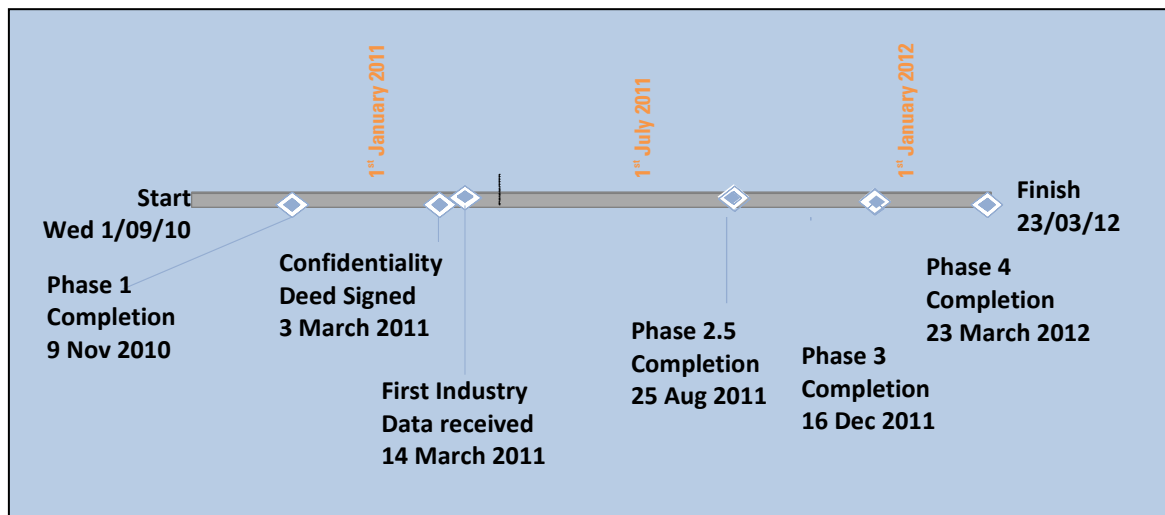
Phase 2 of the Study was initially due for completion on the 9th February 2011. Completion of Phase 2 of the project has been delayed by approximately 6 months due to the necessity for the NSW Department of Trade and Investment, Regional Infrastructure and Services (DTIRIS, formerly the NSW Department of Industry and Investment) to organise and complete Confidentiality Deed agreements with the various Industry Partners. This delay, and the requirement that the project be completed by the original final date, has necessitated that SWS provide additional resources to the project in conjunction with a reorganised project plan and timetable.

SWS therefore developed a revised schedule merging 'Phase 2 Data Collation and Analysis' with the 'Model Conceptualisation' stage (initial third of Phase 3). Additionally, the Phase 2: Data Collation and Analysis Report and the Phase 3: Conceptual Model Report have been combined as one project deliverable for the end of the revised Phase 2 (also known as 'Phase 2.5'). This document therefore conforms with Section G.3.6 and Sections G.3.7.1 a, b and c of the Request for Tender document.

The additional benefits realised through the adoption of the revised 'Phase 2.5 approach' are the:

- Addition of value to Phase 2 completion meetings with the ability to discuss relevant aspects of the Namoi catchment conceptualisation with the Ministerial Oversight Committee (MOC), Stakeholder Advisory Group (SAG) and community prior to commencement of numerical modelling. There was no option for this in the original schedule.
- Phase 2.5 Completion Meeting will be more relevant and informative.
- The MOC and SAG now have the opportunity to comment on the proposed numerical modelling approach and these comments can be considered in the modelling plan.
- A Conceptualisation Report is essentially an outcome of the Data Collation and Analysis process. The combining of the two reports will naturally link these components and reduce the presentation of repetitive information.

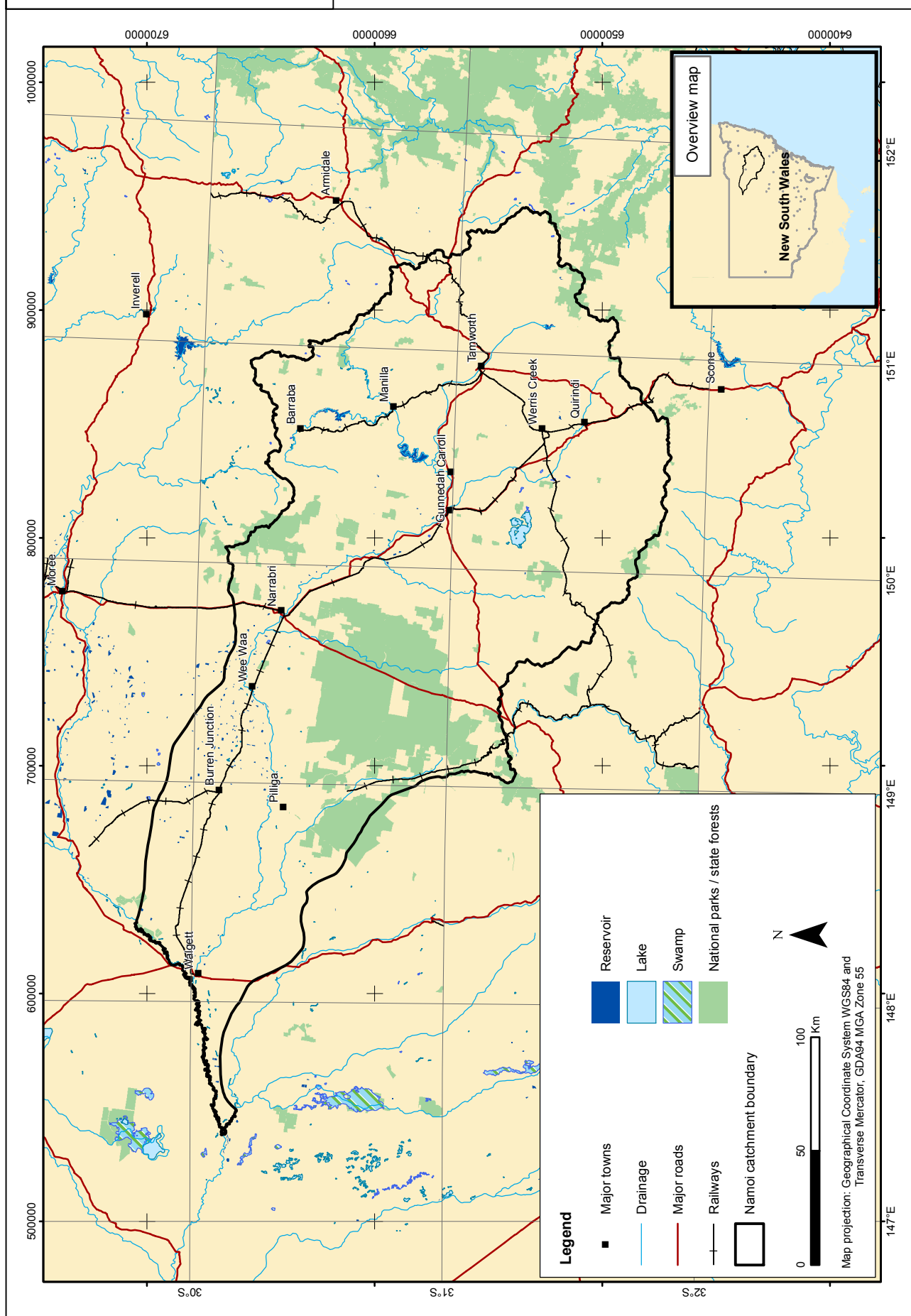
The schematic schedule below presents the revised timetable for the Study.



Phase 2.5 of the Study therefore integrates Data Collation, Data Analysis, and Model Conceptualisation. Phase 2.5 addresses all the aspects of the previous Phase 2 and will include those aspects essential to the formation of an initial conceptual model, as previously assigned to Phase 3 of the Study. The revised reporting format results in the integration of the results of Data Collation, Data Analysis and Model Conceptualisation into one document incorporating the following elements:

- A 'plain English' executive summary to facilitate broader community awareness and understanding of the outcomes of Phase 2.5;
- Identification of how the Study requirements relevant to Phase 2.5 were achieved;
- An outline of how the Deliverables for Phase 2.5 were achieved;

- A description of the Namoi catchment including land use, population centres and regional development features;
- A description of the catchment's water resources by sub-catchment including surface streams, confined and unconfined aquifers, drainage, recharge and discharge zones, and interaction between surface streams and shallow and deep aquifers in a multi-layer aquifer system;
- A description of the geology of the catchment;
- Identification of coal and gas resources including maps of their location;
- Maps showing the spatial distribution of water resources in relation to the spatial distribution of coal and gas resources in their geological context;
- Identification of past, current, and proposed coal and gas developments including maps of their location, the size of the resource, and details of the extraction methods;
- The Model Rationale and Design;
- The Model Assumptions;
- The plan for a rigorous program of calibration, validation, sensitivity analysis and uncertainty analysis; and
- SWS will provide an electronic version of the final Phase 2.5 Report to DTIRIS NSW and the members of the MOC, SAG and community consultative committees. The report will be in 'PDF' file format and of a size suitable for downloading from the internet. Further, SWS will distribute one (1) bound hard copy of the Phase 2.5 Report to each of the council offices and libraries listed in Appendix 4 of the Request for Tender document within one (1) week of finalising the report.



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2 DATA COLLATION AND ANALYSIS

2.1 Introduction

SWS have undertaken to collect and use the most reliable and accurate data available at the highest resolution possible. This has required extensive liaison with government departments, Industry Partners, the MOC, the SAG and other relevant stakeholders (including those listed in Appendix 3 of the Request for Tender document), for the collection and collation of relevant datasets. It has resulted in the collation of wide-ranging disparate datasets and in nearly all instances these have comprised datasets, not functional relational databases. In many instances the information has only been available in non-digital formats and data entry or conversion has been required.

As part of Phase 2 of the Study it has been essential and fundamental to compile a validated relational database, which includes all publicly available information and all data that private companies have been able to release for the purposes of the Study. In order to achieve this, a single, central, live database has been developed which continues to be updated as new information becomes available. This database has the capability of being maintained and enhanced with any new data that may be made available during the course of the Study or post-Study, including through future development. As applicable to the datasets, information can be presented spatially through the direct interface between the database and the Geographical Information System (GIS). The architecture is described in subsequent sections of this document.

This process has resulted in the construction of a comprehensive whole of catchment geological model which, in conjunction with other data and the GIS, facilitates recognition of the spatial relationship between coal mines and coal resources, potential CSG resources, geology, hydrogeology, water resources, abstraction, land use, geography and topography, etc. within a three-dimensional visualisation platform. This then provides the basis for conceptual model development and also facilitates identification of data gaps.

The initial conceptual model of the groundwater and surface water systems for the whole of the Namoi catchment is therefore based around completion of the following activities:

- Review of all relevant data and identification of key issues.
- Compiling and reviewing all relevant geological, geophysical, structural, hydrological and hydrogeological data available.
- Obtaining well records and historical abstraction from both groundwater and surface water.
- Identification of sources of recharge to and discharge from the groundwater system, including stream-aquifer interactions.
- Definition of all the principal hydrogeological units, including preliminary estimates of groundwater transmitting and storage properties.

- Estimates of groundwater elevations and groundwater flow directions.
- Assessment of water chemistry and spatial distribution.
- Characterisation of the catchment including; physical features, climate, geological, hydrogeology and groundwater management, surface water and surface water management, and land use.

The initial conceptual model will form the basis for subsequent implementation in the numerical model. It is important to recognise that the modelling process itself will result in change and enhancement to the initial conceptual model, and that the conceptual model will be continually revisited and modified as the Study continues. That is, the process is iterative, as recognised by the Murray Darling Basin Commission (MDBC) modelling guidelines (MDBC, 2000).

2.2 Data sources and requests

The data collation phase has involved a high level of liaison with the Study stakeholders and negotiation to the mode of data collection and format. Government departments, industry, public libraries, and private sources were all contacted to obtain data for the Study. Datasets ranged from published reports on past research to raw datasets obtained from the relevant government departments and the Industry Partners.

2.2.1 Government departments and stakeholders

A large number of state and federal government departments and agencies, and community stakeholder groups and organisations were contacted directly and indirectly in the pursuit of data. These include but are not limited to:

- New South Wales Department of Trade and Investment, Regional Infrastructure and Services (NSW DTIRIS)
- New South Wales Department of Primary Industries (NSW DPI)
- New South Wales Minerals and Energy Division
- New South Wales Office of Environment and Climate Change
- New South Wales Office of Water (NSW Office of Water)
- State Water Corporation
- Namoi Water
- Namoi Catchment Management Authority (Namoi CMA)
- The Commonwealth Scientific and Industrial Research Organisation (CSIRO)
- Cotton Catchment Communities Cooperative Research Centre (Cotton CRC)
- University of New South Wales
- Flinders University
- Bureau of Meteorology (BOM)
- Bureau of Rural Sciences
- Geoscience Australia

2.2.2 Industry Partners

The process for acquisition of Industry Partner datasets began with initial discussions in September 2010. Discussions focused on the data required for the Study, availability of that data, and the desirable formats of the datasets for use within the Study database. Due to the commercial and confidential nature of this data the Industry Partners determined that a Confidentiality Deed was required prior to the delivery of the data.

Eight Industry Partners have made major contributions to the Study dataset. They are:

- Eastern Star Gas Ltd (Eastern Star Gas)
- Santos Ltd (Santos)
- Dart Energy Ltd (Dart Energy)
- BHP Billiton Pty Ltd Caroon Coal Project (BHP Billiton)
- Shenhua Watermark Coal Pty Ltd (Shenhua)
- Whitehaven Coal Ltd (Whitehaven)
- Aston Resources Ltd (Aston Resources)
- Idemitsu Australia Resources Pty Ltd (Idemitsu).

No data has as yet been received from Coalworks or the Bloomfield Group due to their internal time constraints. However it is understood that data will be forthcoming. This data will be added to the database on receipt, and if possible will be incorporated in the geological and impact assessment tools.

At the commencement of the Study, Red Sky Energy Ltd were the holders of two Petroleum Exploration Licences (PELs) in the northwestern corner of the Namoi catchment. In June 2011 however, they relinquished both licences (Red Sky Energy, 2011). No relevant information was available from Red Sky Energy Ltd for inclusion into the database.

2.2.3 Data receipt and extent

Various data delivery methods were employed in the physical acquisition of the data such as DVD/CD, File Transfer Protocol (FTP) download and email. Once received the data was stored on a secure SWS data server and the data logged along with contact, client and file-based location details. Initial data analysis took place in order to record data types, assess data quality and establish any data gaps. Data format issues, data gaps and errors were referred to the data provider contact in order to resolve such issues.

The datasets received from the various NSW Government Departments and Industry Partners represent the most comprehensive and spatially extensive datasets available for the catchment. Government data was received in various formats including text file, spreadsheets, and GIS spatial coverage, and included the large scale Pinneena databases of the NSW Office of Water. The Pinneena datasets are the foundation for the historical records of regulatory water datasets within NSW and as such are important to the Study.

A total of 22.8 million records for surface water (including discharge, stream levels, temperature and turbidity) are available within the Pinneena 9.3 CM (continuous monitoring) data set for the Study area.

The Pinneena 3.2 GW (groundwater) data set contains in excess of 126,000 records of water bore locations, 112,000 works locations, over 90,000 drillers logs, and a further 328,469 groundwater level records. Of these over 21,000 bores are located within the Namoi catchment. Records for more than 4,000 additional borehole locations were provided by Industry Partners.

Geology datasets were provided by the NSW Department of Primary Industries (DPI), the NSW Office of Water and the Industry Partners and included 172,000 facies interpretations, 22,804 stratigraphic log records, and stratigraphic surface interpretations containing in excess of 1.1 million records.

Rainfall data for the catchment was provided by the Bureau of Meteorology and provided 6.5 million daily rainfall records for the 412 rainfall stations within the catchment.

These datasets all required extensive review, collation and analysis prior to use. The collation of the datasets represents a significant achievement for the Study and should become a significant resource in its own right.

SWS has maintained a detailed log of requests and data receipt, and a summary listing of the main sources of data and data content is provided as Appendix A.

2.3 Data preparation

An ESRI ArcSDE (spatial database engine) GeoDatabase (ESRI, 2004) is used to store all geospatial map data for the project. ArcSDE is a powerful system which can efficiently store and organise project map layers in a single location. Security levels are defined in the database to enable protection of confidential datasets, ensure base data is maintained, and subsequent iterations of datasets are uniquely identified.

Geographic Information System (GIS) software ArcMap (ESRI, 2006), ArcCatalog (ESRI, 2006) and Global Mapper (Global Mapper, 2011) were used to process and manipulate geospatial data. The Namoi project uses the geographic coordinate system Geocentric Datum of Australia 1994 (GDA94) and deploys the Universal Transverse Mercator (UTM) Map Grid of Australia Zone 55 (MGA55).

The majority of the catchment lies within the MGA55 zone, with the eastern edge of the catchment located within the MGA56 zone. Therefore any data received in MGA56 or as GDA94 (latitude, longitude) was re-projected to the MGA55 zone. Both latitude-longitude and UTM coordinates are stored for map layers in ArcSDE and the Namoi project database.

2.4 Project database

The Namoi project relational database is built on Microsoft SQL Server 2008 (Delaney et al., 2009) and Microsoft Access 2007 technology. The relational database model enables data administrators to define relationships between tables and structured query objects. The advantages of the relational database are that large datasets are grouped into smaller, formally-described tables and can be queried and manipulated efficiently. Further information on relational databases is provided in Date (2003).

SQL Server 2008 is a database with an architecture that provides scalability and security for complex and confidential datasets. Based on user access, the security level of specific data can be set in order to protect specific data records or datasets. Access 2007 queries and forms are used in order to facilitate data presentation by linking to the SQL Server 2008 database.

The database is structured around the main location tables which describe the position of all boreholes, surface water stations and weather stations (COLLARS, SW_STATIONS and WEATHERSTATIONS) inside the Namoi catchment. Each collar, surface water station or weather station has a unique index and name which is used to define its relationship with other data tables such as interpreted stratigraphy, construction and completion details, as well as time series monitoring data such as levels, flows and water quality.

A diagrammatic representation of the data acquisition process, the internal data workflow processes, and a comprehensive list of the datasets received from each source is provided in Appendix A.

2.5 Data analysis process

The database has been used as a platform to query data relevant for the:

- Analytical interpretation of the physical characterisation of the catchment.
- Construction of the geological model.
- Numerical interpretation of the temporal and spatial distribution of the water resources.
- Location of coal mines and potential coal and CSG resources.

Information from government and industry sourced exploration and monitoring bores has been used to define the catchment stratigraphy and undertake facies and formation analysis, enabling the construction of surfaces for development of the geological model.

The temporal distribution of water data has been analysed to allow the creation of groundwater contour and flow maps, flow and use patterns for surface water and flood characteristics.

Rainfall data has been extracted from the database to locate and analyse spatial and temporal precipitation patterns for the catchment.

The interface of the project database with the GIS facilitates the data analyses and diagrammatic representation of results in the form of maps, as discussed in subsequent sections of this report.

2.6 Confidentiality Deed

Confidentiality Deed agreements have been signed between Industry Partners and SWS. The Deed allows for the acquisition and use of confidential and commercially sensitive data by SWS for the express purpose of completing the Study. As the Recipient, SWS are bound to the following principal conditions of the Deed:

- The Recipient must keep the Confidential Information secret and preserve its confidential nature.
- The Recipient must not use Confidential Information for any purpose other than the Express Purpose.
- The Recipient must not disclose or permit the disclosure of Confidential Information to any person other than:
 - with the written consent of the provider,
 - a representative of SWS who needs the confidential information for the Express Purpose,
 - when disclosure is required by law.
- The Recipient must not reverse engineer, decompile or disassemble any Confidential Information.
- The Recipient may only copy or reproduce Confidential Information for the Express Purpose, or with the written consent of the Provider.

SWS must also ensure that Study personnel are made aware of the confidential nature of the Confidential Information and the terms of the deed, do not breach the deed, and maintain a register of personnel provided access to confidential information. The confidential information is to be securely protected and any possible, suspected or actual breach must be reported immediately to the data provider. The confidential information remains the property of the provider at all times.

The effects of the Confidentiality Deeds on the Namoi Catchment Water Study are as follows:

- Access is provided to significant and important datasets which enhance the detail and relevance of the Study;
- It provides access to factual information relating to the operation of both coal and gas extraction within the Namoi catchment;
- Information produced from datasets obtained under the deeds can only be displayed in such a way that the data cannot be reverse engineered to reveal the underlying confidential data;
- Data cannot be given to third parties without the express written consent of the data provider.

The implications of the Confidentiality Deed to the Study are such that the display of data to the MOC, the SAG and the community are limited to broad interpretations of the raw data. The database and models cannot be handed over to a third party without the express permission of the data providers or until the future recipient has a formalised Confidentiality Deed with the data providers.

In the event that Confidentiality Deeds are not forthcoming to the intended final recipient of the Study data and model, SWS is obligated by the Confidentiality Deed to remove any data, or information which can be reverse engineered, from the database or model.

It should, however, be noted that mineral exploration data can be released to 'Open file' and therefore deemed no longer confidential under certain circumstances such as by the express permission of the data owner, the expiration of an authority, relinquishment or partial relinquishment of an Exploration Licence or authority. Under the Petroleum (Onshore) Act 1991, all basic data supplied to the NSW Department of Primary Industries is released as "Open file" after 2 years (subject to any qualifications of Sections 118, 119, and 120 of the Act) and interpretative data is released after 5 years. All data acquired within a Petroleum Assessment Lease (PAL) or Petroleum Production Lease (PPL) shall remain confidential throughout the life of the lease.

The Industry Partner data is considered critical to obtaining a successful outcome for the Study. Although wide-ranging publically available data exists for the Namoi alluvium and river channels that form the primary groundwater and surface water resources in the catchment, there is a paucity of information in the 'hard rock' areas outside or beyond the alluvium deposits. The coal and CSG resources are hosted within the hard rock zones and these resources do not exist within the alluvium bodies and river channels. The Industry Partners have obtained the most valuable and comprehensive datasets for these hard rock (solid geology) areas.

The immediate effect of Confidentiality Deeds has been on the production of this Phase 2.5 report with denial of consent to publish geological cross-section information extracted from the SWS geological model (Section 5). Several large-scale geological cross-sections were provided to all Industry Partners with a request for consent to reproduce these in this report. The locations of the proposed sections were chosen to illustrate basin-scale (catchment-wide) geological interpretation and relationships. However, as consent to publish could not be obtained from all Industry Partners these have been omitted as figures from subsequent sections of this document.

In terms of the use of the Industry Partner data in the numerical model(s) being developed as Phase 3 of the Study, it is the understanding of SWS that we are able to use the stratigraphic surfaces developed in the geological model as a primary input for configuration of the numerical model(s) geometry. Therefore, although some specific geological data and interpretations need to be omitted from this document, the data can still be used in the numerical modelling, and ultimately the Study goal of developing an integrated suite of models for the assessment of the nature and extent of the potential effects from coal and CSG developments on the water resources of the catchment should not be compromised.

2.7 Summary

Data collation and analysis is an important aspect of any modelling study. The following summarises the critical components in achieving this outcome:

- A validated relational database has been constructed which includes all publicly available information and Industry Partner data. In order to achieve this, a single, central, live database has been developed which has the capability of being maintained and enhanced with any new data that may be made available during the course of the Study or post-Study.
- A secure ESRI ArcSDE GeoDatabase is being utilised as a repository of public and confidential datasets, ensuring base data is maintained, and subsequent iterations of datasets are uniquely identified. Geographic Information System (GIS) software ArcMap, ArcCatalog and GlobalMapper were used to process and manipulate geospatial data.
- The Namoi project relational database is built on Microsoft SQL Server 2008 and Microsoft Access 2007 technology. The relational database enables data administrators to define relationships between tables and structured query objects. Microsoft Access 2007 queries and forms are used in order to facilitate data presentation by linking to the SQL Server 2008 database.
- Confidentiality Deed agreements have been signed between Industry Partners and SWS. The Deed allows for the acquisition and use of confidential and commercially sensitive Industry Partner data by SWS for the express purpose of completing the Study. The requirement for this Deed and its restrictions has resulted in the omission of some specific geological data and interpretations from this document. Ultimately the Study goal of developing an integrated suite of models for the assessment of the nature and extent of the potential effects from coal and CSG developments on the water resources of the catchment should not be compromised.

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3 PHYSICAL CHARACTERISATION

3.1 Topography

The Namoi catchment covers an area of approximately 42,000 km² with elevations ranging from 1,400 mAHD in the Great Dividing Range in the east of the catchment to 130 mAHD on the alluvial plains around Walgett in the west (Figure 3.1). The catchment is bounded by the Great Dividing Range in the east, the Liverpool Ranges and Warrumbungle Ranges in the south, and the Nandewar Ranges and Mt. Kaputar in the north.

The catchment can be split into three different regions based on topography. To the east the high, rolling terrain of the Great Dividing Range and foothills extends to the ridge line to the east of the towns of Gunnedah and Quirindi, which marks the surface expression of the Hunter–Mooki Fault System. In the higher elevation areas the slopes are steep with well defined stream valleys. As the elevation decreases so too does the gradient with valleys widening and increasing areas of floodplain.

To the west of the Hunter–Mooki Fault System the ground becomes significantly flatter, with smaller and more isolated regions of higher ground seen within an extensive alluvial floodplain. A spur of higher ground forms a natural break across the catchment, leaving a small area near Narrabri for the river to flow through. This effectively splits the catchment into two further areas. The floodplain areas to the west are extremely flat, with a dense network of artificial drainage channels present in addition to natural stream channels.

The topographic coverage of the catchment was provided as a Digital Elevation Model (DEM) of 25 m resolution by NSW DTIRIS in February 2011. A section of the far northwest of the catchment surrounding the town of Walgett was only available as 90 m resolution coverage and has been appended to the higher resolution data through the use of ArcGIS.

3.2 Urban areas and infrastructure

3.2.1 *Population*

The Namoi catchment has a population of approximately 89,540 people according to the 2006 Census (Australian Bureau of Statistics, 2011). The major population centre is Tamworth with 42,499 recorded residents in 2006, followed by Narrabri and Gunnedah with 13,120 and 11,525 respectively (Australian Bureau of Statistics, 2011). Smaller population centres are located throughout the catchment, including Walgett, Boggabri, Wee Waa, Quirindi, and Werris Creek, with most lying along the Namoi River or main tributaries. Local government areas and major towns are shown on Figure 3.2.

In their 2008 report the NSW Department of Planning presents population projections for the period 2006 to 2036 for the Statistical Local Areas and Local Government Areas of New South Wales. The projections take into account 2006 Census data and the latest expertise on fertility, mortality and migration. Population growth projections for all local government areas within the Namoi catchment, except Tamworth, indicate a period of declining population of between 0.25% and 1.81% annually. Tamworth is projected to maintain a strong growth for the period with projections of annual growth averages of between 0.6% and 0.18% (NSW Department of Planning, 2008). There is no indication in the report if increased activity in the coal and coal seam gas sectors has been accounted for in projections.

3.2.2 Infrastructure

The catchment has an extensive road network with major thoroughfares such as the Oxley Highway traversing the catchment east to west from Tamworth to Coonabarabran where it intersects the north / south Newell Highway. To the east the Kamilaroi Highway transects the catchment in a north westerly direction from Murrurundi in the southwest until it intersects the Newell Highway at Narrabri and then heads west to Walgett. The eastern portion of the catchment is crossed by the north / south New England Highway passing through the regional hub of Tamworth. Numerous minor roads, often unsealed, provide access to the remainder of the catchment. The roads are the primary means of transport for the catchment communities (Figure 3.3).

The Main North Line of NSW railways begins in Sydney and traverses the coal fields of the Hunter Valley before entering the Namoi catchment near Murrundi, passing through Tamworth and ending to the north of Armidale (NSWrail, 2011). The Main North Line was at one time the main rail route between NSW and Queensland, until replaced by the upgraded and standard gauge North Coast Line now joining Sydney and Brisbane via a direct coastal route. The Main North Line still provides the main freight entry and exit to the Namoi Valley, with particular importance to the transport of agricultural and coal mining industries (NSWrail, 2011).

The Mungindi Line, a major spur from the Main North Line, starts at Werris Creek and heads to the Queensland border through the towns of Gunnedah, Boggabri, Narrabri and Moree. The line provides a major access route for the grain and coal industries and is serviced by a number of single track railway lines with loops running through the catchment (NSWrail, 2011). There is one passenger train a day on these lines, and the railways are primarily used to move freight such coal and grain out of the catchment (NSWrail, 2011).

3.2.3 Agricultural and industrial development potential

The 2010 "State of the catchments" report from the NSW Government found that the Namoi region has some strongly performing industries, yet little overall growth is currently being achieved, and the region's contribution to aggregate growth has declined over time. Mining has accounted for much of the region's economic growth since 2001. The analysis indicated that there is poor level of access to the essential services needed to run and grow modern businesses. As a result, the State of the catchments report stated that future economic growth in the Namoi region will rely heavily on increased mining activity and related service industries (NSW Government, 2010a).

The reliance on primary industries in the Namoi region is indicated to continue especially as mining activities in the area increase (NSW Government, 2010a). The study identifies opportunities for the development of industry clusters with expansion of cotton in Narrabri, and cereal and meat processing in Tamworth. Likely future contenders for cluster development are the coal and gas industries, given their expansion in the Gunnedah Basin. Limited rail access to the port of Newcastle was also identified as hampering economic development (NSW Government, 2010a).

3.3 Surface drainage

The Namoi catchment is a westerly draining system with headwaters on the western flank of the Great Dividing Range in Central NSW. The catchment is covered by a dense network of surface streams and artificial channels. Artificial drainage is most prevalent along the alluvial valleys in the western catchment. (Green et al., 2011).

The main drainage channel is the Namoi River system rising in the area to the south of the township of Walcha with flow contributed to 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. The main streams and tributaries are shown on Figure 3.4.

Three key water storage dams, used for both water supply security and flood prevention, are present in the Namoi catchment:

- Split Rock Dam on the Manilla River, built in 1988 and able to store 397,370 ML (Green et al., 2011).
- Keepit Dam on the Namoi River, built in 1960 and able to store 423,000 ML (Green et al., 2011).
- Chaffey Dam on the Peel River, built in 1979 and able to store 62,000 ML (Green et al., 2011).

These three dams regulate the flow of water in the catchment below these points. There are also several smaller on-river dams such as Gunidgera Weir and Mollee Weir, and numerous off-river storage developments such as on-farm dams used for storing off-allocation water from tributaries, or water diverted from the main rivers during high flow events (Lampert and Short, 2004 and Green et al., 2011).

A number of smaller storages are present in the unregulated sections of the Namoi River system. The capacity of these storages, according to the Commonwealth of Australia, Department of Sustainability, Environment, Water, Population and Communities (Commonwealth of Australia DSEWPC, 2009a) are presented in Table 3.1.

Table 3.1 Smaller water storages in the unregulated Namoi catchment area

Name	Location	Capacity (ML)
Barraba Dam	Manilla River near Manilla	360
Nixon	Near Barraba	222
Moore Creek Dam	Near Tamworth	220
Temp weir 10	Barwon River	NA
Burnt Hut Creek No 1	Peel Valley	NA
Burnt Hut Creek No 2	Peel Valley	NA
Knights Regulator	Gunidgera Creek	250
Dungowan Dam	Upper Peel catchment	5,700
Coeypoll Creek Dam No 1	Near Werris Creek	850
Coeypoll Creek Dam No 2	Near Werris Creek	5,400
Total		12,752

(Commonwealth of Australia DSEWPC, 2009a). NA = Not Available.

Additional significant water storages with the regulated streams of the Namoi catchment are presented in Table 3.2.

Table 3.2 Smaller dams in the regulated Namoi catchment area

Name	Location	Capacity (ML)
Dundee Weir	Pian Creek	NA
Gunidgera Weir	Namoi River	1,900
Gunidgera Regulator	Gunidgera Creek	1,250
Manilla Weir	Namoi River	NA
Mollee Weir	Namoi River	3,250
O'Rourkes Dam	Pian Creek	NA
Paradise Weir	Peel River	NA
Pian Creek Weir	Pian Creek	NA
Quinns Billabong Dam No 1	-	NA
Quinns Billabong Dam No 2	-	NA
Weeta Weir	Namoi River	350

(Commonwealth of Australia DSEWPC, 2009b). NA = Not Available.

Thoms et al. (1999) have calculated that over 90% of the total runoff in the Namoi River catchment is generated in the upper 40% of the catchment. Flows along the majority of the Namoi River are regulated by the three large storage dams. Split Rock Dam regulates 93% of inflows, Keepit Dam regulates 77% of inflows, and Chaffey Dam regulates 41% of inflows (CSIRO, 2007). Although the streams are regulated the average flow is still highly dependent on annual rainfall. The total surface water resource in the Namoi region is estimated to be an average of 965 GL/yr, and on average flow in the Namoi River at Gunnedah is around 770 GL/yr (CSIRO, 2007).

Chanson and James (1998), report that the large water supply dams also trap sediment. This gradually infills the available storage area and also restricts the amount of material that can move downstream to replenish the streambed further down the system. There are several dams within the catchment that are now infilled completely, these include Moore Creek Dam which supplied Tamworth (1898 – 1924), Gap Weir built to supply the railways near Werris Creek (1902 – 1924) and Quipolly Dam built to supply Werris Creek (1932 – 1955) (Chanson and James, 1998).

3.4 Climate

Climate data and statistics for selected stations within the catchment, and monthly gridded datasets for the whole of Australia, were obtained from the Bureau of Meteorology (BOM) website (BOM, 2011). Data was also obtained as text files for each individual station (received from BOM in November 2010). The text files contain all available data on a daily timestep for the period of record of each site.

Climate mapping from the BOM indicates warm wet summers and cold dry winters in the eastern portion of the catchment associated with the higher elevations of the Great Dividing Range (BOM, 2011). To the west of Tamworth the climate pattern is dominated by a pattern of hot dry summers and cold winters (BOM, 2011).

The following summaries are reported (BOM, 2011):

- Long term average maximum temperature of approximately 32.5°C for January in the area of Tamworth with a mean minimum temperature of 2.3°C for July
- Walgett at the western extremity of the catchment returns a mean maximum temperature of 35.4°C for January and a mean minimum of 3.5°C in July.
- Catchment winters are cool to mild, with average maximum July temperatures of 16–17°C.
- Catchment temperatures frequently fall below 0°C during winter months.

3.4.1 Rainfall

Introduction

Rainfall is highly variable across the catchment with the range areas in the east receiving up to 1,300 mm annually, while Gunnedah has a mean annual rainfall of approximately 620 mm, and 480 mm is reported at Walgett (BOM, 2011). Peak precipitation, at Gunnedah, occurs in summer (November to February) with the highest mean monthly averages of 70 mm reported in December and January. Lower precipitation rates are experienced for the months April through to September with a relatively consistent mean monthly average of around 40 mm for that period. The annual rainfall statistics for Gunnedah show high variability, from a low of 247 mm to a high of 1,137 mm.

Rainfall is the principal input of water to the catchment, both as runoff to streams and groundwater recharge. A detailed understanding of the spatial and temporal distribution of historical rainfall rates is critical to give a greater understanding of water availability in water resource zones. The datasets are used as an input to any model approach taken for the catchment.

Data files received from the BOM (received in November 2010) indicate that there are records for 412 individual rainfall stations within the Namoi catchment. A total of 6.5 million daily records were provided, with measurements from 1869 up to 2010. Data from stations outside the catchment were not used because the data coverage within the catchment was sufficient. Figure 3.5 shows the location of the rainfall stations used in the Study.

There are 47 stations within the catchment with over 100 years of data record, all but four of these continue to the present day. There are a further 21 stations with over 80 years of data. The majority of stations have records which start during the late 1950's. Figure 3.6 shows the number of active stations each year. It can be seen that after a peak of approximately 250 active stations in the 1970's the number of stations has decreased to approximately 150 in 2010.

Spatial distribution of data

Figures 3.7 and 3.8 show the density of active rainfall stations every 20 years from 1900 to 2010. The density within the catchment was calculated by counting the number of stations within a 20 km search radius.

The increase in active stations from the late 1950's is noticeable around Tamworth in the 1960 plot. The figure also shows that there is a large area with no stations which includes the Pilliga State Forest, and that the area to the west of Narrabri has a much lower coverage.

The majority of the stations have records up to at least 1990, especially in the eastern portions of the catchment. Several stations in the western portions (Narrabri, Warrumbungle and Walgett) have their latest measurement more than 30 years ago (<1970) which may decrease the accuracy of rainfall regionalisation for recent years.

With respect to length, rainfall records can span as long as 140 years for the stations which start in the 1800's. Fifty percent of the weather stations contain at least 30 years of records, while only 20% of the stations present time series longer than 60 years. As would be expected from the start dates of the records the longest rainfall time series are found in the central portions of the catchment (Narrabri, Gunnedah and Liverpool Plains). The eastern areas of the catchment present the shorter time series periods, ranging mostly between 10 and 30 years (Figure 3.9).

The quality of time series completeness is generally very good. The majority of stations have an almost complete record, with over 71% of the stations having at least 85% of data possible. Weather stations with significant gaps in the time series can be identified on Figure 3.10. The data from the stations with significant data gaps were also included in the analysis. However, these stations were flagged for further data auditing.

Temporal distribution

Figure 3.11 shows the calculated maximum and average monthly rainfall each month over the entire catchment for the period 1869 to 2010 using the raw datasets. Average rainfall shows seasonal patterns; with a dry season from April to September and a wet season from October to March. Eighty percent of average monthly rainfall values lie within the range 47 to 70 mm.

Average annual rainfall totals are approximately 690 mm, with most years having a total between 450 and 850 mm, as illustrated in Figures 3.12 and 3.13. Minimum yearly values for individual weather stations can be as low as 128 mm, while maximum values can reach up to 2,364 mm.

Spatial distribution (station averaged values comparison)

Concentrated statistics were generated for each weather station and further interpolated spatially in order to investigate its distribution. These statistics include:

- maximum / minimum / average monthly rainfall;
- maximum / minimum / average yearly rainfall; and
- maximum / minimum / average number of precipitation days.

The distribution and interpolated values for monthly rainfall for the entire catchment are presented in Figure 3.14. Monthly minimum rainfall values are zero for most stations with a few exceptions.

Monthly maximum rainfall values range from 42 to 480 mm (Figure 3.14 b). No clear pattern could be recognised from the spatial distribution. These are likely to reflect the incidences of localised storm systems within the catchment.

Monthly average values for rainfall show three distinctive zones (Figure 3.14 c). The westernmost zone is characterised by lowest monthly averages (<40 mm). Easternmost areas show the highest values (up to 120 mm). The central zone presents intermediate values ranging from 40 to 60 mm. A plot of monthly average values against station elevation indicates a reasonable correlation (Figure 3.15). This is most likely related to orographic effects, with the ridges that surround the Namoi Valley causing moist air to rise. This air then expands and cools, resulting in condensation. A spatial trend can also be observed, with higher rainfall values towards the east of the catchment (Figure 3.16). This is probably related to the fact that the ridges are located towards the east of the catchment, and therefore orographic effects are more likely to occur in these areas.

Minimum values for yearly rainfall are also lowest in the central and western portions of the catchment (Figure 3.17a), while areas to the east present much higher values. Higher variability in the eastern portion may be related to the higher density of weather stations or the higher elevation of the gauges, but that cannot be confirmed without additional stations. Maximum values (Figure 3.17b) do not present a clear distribution pattern, with exception of slightly higher values observed towards southern and eastern catchment boundaries.

The annual average distribution presents the same patterns identified in the monthly average distribution discussed above. The highest annual average values can be found in the eastern portions of the catchment, near Tamworth, south of the Liverpool Plains and around Walcha. These are all within the higher elevation areas of the catchment. The minimum, maximum and average annual distribution patterns are presented in Figure 3.17.

Statistics generated for the number of rainfall days in a year present relatively similar trends to those observed in the rainfall rates. The distribution of minimum number of rainfall days presents a more homogeneous distribution through the catchment in relation to maximum and average values (Figure 3.18), indicating that drought periods were recorded in the entire catchment, despite the presence of orographic effects on the rainfall.

Plots of the maximum and average number of precipitation days also show higher values towards the southeast of the catchment (Figures 3.18), as observed with yearly and monthly rainfall statistics. On average the number of precipitation days ranges between 40 and 125 days.

3.4.2 Evaporation

Evaporation is an important component of any water catchment study and is a major contributing factor to both surface water and groundwater losses to the system. Evaporation data has been sourced from the Bureau of Meteorology in the form of gridded data compiled from 630 climate data stations Australia wide and extracted for the Namoi catchment. The gridded data were generated using the Barnes 2-D meteorological analysis. Most of the stations used in the analysis have at least 10 years of records, with at least 80% complete data over the recorded period. The evaporation data used in producing the grids are from the BOM Class A pan evaporimeters. The data has been provided in a five kilometre grid in ESRI shapefile format. This data represents the highest resolution data available at this time and while relatively coarse will meet the needs of the Study.

Review of the data shows that the average Class A pan evaporation varies from around 1,000 mm per year in the southeast, to over 2,100 mm per year in the northwest of the catchment. Evaporation is highly seasonal with Gunnedah evaporation rates reported as a maximum daily average of 7.8 mm in December and an average minimum of 1.9 mm in June and July. The annual average daily evaporation for Gunnedah is 4.8 mm.

Actual data for the Namoi catchment is currently available at four BOM stations (station no's 55024, 55054, 55276, and 55327) within the catchment boundary. All evaporation stations are located within the Upper Namoi. An extract of the available evaporation data is presented in Figure 3.19.

3.4.3 *Climate change*

CSIRO in their report 'Climate Change in the Namoi Catchment' (CSIRO, 2006) stated that since 1950, the catchment has experienced warming of around 0.8 °C. This is thought to be partly due to human activities. Rainfall trends in the catchment have been variable, with some areas experiencing trends toward increasing rainfall while others have experienced declines.

The same report (CSIRO, 2006) predicts a warmer and drier climate within the Namoi catchment with increased evaporation, more days of extreme heat, and increases in extreme winds and fire risk. Despite this an increase in extreme rainfall events is also predicted. These projections account for a broad range of assumptions about future global greenhouse gas emissions, as well as differences in how different climate models represent the climate system.

3.5 Soils and land management areas

Soil maps for selected areas of the catchment are available from the NSW Office of Environment and Heritage (2011), however large areas of the catchment remain unpublished at this time. A complete soils map for the catchment at 1:100,000 scale based on reconnaissance surveys was obtained from the Namoi CMA, which had commissioned Soil Futures to produce this in 2008 (Soil Futures, 2008).

The soils mapping splits the catchment into 300 different areas (Figure 3.20). Attributes given to these areas allow them to be grouped into a smaller number of classes based on information such as landform, lithology, and dominant formation processes (Soil Futures, 2008).

The Namoi CMA (2011a) has created 22 different land management units based on the soil mapping, topography, and hydrogeological properties. The classifications are shown in Table 3.3 and Figure 3.21. Each land management unit has a Best Management Practice (BMP) guideline developed which describe the nature of the unit and give suggestions on positive land management practices that will benefit the entire Namoi catchment. BMP guidelines can be accessed via the Namoi CMA website (Namoi CMA, 2011a).

The soils and land management area mapping will provide baseline data for the construction of rainfall and runoff modelling and the calculation of the recharge values for the groundwater modelling process.

Table 3.3 Land management units in the Namoi catchment

Unit	Description	Area (ha)	Land capability classification	Dominant landuse
A	Sedimentary Hilltops and Steep Slopes (Generally > 15%)	396,023	4 to 8	Native forest
B	Sedimentary Slopes (Generally 8 - 15%)	442,300	4 or 5	Pasture, native timber
C	Sedimentary Foothills (Generally 2 - 8%)	329,621	4 to 6	Pasture or improved pasture
C1	Sandy Pilliga Foothills (Generally < 8%)	226,292	5 or 6	Pasture or improved pasture
D	Riparian Corridor	93,827	7	
D1	Upland Bogs and Swamps	2,881	Not given	Light grazing or nature reserve
E	Central Black Earth Floodplains	347,380	2, 7 or 8	Cropping
E1	Recent Western Floodplains	165,420	2 to 5	Dryland and irrigated cropping
E2	High Western Floodplains	178,030	Not given	Dryland and irrigated cropping
E3	Dry Western Floodplains	286,682	Not given	Grazing on native pastures
F	Central Mixed Soil Floodplains (0 - 2%)	224,822	2 to 7	Cropping and grazing
F1	Western Hardsetting Floodplains	115,058	6 +	Grazing on native pastures
F2	Flat Pilliga Outwash	441,308	> 5	Forestry and nature reserves
G	Colluvial Black Earths	229,887	2 to 4	Summer and winter annual cropping
H	Basaltic Slopes and Hills (Generally 8 - 20%)	153,396	4 to 6	Grazing
H1	High Fertility Basalt Uplands	43,413	3 to 6	Forestry and nature reserves
I	Steep Basaltic Hills (Generally > 20%)	103,987	6 to 8	Some grazing
J	Tablelands Granites	193,445	> 5	Grazing on improved pastures
K	Tablelands Sedimentary Hills	67,960	4 +	Grazing on improved pastures
L	Peel Floodplain	10,487	1 or 2	Cropping and intensive pasture
M	Duri Hills	144,827	4 to 6	Winter cereal cropping and grazing
O	Disturbed Land	2,519	Not given	Quarries and landfills

(Namoi CMA, 2011a and NSW Department of Industry and Investment, 2011a)

Land capability is classified on an eight point scale ranging from land with the greatest potential for agricultural or pastoral use (1) to that which is entirely unsuitable for either (NSW Department of Industry and Investment, 2011a). Classification descriptions are given in Table 3.4.

Table 3.4 Land capability classification

Class	Land use	Management options
1	Mainly cropping	Wide variety of uses - vegetables and fruit production, grain crops, energy crops and fodders, sugar cane. No special soil conservation works or practices necessary.
2	Mainly cropping	Soil conservation practices such as strip cropping, conservation tillage and adequate crop rotation.
3	Mainly cropping	Structural soil conservation works such as graded banks and waterways are necessary, together with soil conservation practices as in Class 2.
4	Mainly grazing	Occasional cultivation, better grazing land. Soil conservation practices such as pasture improvement, stock control, application of fertiliser and minimal cultivation for the establishment or re-establishment of permanent pasture, maintenance of good ground cover.
5	Mainly grazing	Similar to Class 4, structural soil conservation works such as diversion banks and contour ripping, together with the practices in Class 4, like the maintenance of good ground cover.
6	Grazing	Not capable of cultivation, less productive grazing, can have saline areas. Soil conservation practices including limitation of stock, broadcasting of seed and fertiliser, promotion of native pasture regeneration, prevention of fire and destruction of vermin. This may require some structural works and maintenance of good ground cover.
7	Tree cover	Land best protected by trees. Very important habitat areas for protecting biodiversity. Timber production or honey is possible.
8	Unsuitable for agriculture	Cliffs, lakes or swamps or other lands where it is impractical to grow agricultural produce or timber.

(NSW Department of Industry and Investment, 2011a)

3.6 Land use / crop types

Land use data has been obtained for several years from ABARES (Bureau of Rural Sciences, 2009). The most recent mapping was compiled on a 50 m raster grid in March 2010 and shows data for 2006. It is based on the Australian Land Use and Management (ALUM) classification system. This classification splits land uses into six primary categories and numerous secondary categories, as shown in Table 3.5. Tertiary categories are also available and are provided in Appendix B. Not all land uses are present in the Namoi catchment. Namoi land use data is presented in Figure 3.22.

Table 3.5 Primary and secondary land use classifications

Class No.	Primary class	Secondary classes
1	Conservation and natural environments	Nature conservation, managed resource protection, other minimal uses
2	Production from relatively natural environments	Grazing natural vegetation, production forestry
3	Production from dryland agriculture and plantations	Plantation forestry, grazing modified pasture, cropping, perennial horticulture, seasonal horticulture, land in transition
4	Production from irrigated agriculture and plantations	Irrigated plantation forestry, grazing irrigated modified pastures, irrigated cropping, irrigated perennial horticulture, irrigated seasonal horticulture, irrigated land in transition
5	Intensive uses	Intensive horticulture, intensive animal husbandry, manufacturing and industrial, residential and farm infrastructure, services, utilities, transport and communication, mining, waste treatment and disposal
6	Water	Lake, reservoir / dam, river, channel / aqueduct, marsh / wetland, estuary / coastal water

Viewing of the primary use map shows the principal land use of the catchment above Narrabri to be 'production from dryland agriculture and plantations', with small areas of each of the other land uses. To the southwest of Narrabri lies a large area of 'production forestry' and 'nature conservation' which includes the Pilliga and Timallallie National Parks, and to the west of Narrabri the land becomes a patchwork of production areas comprising 'relatively natural environments', 'dryland agriculture and plantations', and 'irrigated agriculture and plantations'.

Major industries include cotton, livestock production, grain and hay, poultry and horticulture. The dominant land use is cattle and sheep grazing. Wheat, cotton and other broadacre crops are grown on the alluvial floodplains. Around 112,000 ha were irrigated in 2000 with around 80,000 ha (or over 70%) used for cotton production (MDBA, 2011).

3.7 Irrigation areas

Irrigation has been undertaken in the Namoi catchment since 1961 with the planting of the first cotton crops in the Wee Waa area (CSIRO, 2007). There are no specifically designed irrigation areas within the Namoi catchment, with irrigators accessing water through their own groundwater bores and river pumps. While public water storages account for greater than 50% of the total water storage in the Namoi Valley a large number of on farm storages account for significant volumes of water used in irrigation supply and management. Groundwater accounts for approximately half of the water used for irrigation (CSIRO, 2007).

In the Lower Namoi, cotton remains the major irrigated crop, with cereal crops, fodder crops, fruit and vegetables also being grown within the catchment. The gross value of irrigated agricultural production in the Namoi was reported as \$2,072 million in 2006 (MDBC, 2008). Irrigation in the Peel sub-catchment is dominated by lucerne, pasture cereals and vegetables (MDBC, 2008). Irrigation areas of the Namoi catchment are indicated in Figure 3.23.

A study undertaken by Ashton and Oliver (2008) for the Australian Bureau of Agricultural and Resource Economics found that, on average, irrigation application rates were at an estimated rate of 4 ML per hectare per annum across the irrigated areas of the Namoi catchment. A total of 558 ML of irrigation water use was reported in 2008-2009 water year (Ashton and Oliver, 2011).

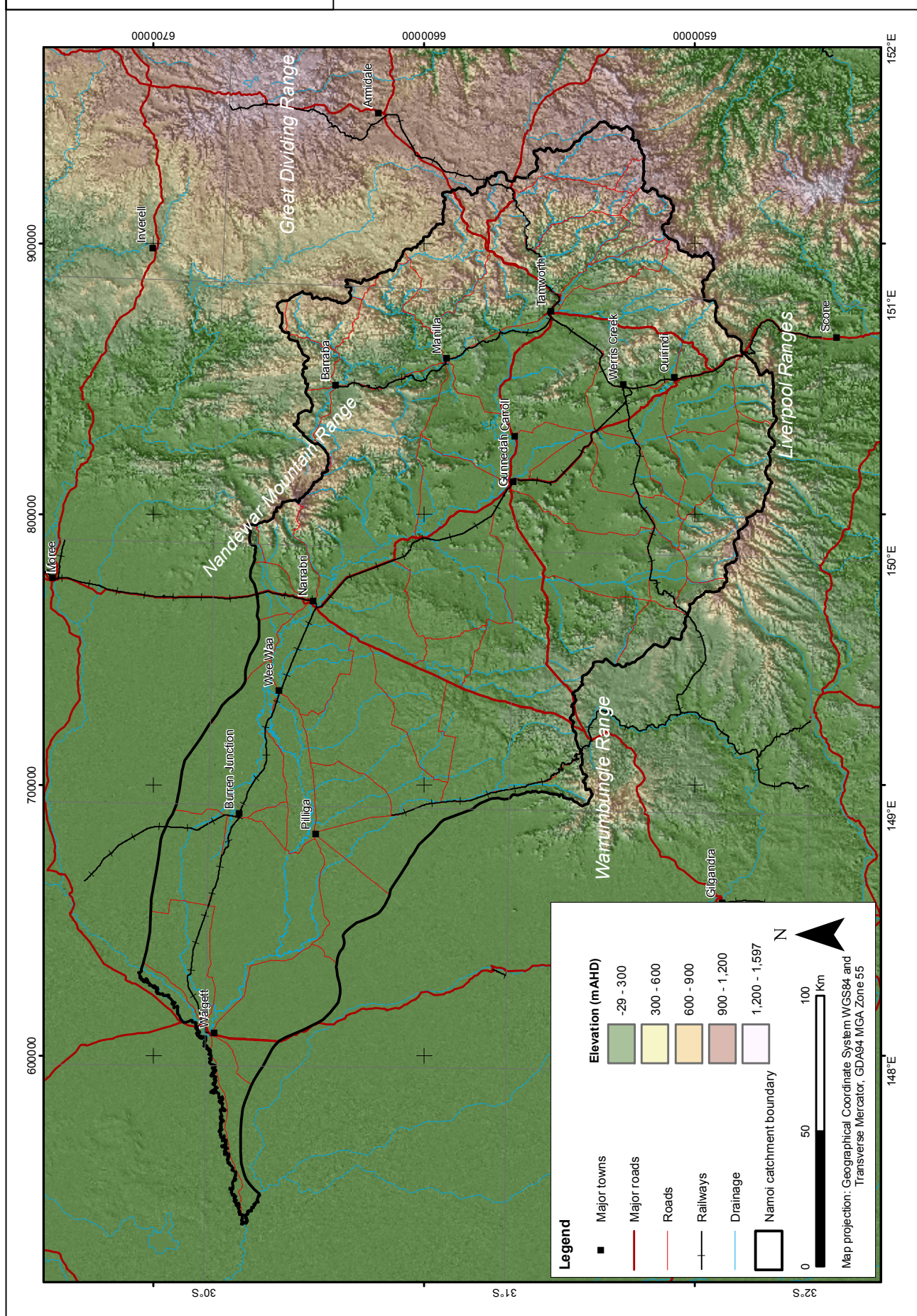
3.8 Summary

The physical character of the Namoi catchment can be summarised as follows:

- The catchment has three distinct topographic regions; the highlands and rolling hills to the east of the Hunter-Mooki Fault, a flatter central region with extensive alluvial plains bounded by low hills and constrained down gradient by Gin's Leap, and further to the west extensive and extremely flat flood plains until the Namoi River intersects with the Barwon River near Walgett.
- The catchment has a population of approximately 90,000 people with major urban centres of Tamworth, Gunnedah, Boggabri, Narrabri, Quirindi, Wee Waa and Walgett.
- The main industries are agriculture and coal mining. Agricultural interests are grazing and cropping with cotton, grain and cereals, orchards and forestry the major crops. Irrigation areas are extensive in the western catchment.

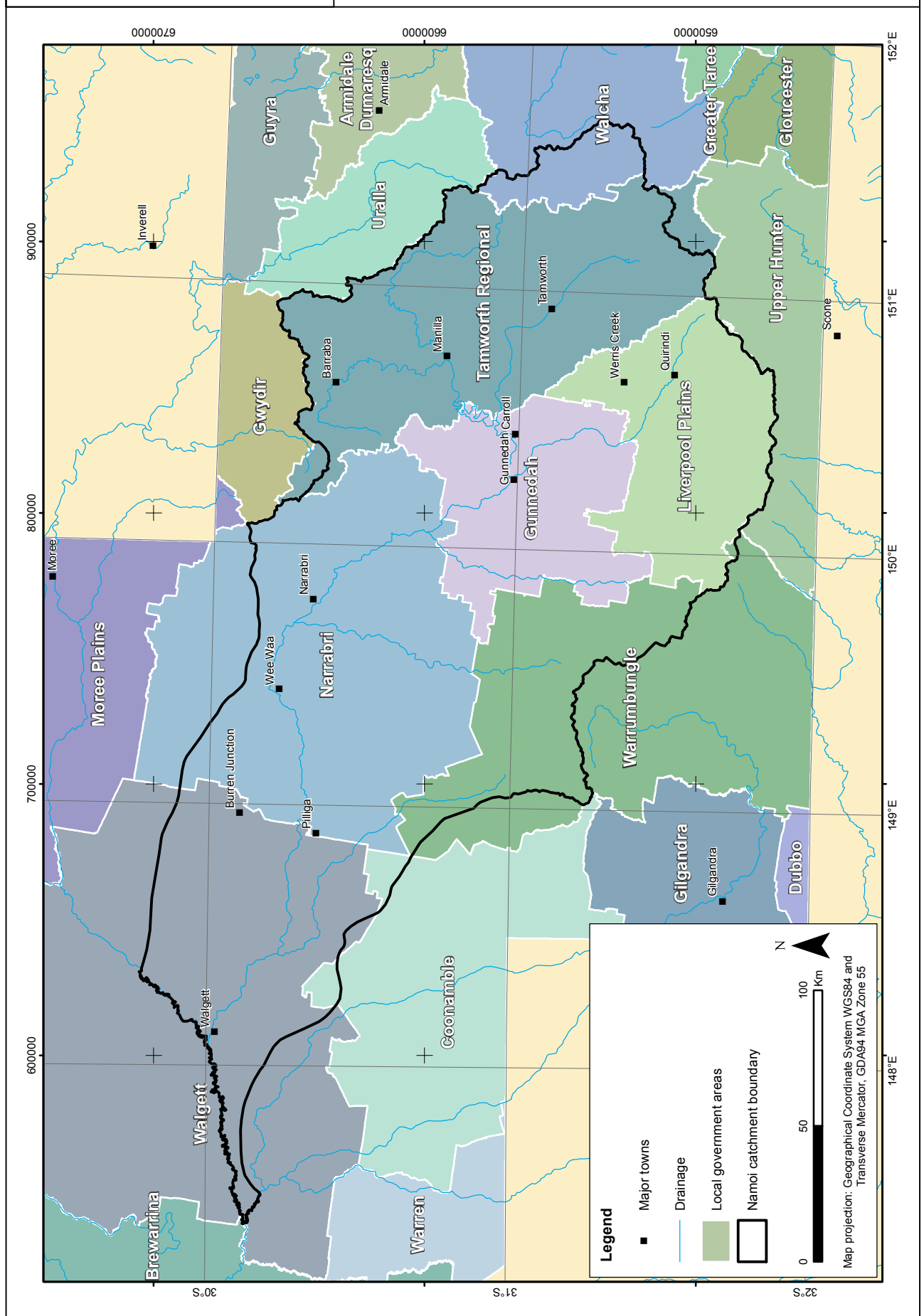
- The climate is characterised by summer dominated rainfall with warm summers and cool to mild winters. The average annual precipitation rate is between 1,300 mm/yr in the east and 480 mm/yr in the west with a catchment average of approximately 690 mm/yr.
- Extensive soils mapping has been undertaken within the catchment and has been used for the creation of land management units and capability classifications across the catchment. These combined with climate and land use data will form the basis for recharge modelling.

Figure 3.1 Topography of the Namoi catchment

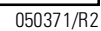


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Figure 3.2 Local government areas

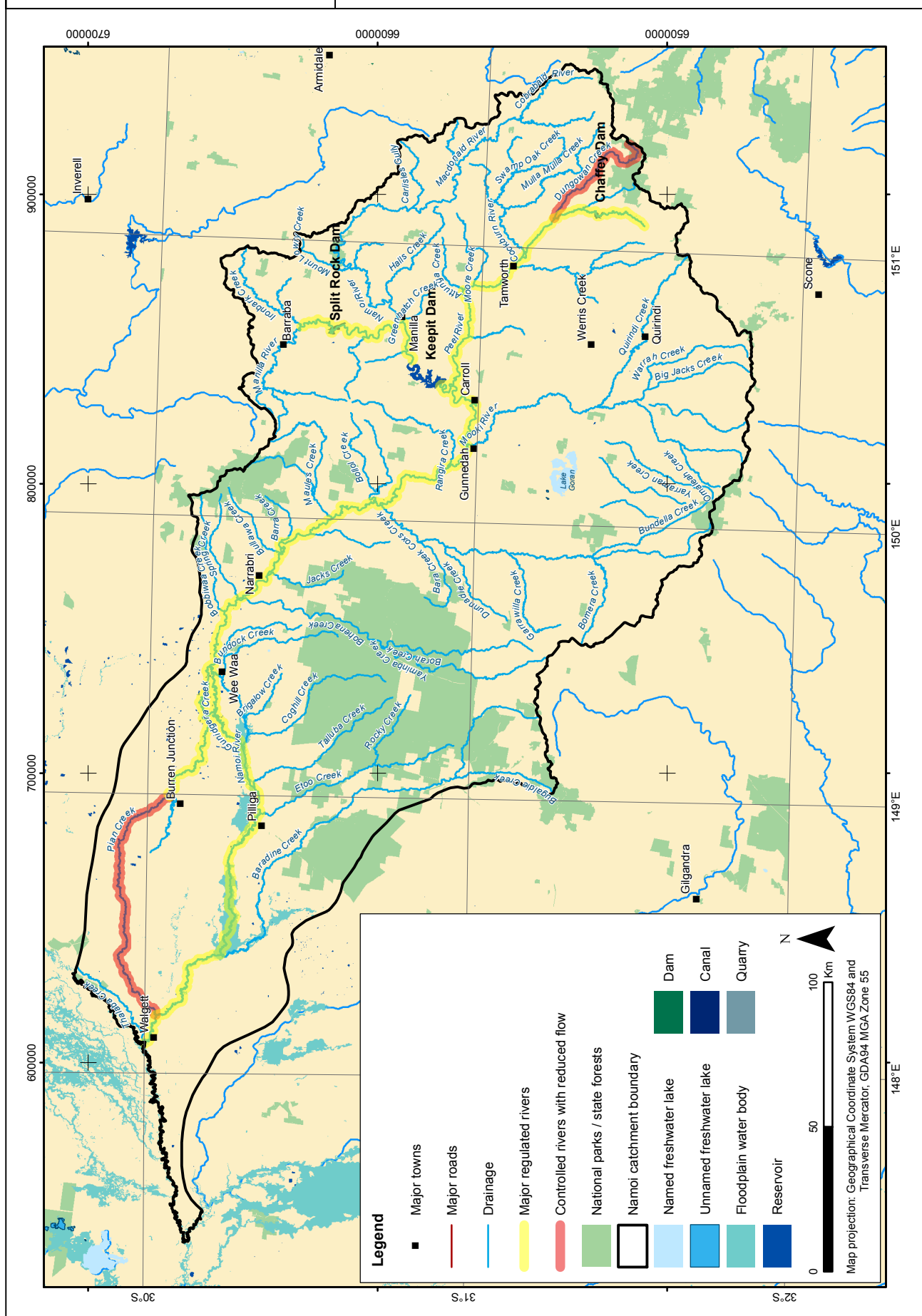


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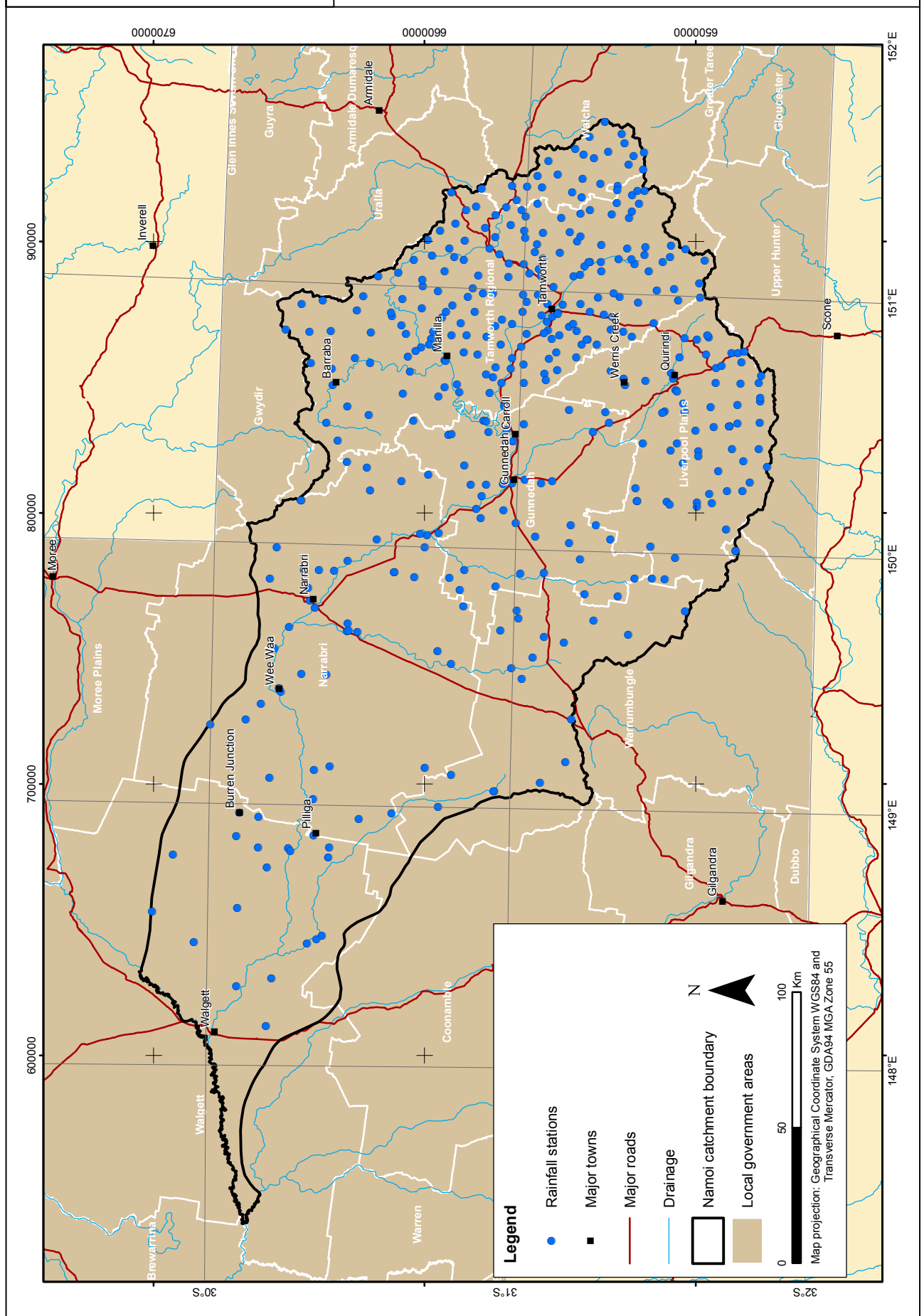
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Figure 3.4 Namoi river catchment



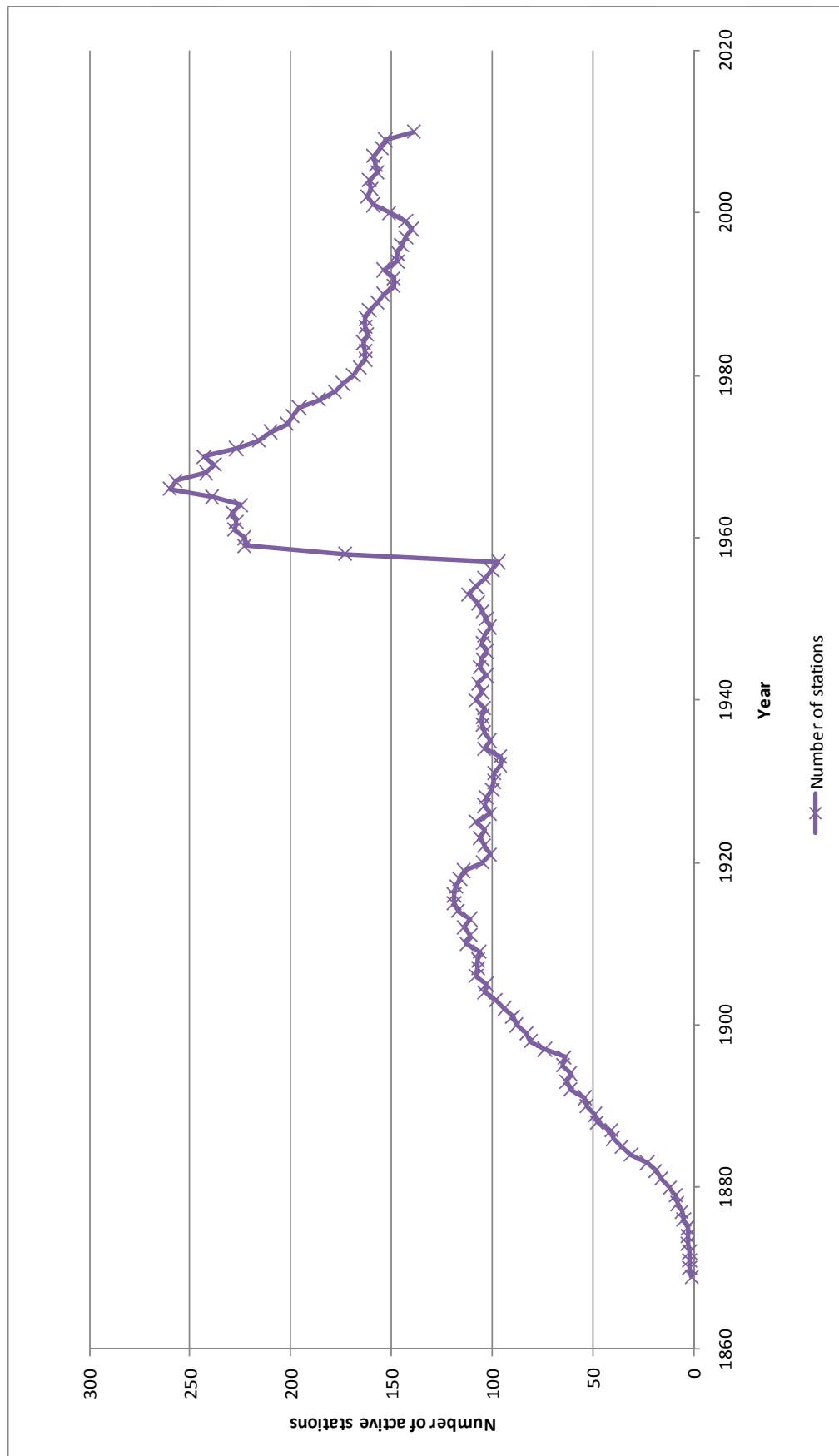
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Figure 3.5 Location of rainfall stations



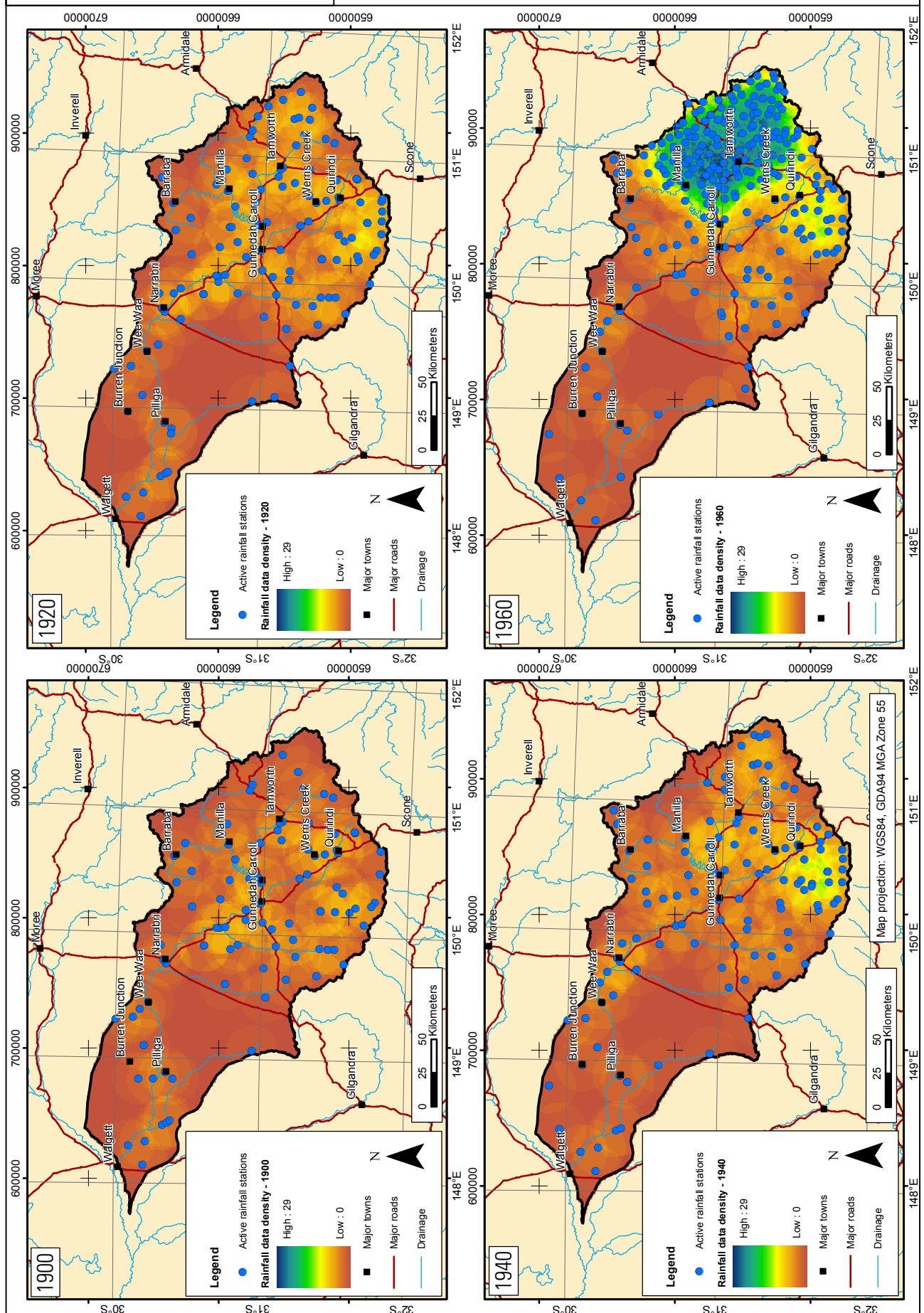
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Figure 3.6 Number of active rainfall stations over time



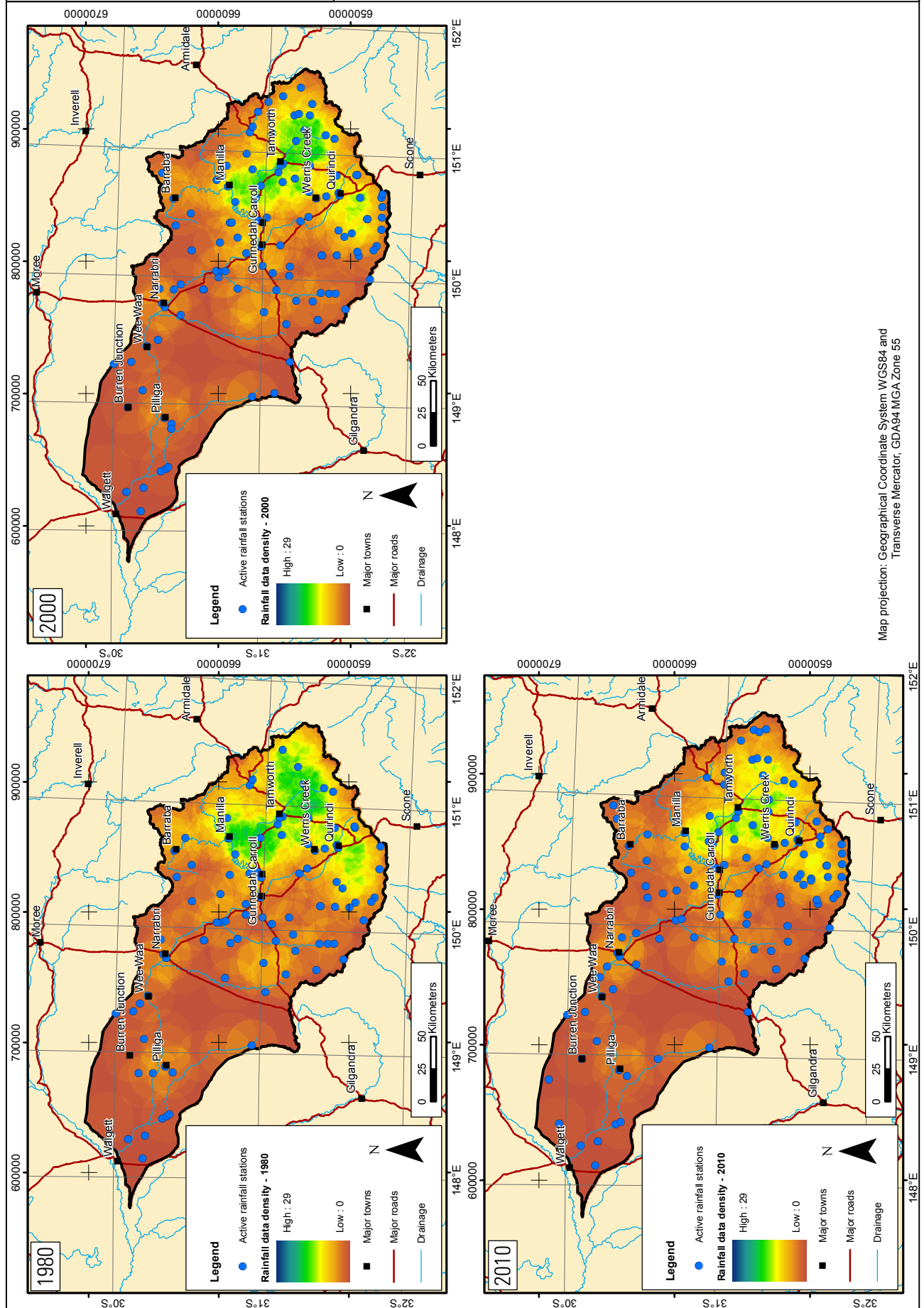
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Figure 3.7 Rainfall data density - 1900, 1920, 1940 and 1960



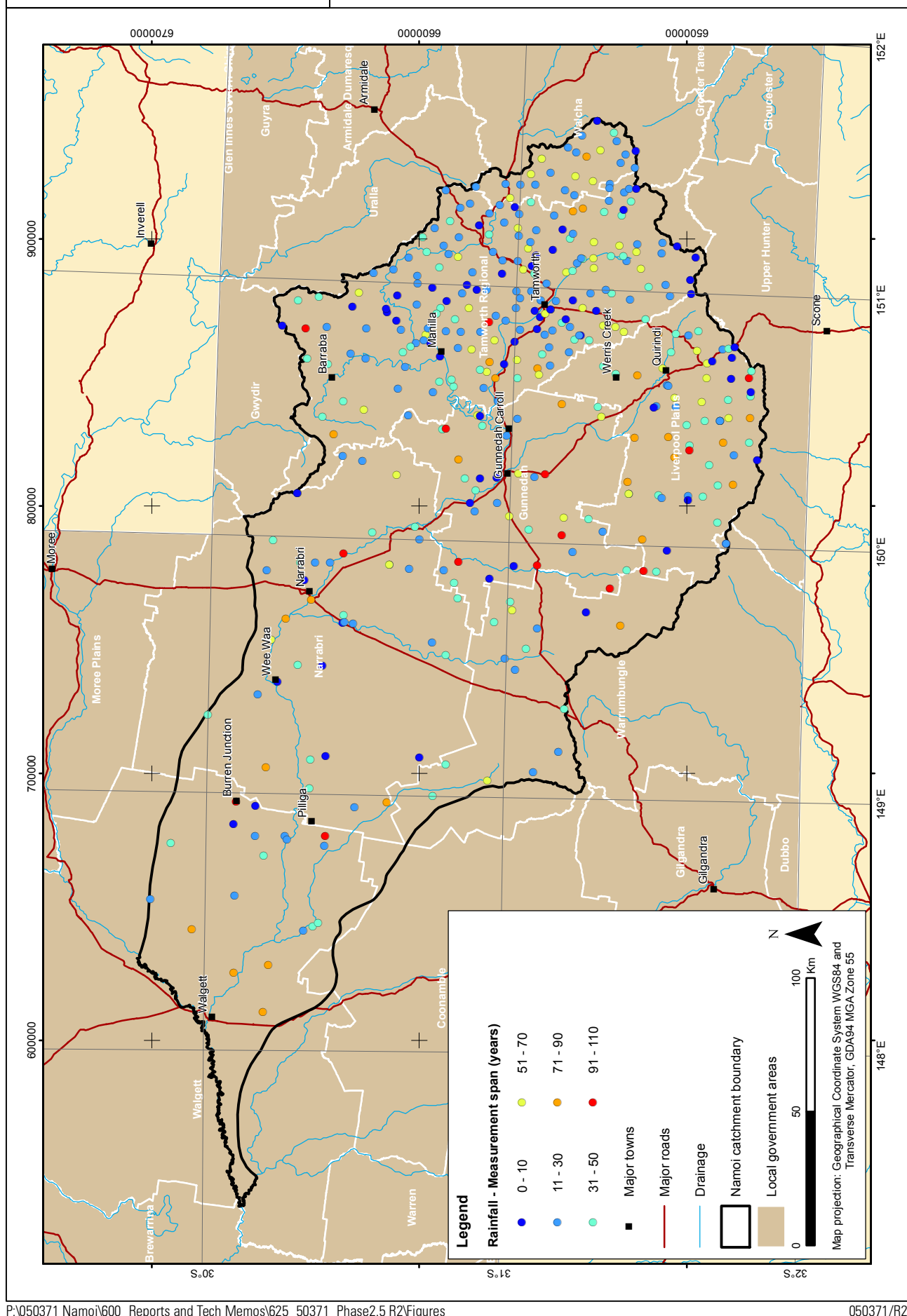
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Figure 3.8 Rainfall data density - 1980, 2000 and 2010



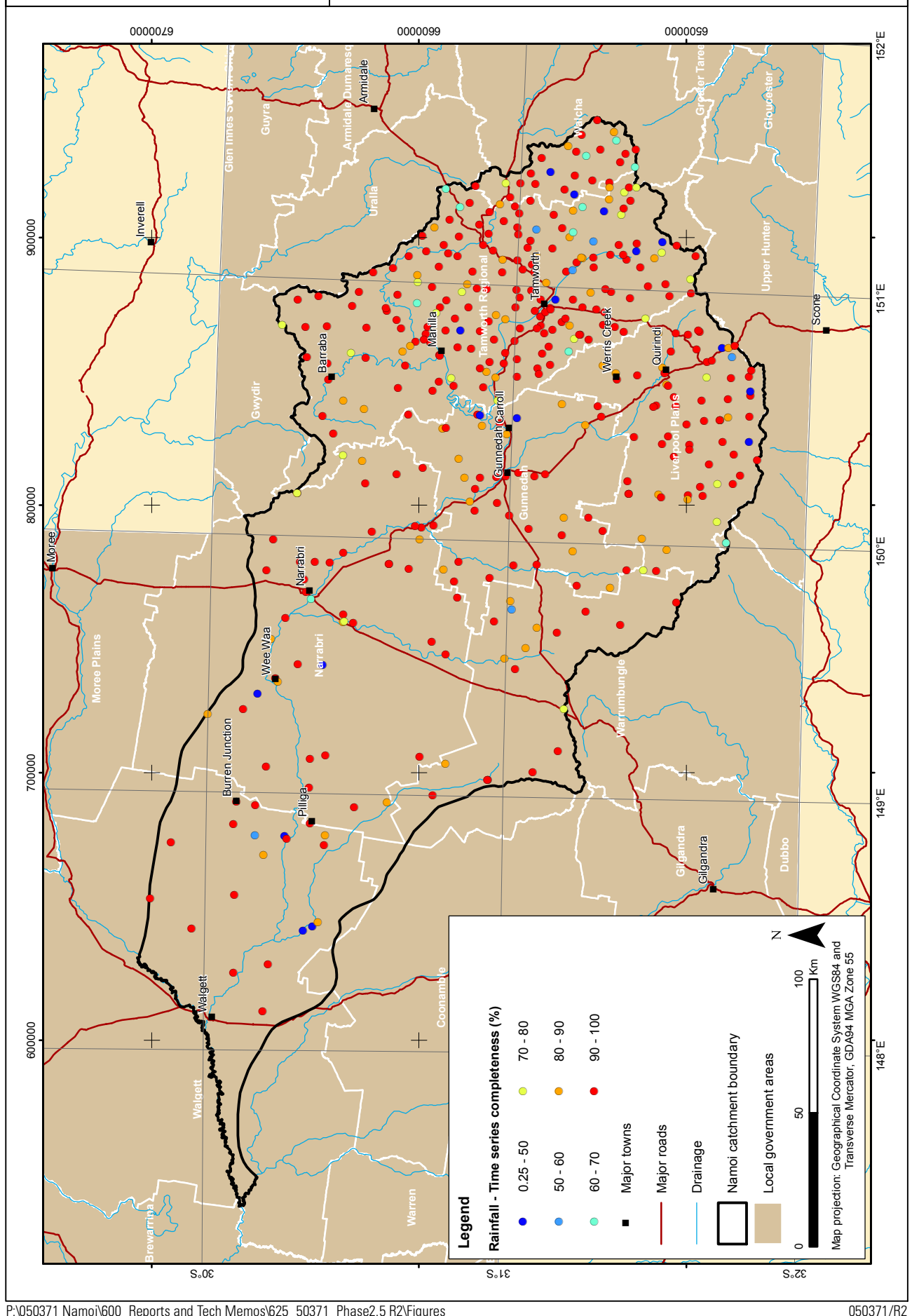
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Figure 3.9 Time series length for each rainfall station



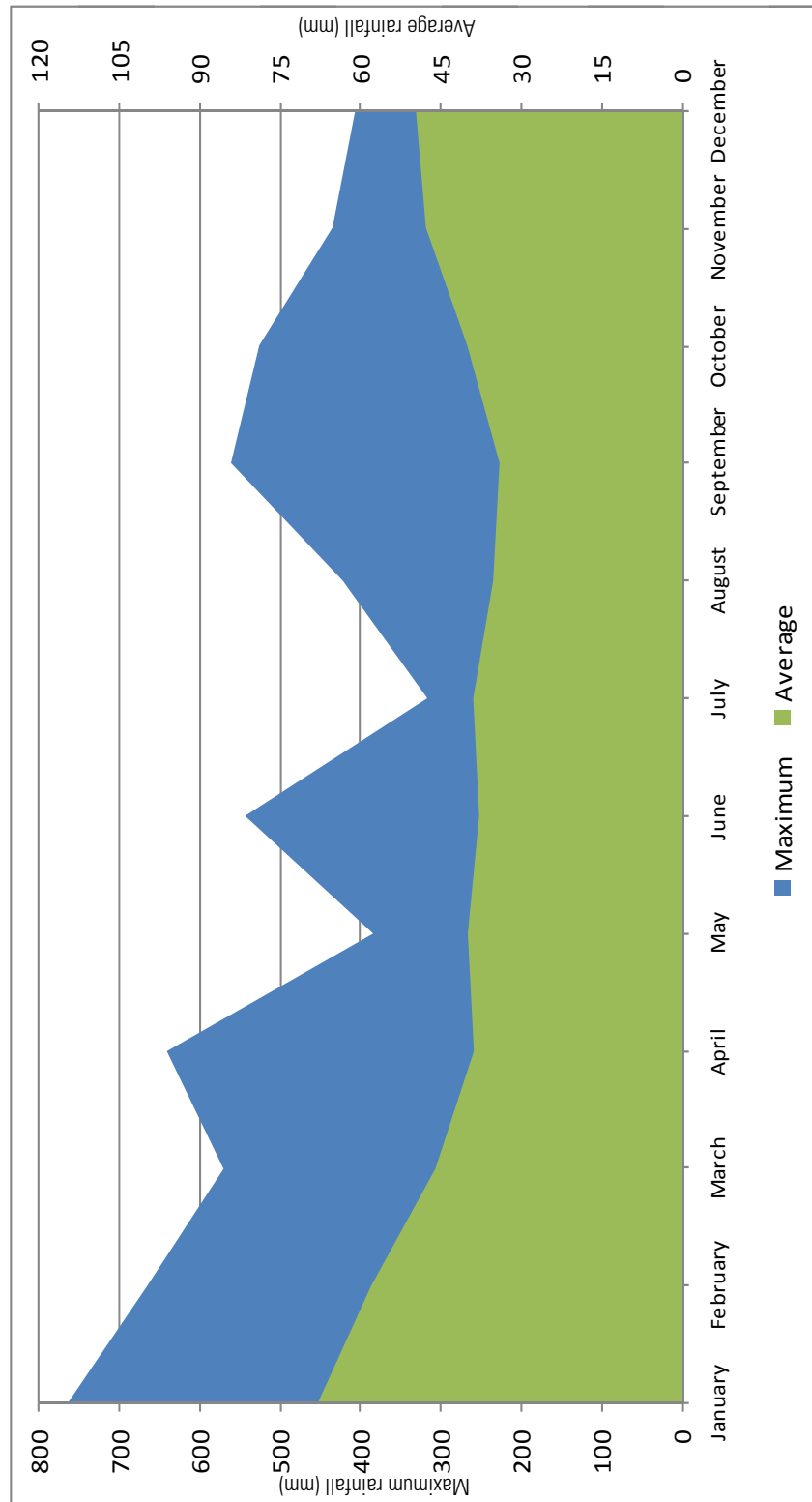
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Figure 3.10 Time series completeness for each rainfall station



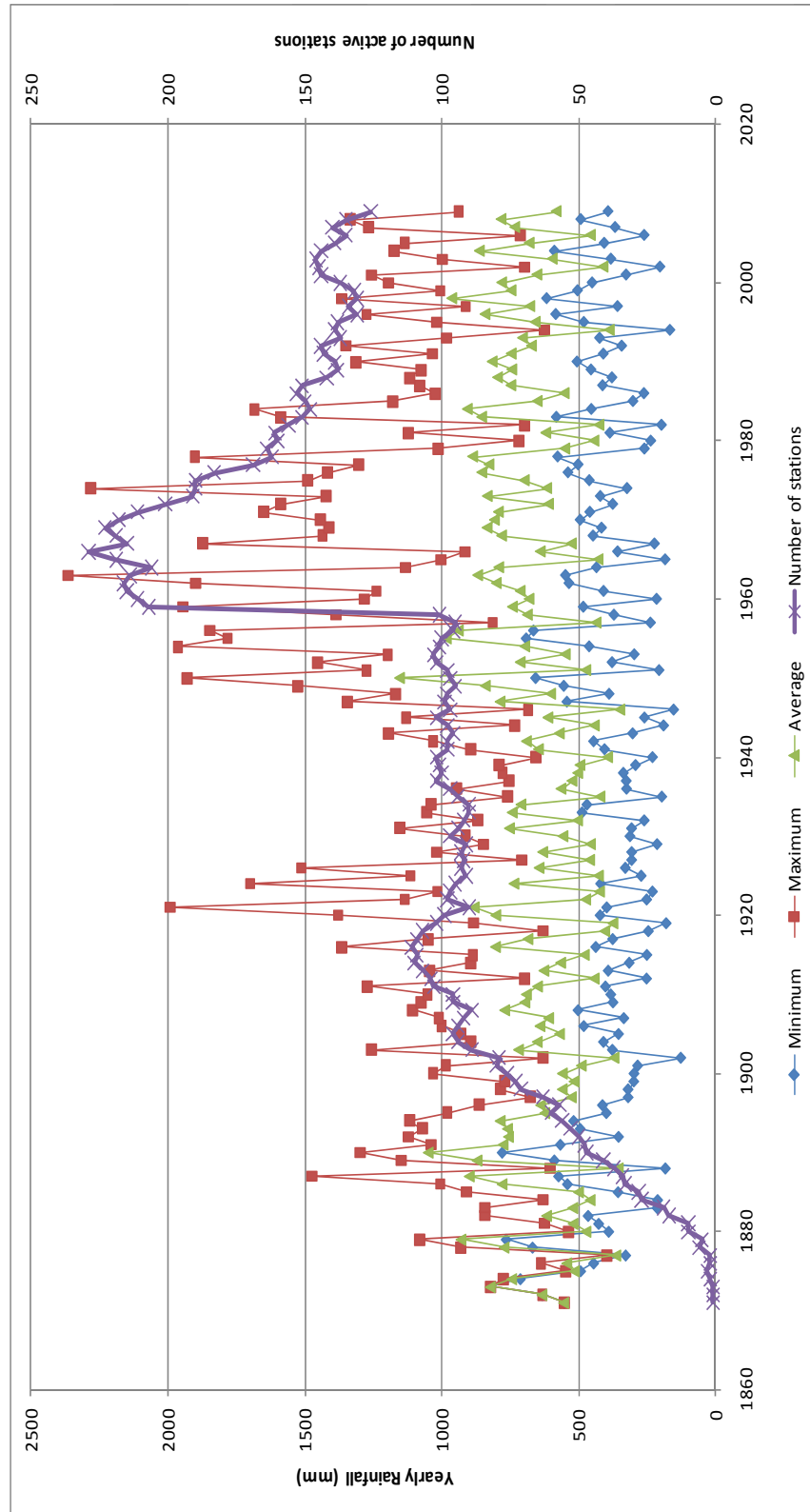
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Figure 3.11 Monthly rainfall statistics for the whole catchment



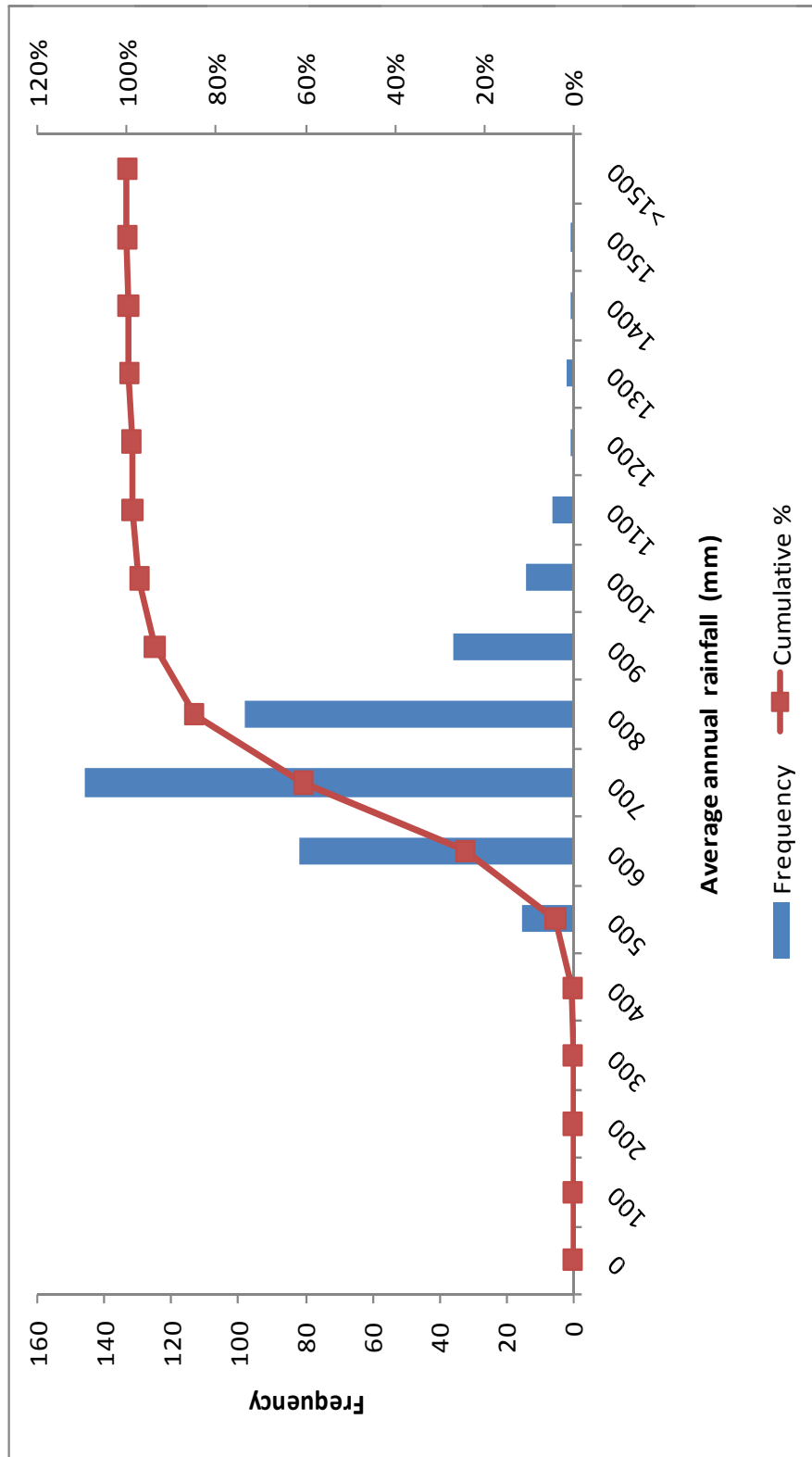
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Figure 3.12 Yearly rainfall statistics for the whole catchment



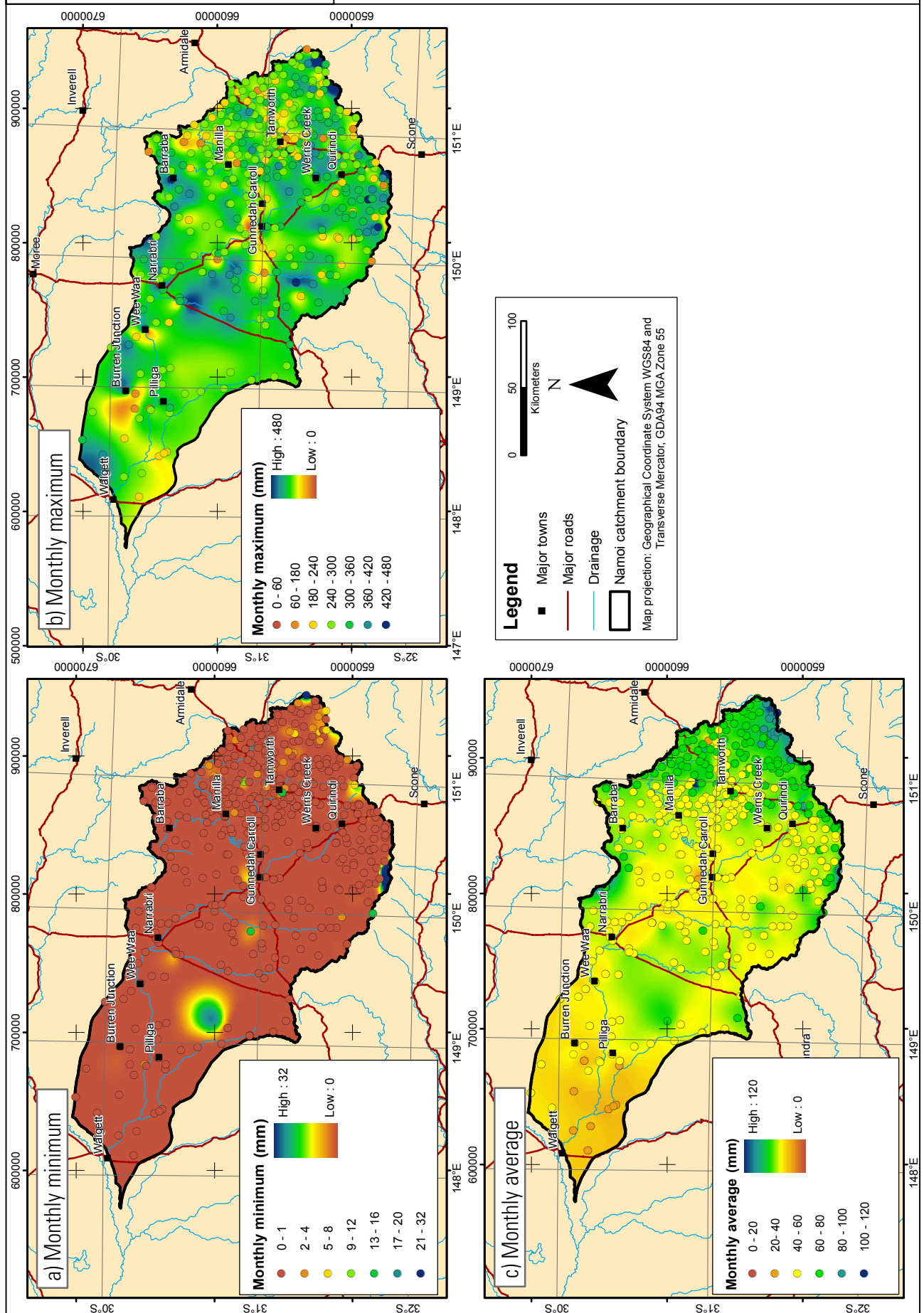
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Figure 3.13 Histogram of average annual rainfall



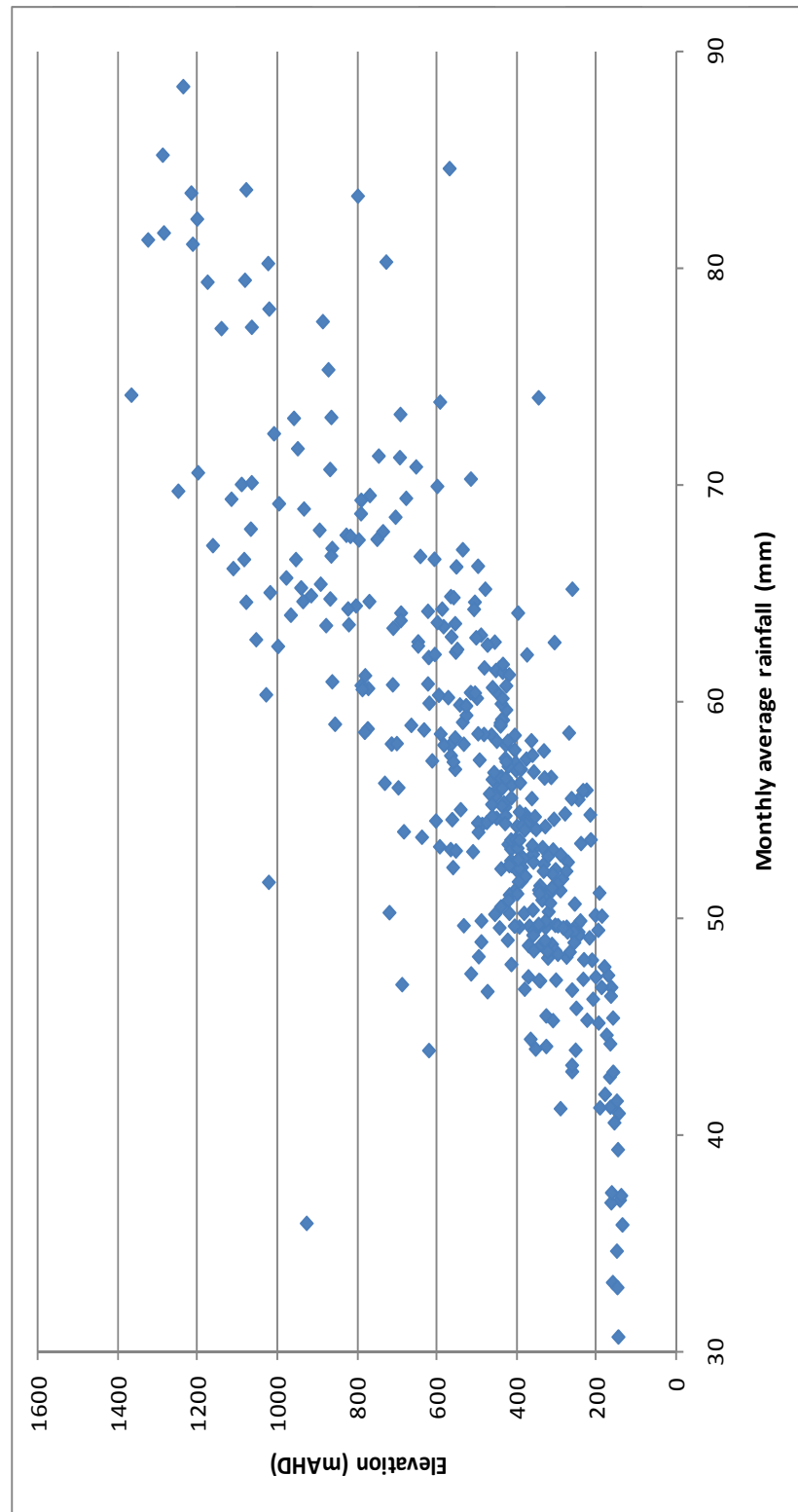
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Figure 3.14 Monthly rainfall distribution



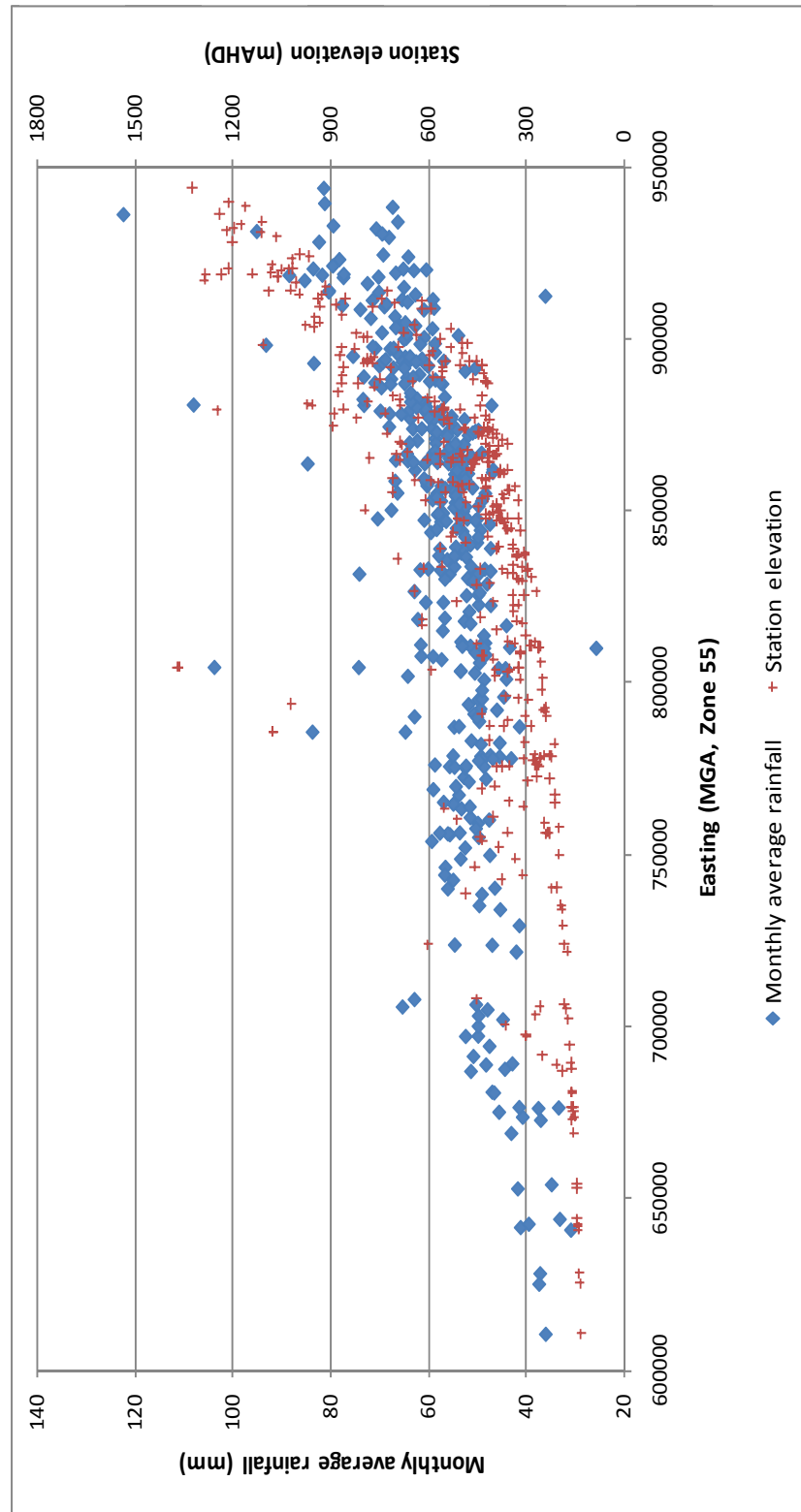
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Figure 3.15 Correlation between average monthly rainfall and elevation



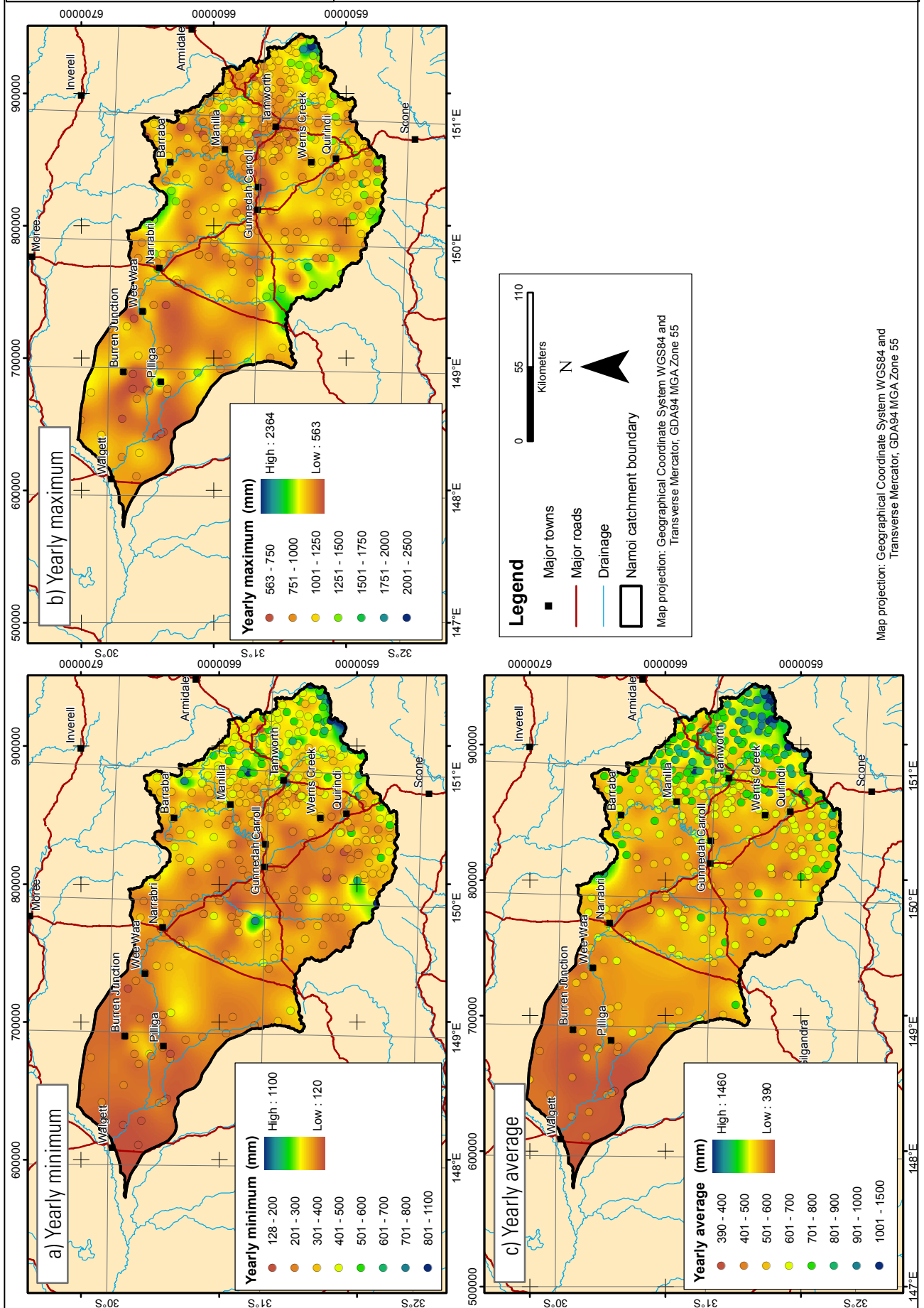
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Figure 3.16 Correlation between average monthly rainfall and longitude



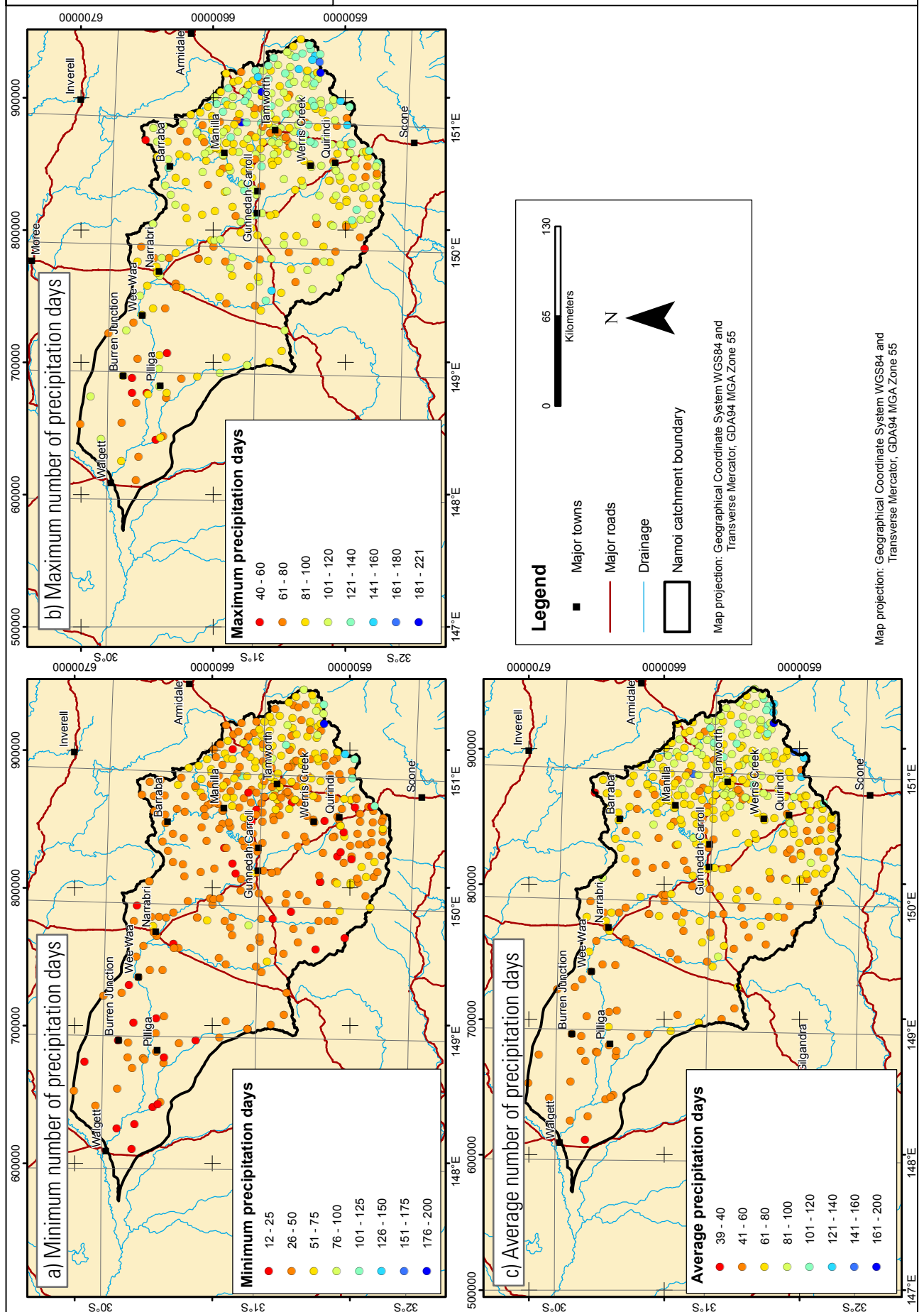
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Figure 3.17 Yearly rainfall distribution



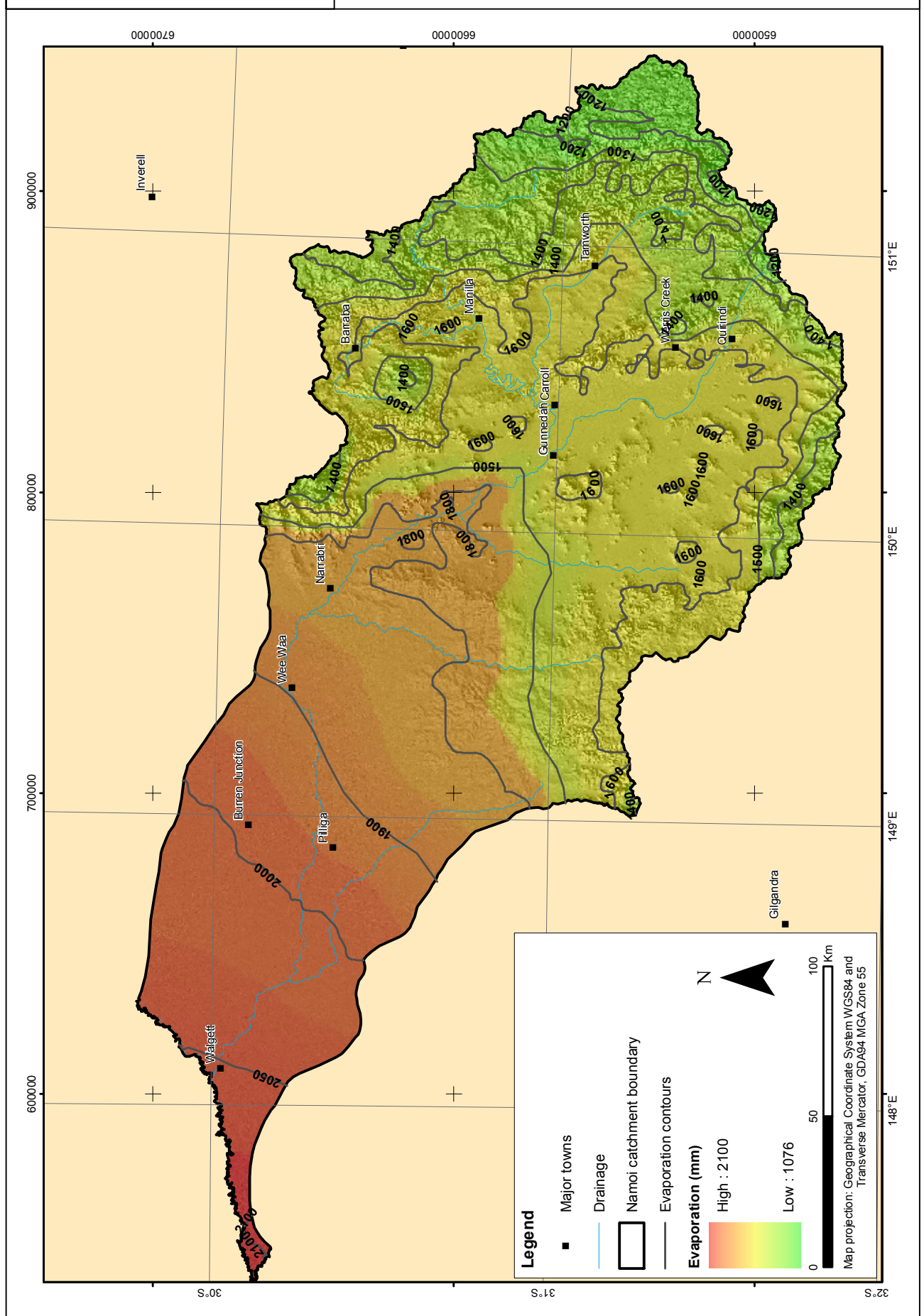
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Figure 3.18 Number of precipitation days per year within the catchment



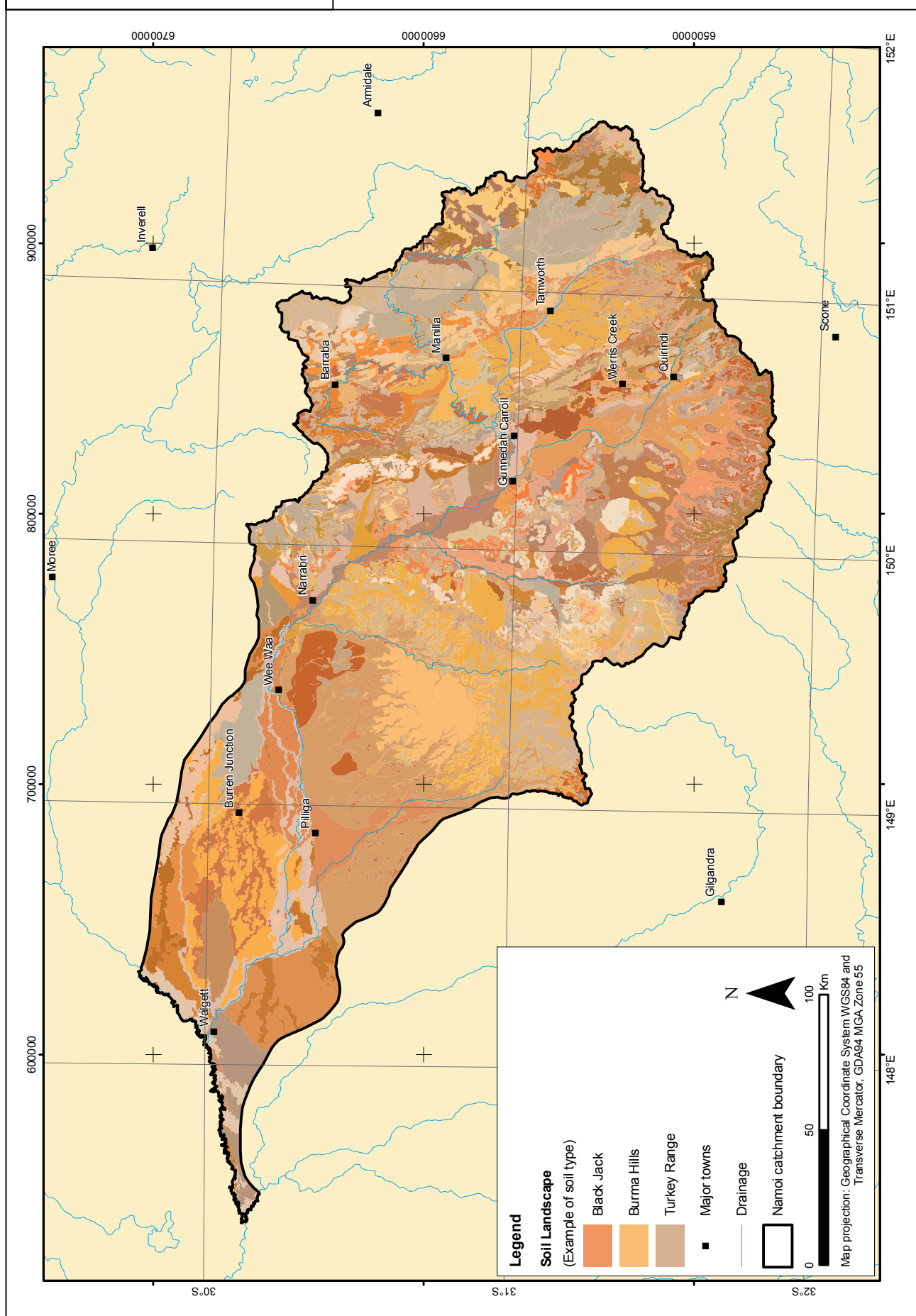
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Figure 3.19 Average annual evaporation



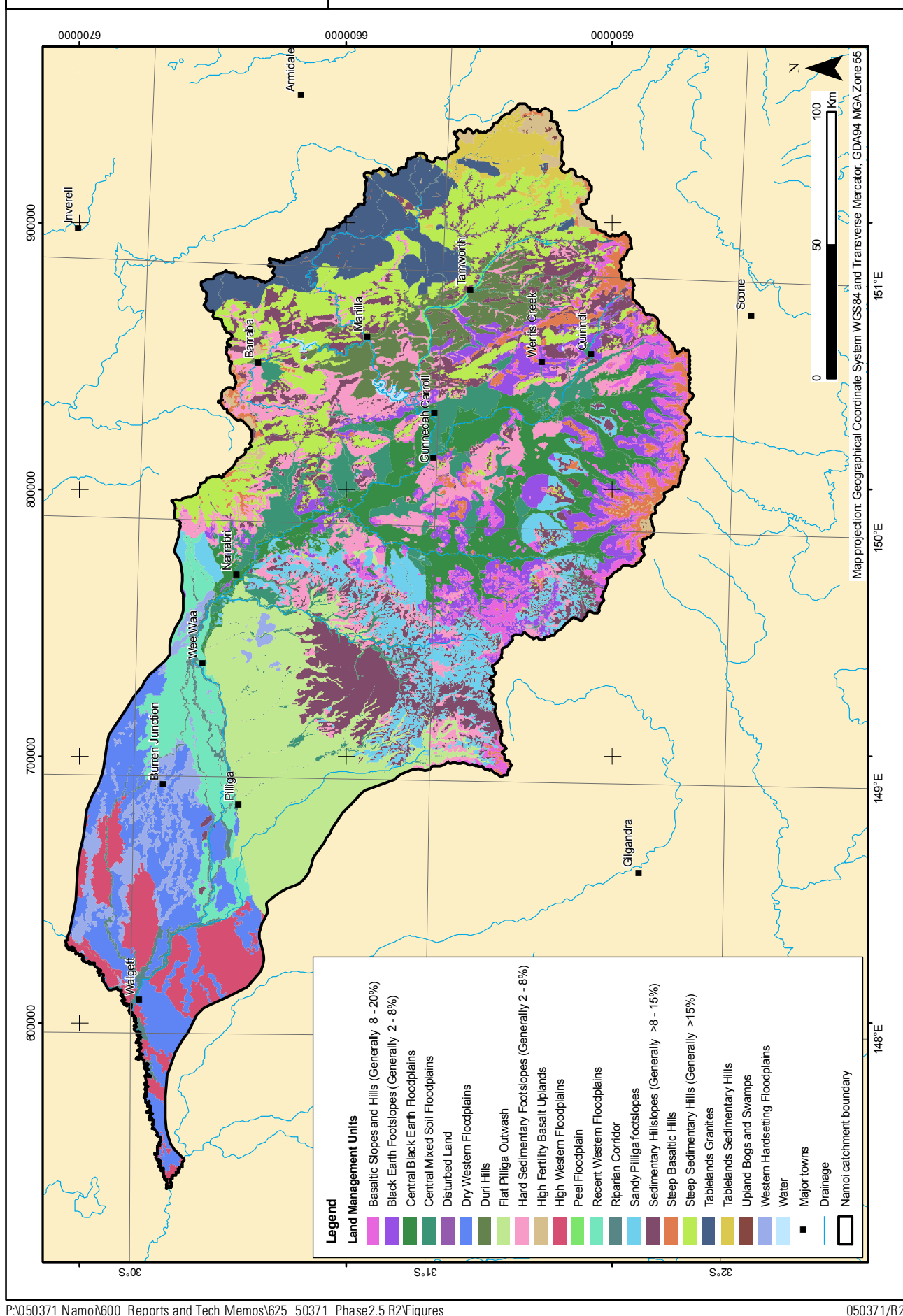
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Figure 3.20 Soil landscape

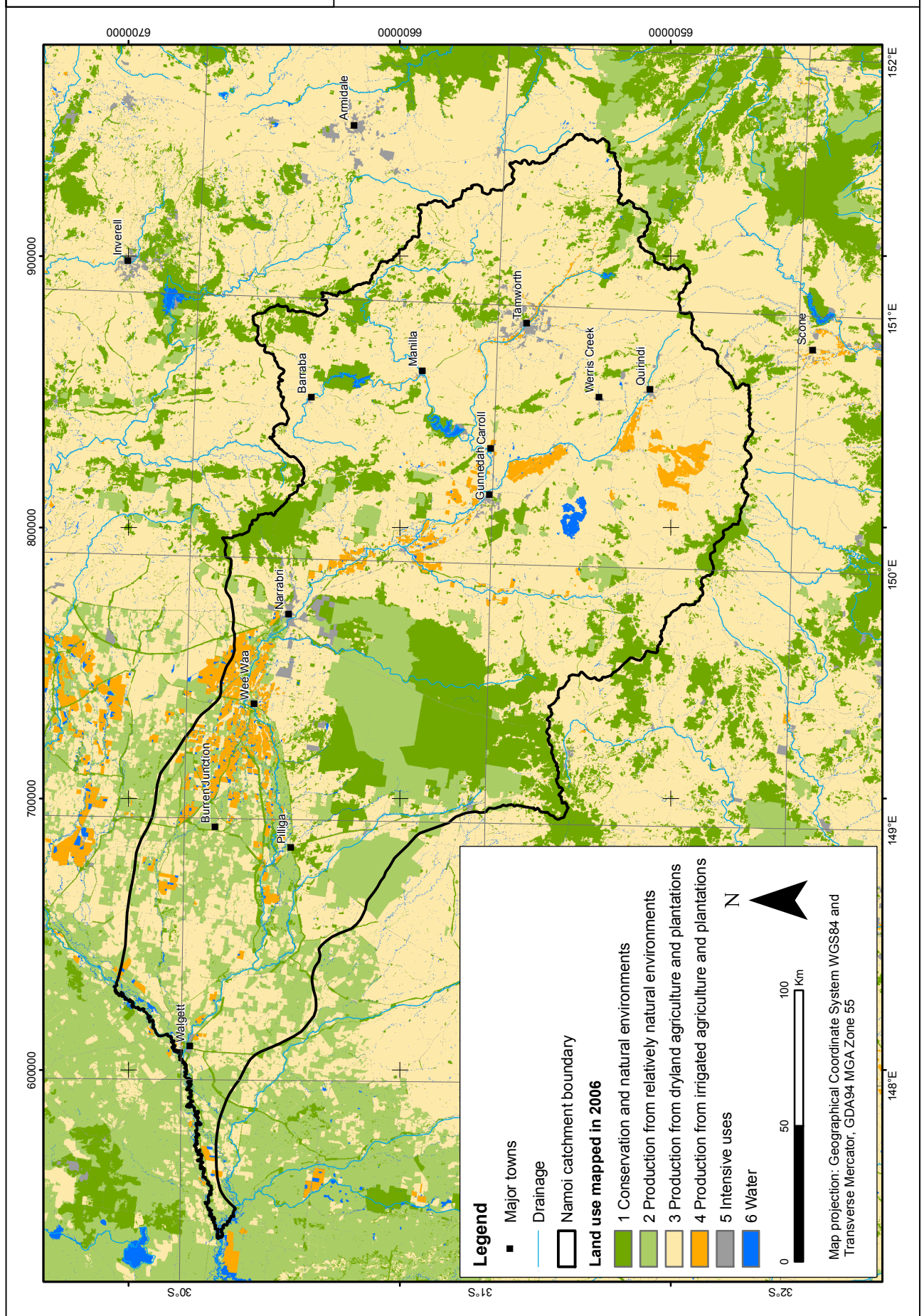


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Figure 3.21 Land management units

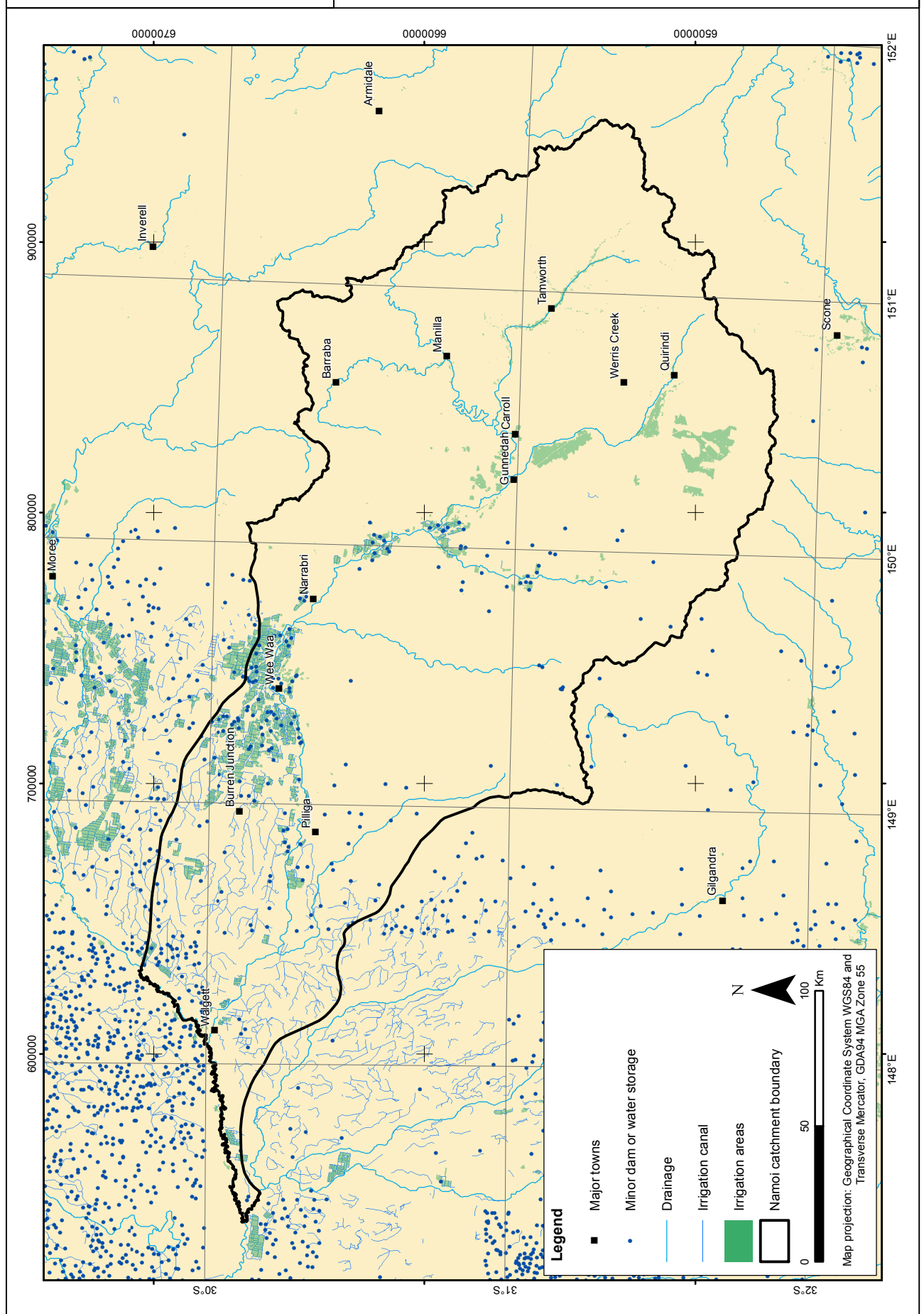


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Figure 3.23 Irrigation areas of the Namoi catchment



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4 REGIONAL GEOLOGY

4.1 Overview

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. Alluvial deposits of Neogene to Quaternary age are found associated with the stream systems of the Upper and Lower Namoi and form large outwash sequences in the Lower Namoi. A plan of the regional geology is presented in Figure 4.1, and major structural elements are provided as Figure 4.2.

4.2 New England Fold Belt

The Devonian to Carboniferous strata of the New England Fold Belt forms the eastern and southeastern margins of the catchment. The New England Fold Belt is a major geological province extending from the Newcastle area to Far North Queensland. It forms the eastern portion of the Tasman Orogenic system (Kingham, 1998).

According to the NSW Department of Mineral Resources (NSW DMR, 2002) the New England Fold Belt has had a complex structural history with the rocks undergoing a series of deformations involving large-scale faulting and folding from the Late Carboniferous to Triassic time. It is faulted against and thrust over the eastern part of the Sydney-Gunnedah-Bowen Basin along the Hunter-Mooki Fault system (NSW DMR, 2002).

In the Namoi region the New England Fold Belt can be subdivided in the two distinct sections; the Tamworth Belt to the west of the Peel fault system and the Tablelands Complex to the east (Kingham, 1998 after Korsch and Harrington, 1981).

The Tamworth Belt contains sedimentary rocks of Cambrian to Early Permian age that were deposited in a forearc basin (Leitch et al., 1988). By comparison, the rocks of the Tablelands Complex have been subjected to low to medium grade regional metamorphism during at least four regional deformations that took place during the late Palaeozoic (Leitch et al., 1988).

The Tablelands Complex was intruded by granite plutons during the Permian and Triassic and is partly covered by the extensive late Permian Emmaville Volcanics and less extensive Tertiary volcanics (Gilligan and Brownlow, 1987).

4.3 Gunnedah Basin

4.3.1 Introduction

The Gunnedah Basin is located in the centre of the catchment, and is considered a part of the Bowen–Gunnedah–Sydney Basin complex. It contains a sequence of marine and non-marine Permian and Triassic sediments and is an important Permian coal bearing basin (Tadros, 1993).

The Sydney-Gunnedah-Bowen Basin is a long composite structural basin separating and bounded by basement highs, the New England Fold Belt in the east and the older Lachlan Fold Belt (continental craton) in the west (Tadros, 1993). The basin sediment is asymmetric in nature and is thickest in the east along the Mooki-Goondiwindi Faults in the Taroom Trough of the Bowen Basin and along the east dipping Hunter-Mooki Fault System in the south (Tadros, 1993). The eastern extent of the basin is basically undefined being over thrust by the New England Fold Belt (Tadros, 1993). The basin sediments thin to the west as it onlaps onto the Lachlan Fold Belt (Tadros, 1993).

The Gunnedah Basin is separated from the New England Fold Belt by the Hunter-Mooki Thrust. In the south the boundary between the Gunnedah Basin and the Sydney Basin is argued as being either the Mount Coricudgy Anticline or the Liverpool Range (NSW DPI, 2011a).

Tadros (1993) describes the Gunnedah Basin as containing up to 1,200 metres of marine and non-marine Permian and Triassic sediments resting unconformably over Early Permian and possibly Late Carboniferous silicic and mafic volcanics, which form the basement to the east of Rocky Glen Ridge. Metavolcanics, metasediments and minor ignimbritic volcanics of the Lachlan Fold Belt form the majority of the basement to the western part of the Gunnedah Basin (Rocky Glen Ridge and Gilgandra Sub-basin) (Tadros, 1993). In the east, the silicic and mafic basement volcanics outcrop to form the eastern basin extent as the Boggabri Ridge, prominent between Gunnedah and Narrabri (Tadros, 1993).

Basin extension and subsequent subsidence initiated deposition in the Gunnedah Basin during the early Permian, commencing with the fluvial Maules Creek Formation containing numerous coal seams (Tadros, 1993). This formation is conformably overlain by the Late Permian marine shelf sediments of the Porcupine Formation and the regressive marine Watermark Formation (Tadros, 1993). A second coal sequence, the Black Jack Group, was deposited in a deltaic and fluvial environment in the Late Permian (Tadros, 1993).

The Gunnedah Basin sequence includes a number of basic intrusions of Mesozoic and Tertiary rocks (Tadros, 1993). These are associated with massive extrusions of the Garrawilla Volcanic complex and the Liverpool, Warrumbungle and Nandewar Ranges (Tadros, 1993).

To the north of the Liverpool Range the Jurassic Sediments of the Surat Basin unconformably overlie the Gunnedah Basin sediments. The Gunnedah Basin sequence outcrops as a narrow north-northwest trending zone from the south of Quirindi to the north of Narrabri (Figure 4.1) (Tadros, 1993).

Tadros (1993) notes that the structural highs within the Late Carboniferous to Early Permian volcanic units which form the effective basement for the Gunnedah Basin outline three north-northwesterly orientated sub-basins (Figure 4.2). The Boggabri Ridge in the east separates the Maules Creek Sub-basin from the Mullaley Sub-basin which is further separated from the western Gilgandra Sub-basin by the Rocky Glen Ridge (Tadros, 1993). Tadros (1993) after Russell (1981) and Hill (1986) suggest that the Boggabri Ridge is continuous in the subsurface between outcrops extending from the southeast of Bellata to the south through the Deriah Forest area to Baan Baa and through Boggabri to southeast of Gunnedah where it is truncated by the Mooki Fault system. It is thought probable that the ridge extends to the north past Moree (Tadros, 1993).

The Rocky Glen Ridge is located in the Coonabarabran area as a subcrop of Ordovician–Carboniferous metasediments, Carboniferous granites and volcanics (Tadros, 1993). Silicic volcanics consisting of ignimbrite and ashfall tuff, which correlate to the Boggabri Volcanics, form the eastern flank (Tadros, 1993).

The Maules Creek Sub-basin (a remnant basin) is bound by the Hunter-Mooki Fault System, to the east, and the Boggabri Ridge, to the west (Tadros, 1993). However the New England Fold Belt is now thrust over the eastern margin of the basin (Tadros, 1993). The basin thickens rapidly in the east and northeast to over 800 m thick against the Mooki Thrust in the northeast (Tadros, 1993). It unconformably overlies the basement rocks of the Boggabri Volcanics, or the Leard Formation and Goonbri Formation where present (Tadros, 1993). The Maules Creek Sub-basin contains coal seams, and sedimentary and volcanic rocks of mainly Early Permian age (Tadros, 1993). Large areas of the sub-basin are covered by recent alluvial deposits, mainly constrained to the central and eastern extents (Figure 4.1) (Tadros, 1993).

The Mullaley Sub-basin extends the entire length of the Gunnedah Basin, from Moree in the north, to the Mount Coricudgy Anticline in the south (Tadros, 1993). It is divided by prominent transverse highs including the Walla Walla and Narrabri Highs (Tadros, 1993). The most important troughs lie within the Pilliga region and include the north-northwesterly orientated Bellata, Bohena and Bando Troughs (Tadros, 1993).

The area to the west of the Rocky Glen Ridge has been defined by Tadros (1993) after Yoo (1988) as the Gilgandra Sub-basin. Consisting of Permian to Triassic sediments extending westward to the Mount Forster Structural Zone and northward to the Cobar–Inglewood Kink Zone the Gilgandra Basin is divided by a transverse basement high forming northern and southern troughs (Tadros, 1993).

The Mount Coricudgy Anticline is described by Tadros (1993) as a major transfer fault showing large movement between basin compartments. The spine of the anticline runs from the south of Rylstone to Muswellbrook and forms the structural boundary between the Sydney and Gunnedah Basins (Tadros, 1993).

4.3.2 *Gunnedah Basin units*

The Permian section of the Gunnedah Basin consists of the Upper and Lower Coal Measures (Black Jack and Maules Creek Formations respectively), separated by the marine sediments of the Porcupine and Watermark Formations and underlain by the basal Goonbri and Leard Formations (Tadros, 1993). The stratigraphic section for the Gunnedah Basin and the overlying Surat Basin is presented in Figure 4.3 (Tadros, 1993). A generalised geological cross section is presented as Figure 4.4.

Goonbri and Leard Formations

The Goonbri and Leard Formations forming the basal units of the Gunnedah Basin receive little attention from Tadros (1993). They unconformably overlie the regional volcanic basement and consist of colluvial and lacustrine sediments, pelletaloid claystone and organic rich sequences of claystone to sandstone (Geoscience Australia, 2011). These Formations are absent in some areas within the catchment (Geoscience Australia, 2011).

Maules Creek Formation

Tadros (1993) reports the Maules Creek Formation as up to 800 metres thick and consisting of lithic granule to pebble conglomerate, lithic and quartzose sandstone, siltstone, and claystone. The formation is described as containing numerous coal seams, some up to 8 metres thick and forming a minable resource amenable to open-cut or underground extraction. The coals are characterised as low ash, high energy, high volatile coal with low phosphorous suitable as thermal and soft coking coals (Tadros, 1993).

Porcupine and Watermark Formations

A Late Permian marine sequence, consisting of the Porcupine and Watermark Formations, conformably overlies the lower coal measures of the Maules Creek Formation. The upper part of the Watermark Formation consists of prodelta and delta front sediments, forming the foundation for the major deltaic deposits in the lower part of the overlying Black Jack Group (Tadros, 1993).

Black Jack Group

The Black Jack Group is described by Tadros (1993) as Late Permian coal measures outcropping in a narrow north-northwest trending line of hills extending from Breeza in the southeast to Boggabri in the north. Tadros (1993) describes the Black Jack Group as deltaic and fluvial deposits of up to 470 metres thick and consisting of lithic conglomerate and sandstone, quartzose sandstone, siltstone, claystone, tuff and numerous coal seams. The Black Jack Group consists of three subgroups; the Brothers, Coogal and Nea subgroups (Geoscience Australia, 2011).

The Brothers Subgroup contains the Arkarula, Brigalow and Pamboola Formations collectively described as consisting of fining-up sequences of fine-medium grained quartzose and lithic sandstone, siltstone and conglomerate (Geoscience Australia, 2011). Significantly, the Pamboola Formation contains the Melvilles coal seam with reported maximum thickness of five metres (Geoscience Australia, 2011).

The Coogal Subgroup is described as containing sandstone and coal consists of the Benelabri Formation, the Clare Sandstone and Hoskissons seam (Golder Associates, 2010). The Clare Sandstone, immediately overlying the Hoskissons seam, has potential as a groundwater resource but water quality may prove an issue due to interbedded coals (Golder Associates, 2010). The Breeza seam represents a significant coal resource within the Clare Sandstone (Golder Associates, 2010).

Overlying the Clare Sandstone is the Wallala Formation of the Nea Subgroup which consists of claystone, siltstone, fine-grained sandstone, tuff, carbonaceous claystone and tuffaceous stony coal (Geoscience Australia, 2011). The Wallala Formation is in turn overlain by the Trinkey Formation which forms the upper unit of the both the Nea Subgroup and the Black Jack Group as a whole (Geoscience Australia, 2011). Geoscience Australia (2011) reports the Trinkey Formation as consisting of a fining-upwards sequence of lithic conglomerate, sandstone, siltstone, claystone, coal; minor tuff and tuffaceous sediments.

The Hoskissons, Melvilles, and Breeza coal seams are the most significant seams (Tadros, 1993). They contain medium to high ash thermal coals (Tadros, 1993). Tadros (1993) reports that small quantities of low ash, low phosphorous, soft coking coal are produced from two small collieries near Gunnedah for blending. These are believed to be the now closed Gunnedah and Preston collieries.

The Triassic section of the Gunnedah Basin sequence, consisting of the Digby, Napperby and Deriah Formations, unconformably overlies the Black Jack Group over much of the basin except on the eastern and western margins where it overlies the regional basement rocks (Geoscience Australia, 2011).

The Digby Formation

The Digby Formation consists of a lower part of lithic conglomerate known as the Bomera Conglomerate Member and an upper part comprising the overlying Ulinda Sandstone Member, itself consisting of a lower part of lithic and quartz lithic sandstones and an upper part of quartzose sandstone (Geoscience Australia, 2011). The sequence is generally capped by a palaeosol horizon. (Tadros, 1993). The Ulinda Sandstone Member is noted as a potential to poor regional aquifer (Golder Associates, 2010).

The Napperby Formation

Tadros (1993) reports the Napperby Formation as consisting of an upward coarsening sequence of dark grey claystone, interbedded siltstone and sandstone with common bioturbation and medium to coarse sandstone. The Napperby Formation forms the uppermost unit in the Gunnedah Basin Sequence except where the Deriah Formation exists, and is marked by a regional unconformity between the Triassic and Jurassic sediments (Golder Associates, 2010). The Napperby Formation is considered to be an inconsistent aquifer with reportedly low yields (Golder Associates, 2010).

The Deriah Formation

The Deriah Formation is noted by Tadros (1993) as the upper limit of the Gunnedah Basin in the northern areas. The Deriah Formation consists of green lithic sandstone rich in volcanic fragments and mudclasts (Tadros, 1993).

Igneous intrusions and flows

Many areas of the Gunnedah Basin contain basic intrusion of Mesozoic and Tertiary rocks associated with the massive extrusions of the Garrawilla Volcanics complex and the Liverpool, Warrumbungle and Nandewar Ranges in the central, south, southwest and northeast respectively (Tadros, 1993). Mesozoic phonolite intrusions and Tertiary igneous rocks consisting of basalt and dolerite plugs, sills, and diatremes, also occur in the southwestern part of the basin (Tadros, 1993 after Yoo, 1991).

4.3.3 Coal resources of the Gunnedah Basin

Significant coal resources are present within the Maules Creek and Mullaley Sub-basins within the Gunnedah Basin (Tadros, 1993). Coal mining has been undertaken in the basin since the 1890's and continues today (Tadros, 1993). Major coal deposits are found within the Maules Creek Formation and the Black Jack Group (Tadros, 1993).

Both the Maules Creek Formation and the Black Jack Group contain coal seams that are prospective for coal mining and coal seam gas (NSW DPI, 2011a). These units contain numerous coal seams with exceptionally thick seams and net coal thickness reaching 50-60 metres located adjacent to the Hunter-Mooki Thrust (NSW DPI, 2011a). The Hoskissons seam averages greater than 16 metres in the southeast of the basin (NSW DPI, 2011a).

The Maules Creek Formation contains a multi-seam coal resource in a sedimentary section dominated by lithic conglomerate, lithic sandstone, siltstone and minor claystone (Corkery and Co Pty Ltd, 2004). The coal seams are generally thicker and closer together along the eastern side of the basin (Corkery and Co Pty Ltd, 2004). To the east and southeast the coals seams are split by an increasingly thick section of clastic rocks (Corkery and Co Pty Ltd, 2004).

Numerous coal seams have been identified within the Maules Creek Formation including the Bohena, Braymont, Merriown, Bollol Creek, Lower Merriown, Jeralong, Veryama, Lower Jeralong, Tarrawonga and Templemore seams (Whitehaven, 2010c). These various seams form the extractable resource at the Tarrawonga, Maules Creek, and Boggabri Coal Mines (Whitehaven, 2010c) and the Bohena seam is a notable target for the coal seam gas operations to the west of Boggabri (Eastern Star Gas, 2009).

The Black Jack Group has significant coal resources within the Hoskissons, Breeza and Melvilles seams (NSW DPI, 2011a). The Hoskissons seam has a reported maximum thickness of 18 metres and is laterally extensive from the Hunter-Mooki Fault to west of the Rocky Glen Ridge system (NSW DPI, 2011a). The Melvilles seam has a reported maximum thickness of 5 metres (NSW DPI, 2011a).

4.4 Surat Basin

4.4.1 Introduction

The sediments of the Surat Basin, a sub basin of the Great Artesian Basin (GAB), overlie the western portion of the Namoi catchment from the west of Narrabri. The Surat Basin consists of up to 2,500 metres depth of mainly Jurassic clastic continental sedimentary rocks and lower Cretaceous marine beds largely obscured by Cainozoic alluvium (Exon, 1976).

The Jurassic to Cretaceous age Coonamble Embayment of the Surat Basin unconformably overlies the Permian to Triassic sediments of the Gunnedah Basin in the north and west (Tadros, 1993). The Garrawilla Volcanics form the basal unit of the Surat Basin sequence and outcrop mainly in the central area of the Gunnedah Basin around Mullaley and Coonabarabran (Tadros, 1993). The sequence is described by Tadros (1993) after Bean (1974) as up to 180 metres of alkali basaltic lava flows, pyroclastic units and subordinate intercalated claystones. Overlying the Garrawilla Volcanics are the Early to Mid-Jurassic fluvial and lacustrine sediments of the Purlawaugh Formation, consisting of up to 75 metres of thinly bedded carbonaceous mudstone, silty sandstone and subordinate coal (Tadros, 1993).

In the absence of the Garrawilla Volcanics the Purlawaugh Formation unconformably overlies the Gunnedah Basin (Tadros, 1993 after Yoo et al., 1983). Conformably overlying the Purlawaugh Formation is the Middle to Late Jurassic Pilliga Sandstone (Tadros, 1993 after Yoo et al., 1983). The Pilliga Sandstone consists of medium to coarse-grained fluvial quartzose sandstones which outcrop over much of the Gunnedah Basin area (Tadros, 1993 after Yoo et al., 1983). The Pilliga Sandstone is considered the primary recharge beds to this area of the Coonamble Embayment and forms the main productive aquifer in the western portions of the catchment outside of the alluvial deposits (Golder Associates, 2010).

A stranded portion of the Surat Basin is the hydraulically disconnected Oxley Basin (Commonwealth of Australia DSEWPC, 2009a). The Oxley Basin is comprised of Pilliga Sandstone equivalent sediments. The Oxley Basin directly overlies the Gunnedah Basin and is located in the south of the catchment and to the west of Quirindi and forms a localised groundwater resource (Golder Associates, 2010).

The Pilliga Sandstone is overlain in the west by the Cretaceous Orallo Formation, consisting of sandstone, siltstone, mudstone, conglomerate, and coal (Pratt, 1998). The Orallo Formation outcrops to the south and west of Narrabri and has a maximum depth of 245 metres.

A stratigraphic equivalent of the Hooray Sandstone of the Eromanga Basin the lower Cretaceous Mooga Sandstone directly overlies the Orallo Formation in the west of the catchment (Geoscience Australia, 2011). The Mooga Sandstone consists of fine to medium grained sandstone and shales (Geoscience Australia, 2011). The Cretaceous Bungil Formation consists of sandstone, laminated and interbedded siltstone, mudstone and minor thin coal (Geoscience Australia, 2011). Stratigraphically equivalent to the Cadna-owie Formation in the greater Surat Basin, the sandstones within the Bungil Formation are regarded as reliable aquifers (Welsh, 2006, and Herczeg, 2008). The Mooga Sandstone and the Bungil Formations are limited in spatial extent to the western portion of the catchment (Geoscience Australia, 2011).

Forming the upper unit of the Surat sediments within the Coonamble Embayment is the Rolling Downs Group, consisting of clays and claystone, minor sandstone and rare conglomerate and gravel. Coal, and calcareous clay and calcarenite are found as basal units (Geoscience Australia, 2011). The Rolling Downs Group is absent in the eastern portions of the basin and is covered by undifferentiated Quaternary deposits in the west (Tadros, 1993).

During the Jurassic period there were 5 cycles of terrestrial deposition. These cycles are characterised by coarse sand braided stream deposits grading up into finer sand and silt deposits of meandering streams (Kingham, 1998). Labile sand, silt, mud and coal were laid down in swamps, lakes, deltas and shallow seas to complete the cycle of deposition (Kingham, 1998).

4.4.2 *Surat Basin units*

Garrawilla Volcanics

The Garrawilla Volcanics are basal units of the Surat Basin which unconformably overlie the Triassic Napperby Formation or the Deriah Formation where they are present. The volcanics reach reported thicknesses of up to 180 metres and consist of flows and intrusions of dolerite, basalt, trachyte, tuff, and breccia (Geoscience Australia, 2011).

Purlawaugh Formation

A stratigraphic equivalent to the middle Jurassic Walloon Coal Measures and the Hutton Sandstone as described in the Queensland section of the Surat Basin (Geoscience Australia, 2011). The Purlawaugh Formation is described as fine to medium grained lithic to labile sandstone thinly interbedded with siltstone, mudstone and thin coal seams (Geoscience Australia, 2011). The unit has abundant carbonaceous fragments with thin beds of flint clay. Thin stony coal seams are present in the lower part of the unit (Geoscience Australia, 2011).

Pilliga Sandstone

Formally known as the Pilliga Formation, the Pilliga Sandstone consists of medium to very coarse grained, well sorted, angular to subangular quartzose sandstone and conglomerate, with minor interbeds of mudstone, siltstone and fine grained sandstone and coal (Geoscience Australia, 2011). It commonly contains carbonaceous fragments and iron staining, with rare lithic fragments (Geoscience Australia, 2011). It reportedly has a maximum thickness of 300 metres (Geoscience Australia, 2011). The Pilliga Sandstone is considered a highly productive groundwater aquifer (Herczeg, 2008).

Orallo Formation

The late Jurassic to early Cretaceous Orallo Formation consists of sandstone, siltstone, mudstone, conglomerate and coal (Geoscience Australia, 2011). It was formally known as the Orallo Coal Measures, with thicknesses that can extend to a maximum of 245 metres (Geoscience Australia, 2011). The Orallo Formation is generally considered a hydraulic confining unit but is a known minor aquifer in some areas (NSW DMR, 2002). The Orallo Formation was previously considered the lower unit of Keelindi beds in NSW geological mapping and is reported as such in some literature (NSW DMR, 2002).

Mooga Sandstone

The lower Cretaceous Mooga Sandstone consists of fine to medium grained sandstones and shales (Geoscience Australia, 2011). Previously mapped as the upper unit of the Keelindi Beds, the Mooga Sandstone is considered a moderate aquifer and is also a hydrocarbon reservoir target in other parts of the Surat Basin (NSW DMR, 2002). Its spatial extent is limited to the western portion of the Namoi catchment (NSW DMR, 2002).

Bungil Formation

A stratigraphic equivalent to the Cadna-owie Formation, the Cretaceous Bungil Formation consists of labile to quartzose sandstone, laminated and interbedded siltstone, mudstone and minor thin coal (Geoscience Australia, 2011).

Rolling Downs Group

The upper unit of the Surat Basin within the Namoi catchment the Cretaceous Rolling Downs Group is described as semi-consolidated grey to brown clay and claystone with minor fine clayey quartz sandstone and rare conglomerate and gravel (Geoscience Australia, 2011). Coal, and calcareous clay and calcarenite are found towards the base (Geoscience Australia, 2011).

4.5 Neogene to Quaternary alluvium deposits

Alluvial sediments of the Upper Namoi are usually subdivided into two formations. The uppermost formation is the Pleistocene to recent Narrabri Formation (approximately 30 m in average thickness) which predominantly consists of clays with minor sand and gravel beds (Williams, 1986). These lens-shaped deposits provide generally low yielding aquifers of low to medium salinity (Williams, 1986).

Underlying the Narrabri Formation is the Pliocene to early Pleistocene Gunnedah Formation (up to 115 m in thickness), which consists predominantly of gravel and sand with minor clay beds and is the principal aquifer used for irrigation (Broughton, 1994 and McNeilage, 2006). The gravels and sands are often high yielding good water quality aquifers (Broughton, 1994 and McNeilage, 2006). The most productive aquifers of the Gunnedah Formation are within the palaeochannels which contain coarser sediments deposited by powerful streams (Broughton, 1994 and McNeilage, 2006). The maximum combined depth of the two formations is unlikely to exceed 170 m. The two formations have been found to be strongly hydraulically connected (McNeilage, 2006).

The Lower Namoi alluvium is split into three separate layers; the Narrabri, Gunnedah, and Cubbaroo Formations. It reaches a maximum thickness of 120 m. At the base of the alluvial sequence in the Lower Namoi is the Cubbaroo Formation consisting of sand and gravel with interbedded brown to yellow and grey clay from middle to late Miocene (Williams, 1986). Cubbaroo Formation sediments infill the pre-tertiary channels of the Lower Namoi (Williams, 1986).

4.6 Summary

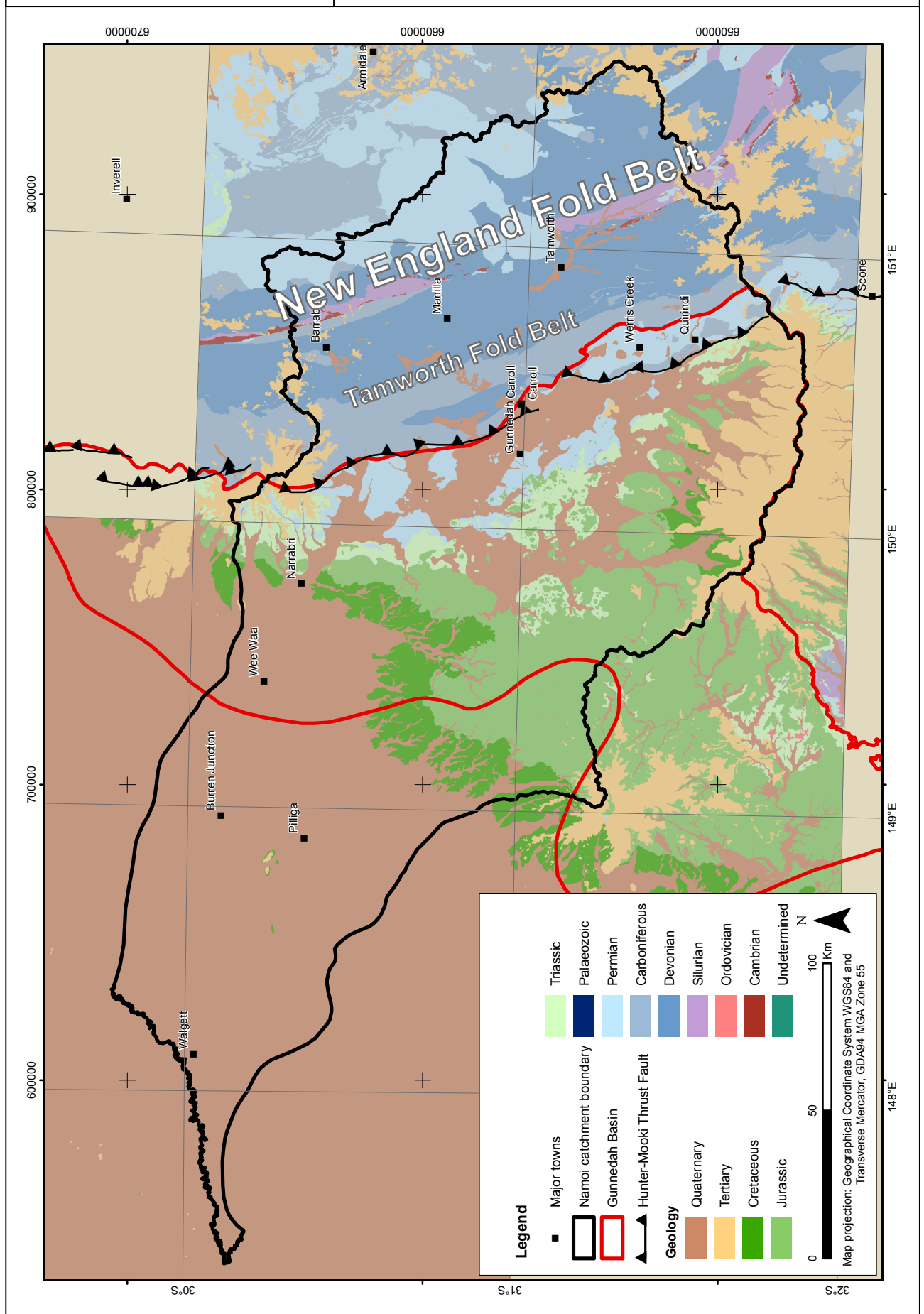
The regional geology of the Namoi catchment has been described in this section. The key points are summarised below:

- The solid geology 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.
- The Devonian to Carboniferous strata of the New England Fold Belt forms the eastern and southeastern margins of the catchment. The New England Fold Belt is a major geological province extending from the Newcastle area to far north Queensland. The New England Fold Belt has had a complex structural history with the rocks undergoing a series of deformations involving large-scale faulting and folding from the Late Carboniferous to Triassic time. It is faulted against and thrust over the eastern part of the Sydney-Gunnedah-Bowen Basin along the Hunter-Mooki Fault system (NSW DMR, 2002).
- The Gunnedah Basin is separated from the New England Fold Belt by the Hunter-Mooki Thrust. In the south the boundary between the Gunnedah Basin and the Sydney Basin is argued as being either the Mount Coricudgy Anticline or the Liverpool Range (NSW DPI, 2011).

- Tadros (1993) describes the Gunnedah Basin as containing up to 1,200 metres of marine and non-marine Permian and Triassic sediments resting unconformably over Early Permian and possibly Late Carboniferous silicic and mafic volcanics, which form the basement to the east of Rocky Glen Ridge. Metavolcanics and metasediments and minor ignimbritic volcanics of the Lachlan Fold Belt form the majority of the basement underlying the western part of the Gunnedah Basin (Rocky Glen Ridge and Gilgandra Sub-basin). In the east, the silicic and mafic basement volcanics outcrop to form the eastern basin extent as the Boggabri Ridge, prominent between Gunnedah and Narrabri.
- To the north of the Liverpool Range the Jurassic sediments of the Surat Basin unconformably overlie the Gunnedah Basin sediments. The Gunnedah Basin sequence outcrops as a narrow north-northwest trending zone from the south of Quirindi to the north of Narrabri (Tadros, 1993).
- The Jurassic to Cretaceous age Coonamble Embayment of the Surat Basin unconformably overlies the Permian to Triassic sediments of the Gunnedah Basin in the north and west. The Garrawilla Volcanics form the basal unit of the Surat Basin sequence and outcrop mainly in the central area of the Gunnedah Basin around Mullaley and Coonabarabran (Tadros, 1993). The sequence is described by Tadros, (1993) after Bean (1974) as up to 180 metres of alkali basaltic lava flows, pyroclastic units and subordinate intercalated claystones. Overlying the Garrawilla Volcanics are the Early to Mid-Jurassic fluvial and lacustrine sediments of the Purlawaugh Formation consisting of up to 75 metres of thinly bedded carbonaceous mudstone, silty sandstone and subordinate coal (Tadros, 1993).
- Both the Maules Creek Formation and the Black Jack Group contain coal seams that are prospective for coal mining and coal seam gas. These units contain numerous coal seams with net coal thickness reaching 50 - 60 metres adjacent to the Hunter-Mooki Thrust. The Hoskissons seam averages greater than 16 metres in the southeast of the basin (NSW DPI, 2011).
- Alluvial deposits of Neogene to Quaternary age are found associated with the stream systems of the Upper and Lower Namoi and form large outwash sequences in the Lower Namoi.
- Alluvial sediments of the Upper Namoi are usually subdivided into two formations. The uppermost formation is the Pleistocene to recent Narrabri Formation (approximately 30 m in average thickness) which predominantly consists of clays with minor sand and gravel beds (Williams, 1986). Underlying the Narrabri Formation is the Pliocene to early Pleistocene Gunnedah Formation (up to 115 m in thickness), which consists predominantly of gravel and sand with minor clay beds and is the principal aquifer used for irrigation.
- Alluvial sediments of the Lower Namoi are usually subdivided into the Narrabri, Gunnedah, and Cubbaroo Formations. The Cubbaroo Formation consists of sand and gravel with interbedded brown to yellow and grey clay from middle to late Miocene (Williams, 1986).

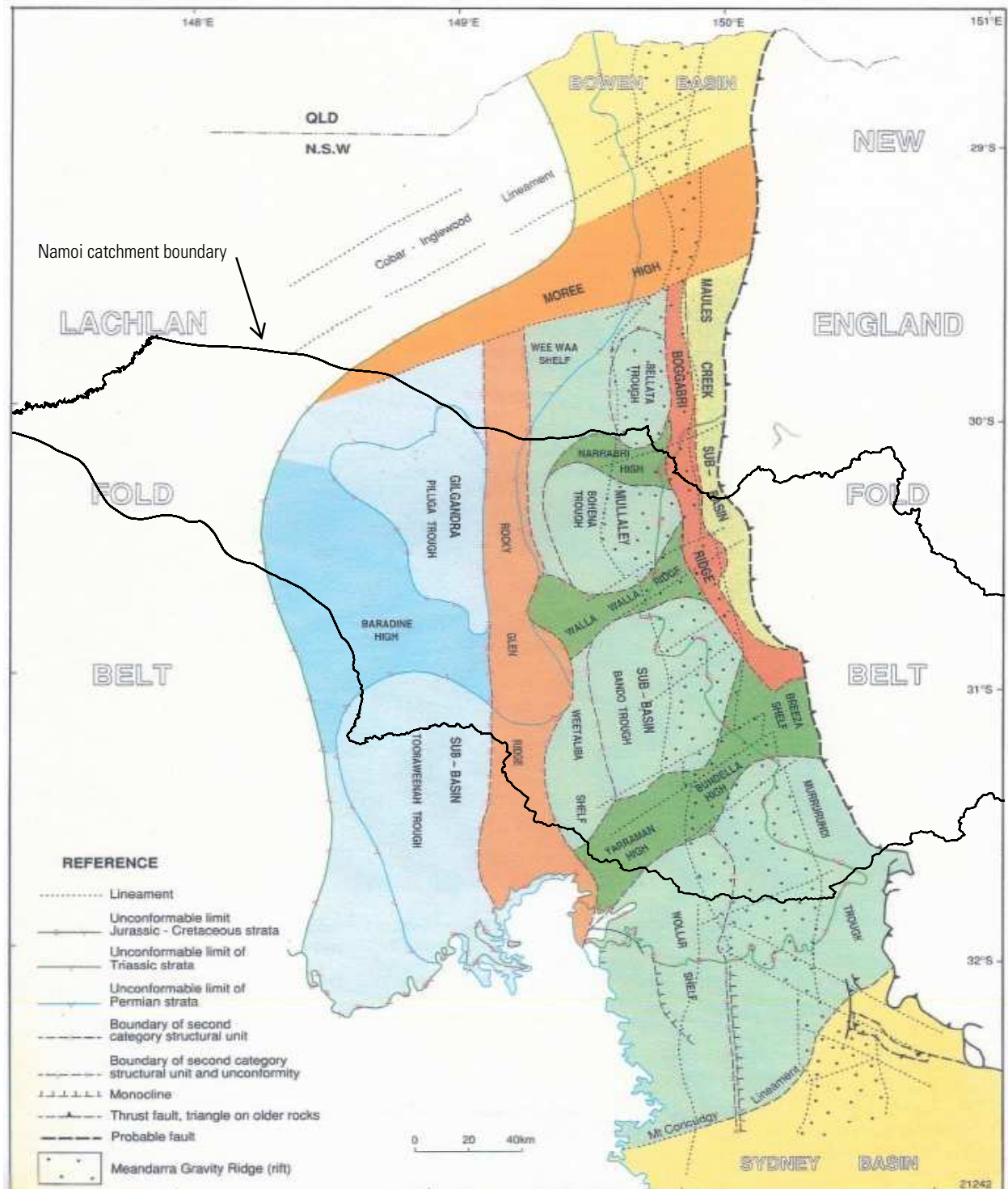
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Figure 4.1 Namoi catchment regional geology



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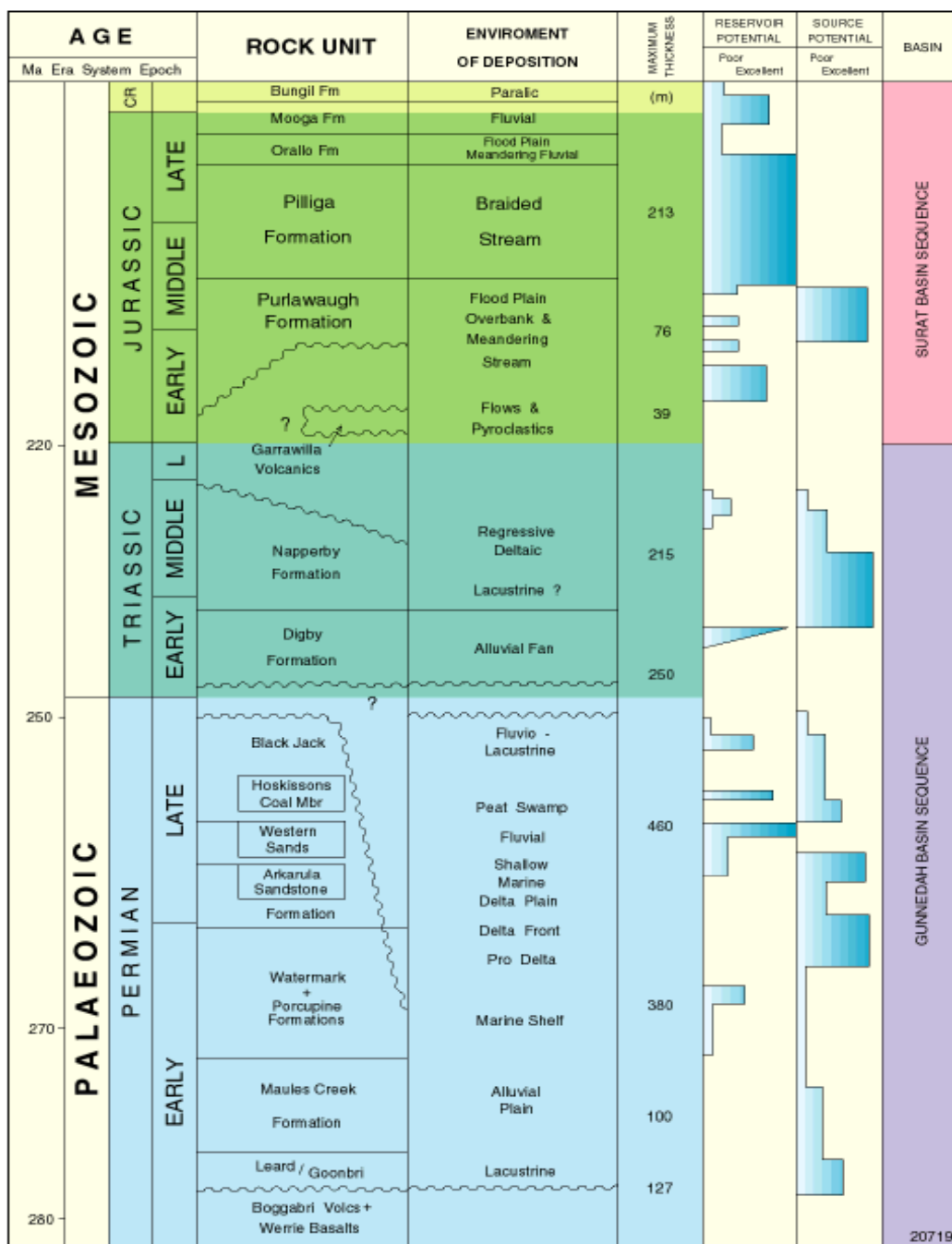
Figure 4.2 Major structural elements of the Gunnedah Basin



(Original figure after Gurba et al., 2009)

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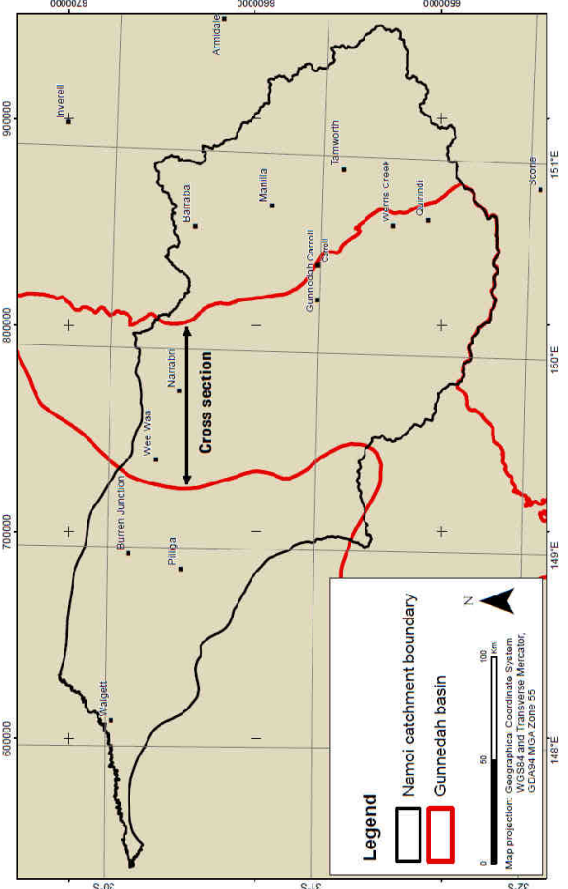
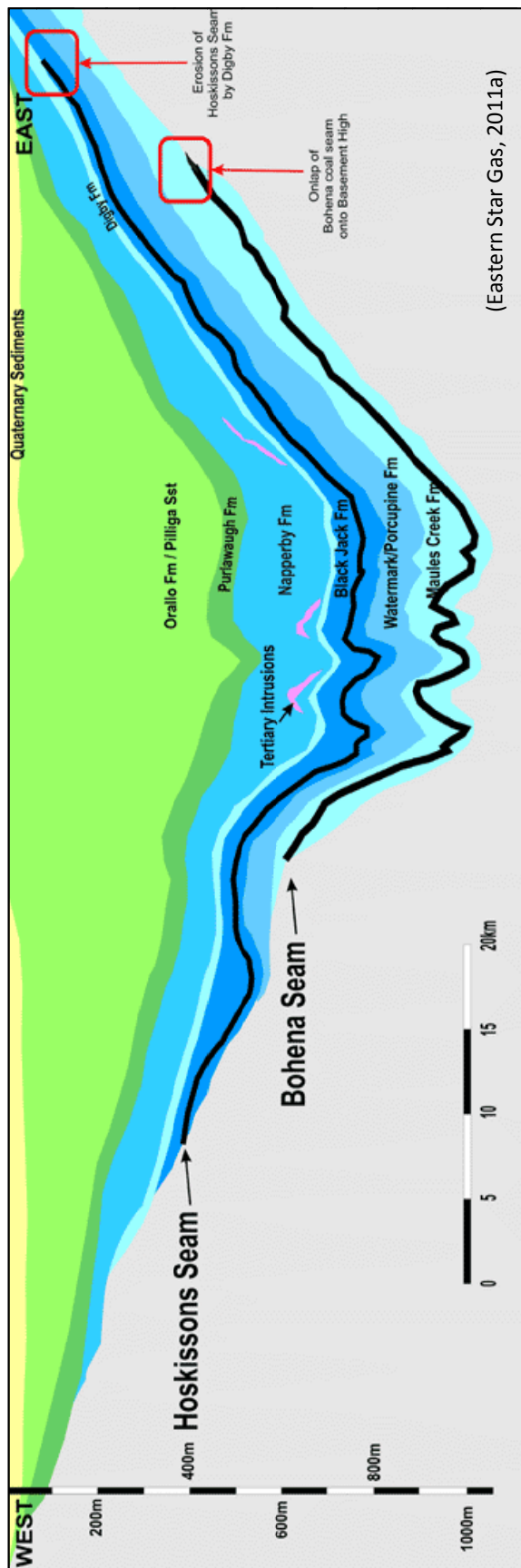
Figure 4.3 Stratigraphic section - Gunnedah Basin and Surat Basin



(NSW DPI, 2011b)

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Figure 4.4 Representative geological cross section



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5 GEOLOGICAL MODEL

5.1 Introduction

A preliminary geological model has been produced using Petrel software (v2010.2) (Schlumberger, 2011). Petrel is an oil and gas industry standard platform for handling and interpreting a range of sub-surface data types with the ultimate aim of producing three dimensional (3D) geological models. It is ideal for assimilating and modelling geoscience data at basin-wide scale.

Prior to the Namoi Study, a digital 3D geological model of the entire Namoi catchment did not exist, but is required for two main reasons:

- To develop an understanding of the spatial relationship between the occurrence of coal (suitable for mining and gas extraction) and the water resources in the catchment;
- To provide a platform for numerical modelling of the aquifer systems in the catchment.

The catchment aquifer systems are the primary water systems that can be impacted by coal mining and CSG developments. A fundamental step in developing any integrated regional numerical model of the water systems requires a comprehensive catchment-scale geological model; in essence the Petrel 3D geological model forms a major component of the Conceptual Model.

This section describes the data available for geological model construction, the process and the result. Since the outcome of 3D geological model construction is the tool (itself) and its utility, the 'results' are difficult to display in report format and this section is only able to provide an overview of the process and a snapshot of some 'results'. This is particularly the case with respect to the presentation of hard copy cross sections which can be produced from the model in any orientation. However, since consent was not forthcoming from all Industry Partners by report publication, these have been omitted from this report to ensure SWS does not breach provisions of the Confidentiality Deed.

As with the Conceptual Model, the model described is preliminary and will undergo continuous development and refinement throughout the numerical modelling phase of the project (Phase 3). As more data is collected, whether from private or public sources, it can be used to validate and update the geological model. The processes involved in geological model construction will be fully documented as part of this project, and there is no 'hard wiring' (fixing of model inputs, settings or interpretations) within the model or software to constrain this in the future.

5.2 Datasets

A number of diverse datasets were imported into the Petrel software. Those derived from public sources are displayed in the Petrel model in their entirety. Those from private sources (i.e. Industry Partners) have been imported and used in model construction but may not be fully displayed in the written report. A listing of the main sources of data, the data content and the date of receipt is provided in Appendix A.

The datasets were:

- Two dimensional (2D) seismic data. Numerous lines were available, both from the NSW Department of Industry and Investment and Industry Partners, however, they were not incorporated into Petrel model since most seismic lines were in 'time' and few conversions to 'depth' were available. There are a number of factors that make the inclusion of this data in the geological modelling inappropriate at this time. The most significant are:
 - In most areas where seismic is available, this data has been superseded by more accurate drilling data, which is used in its place, or the two datasets have been combined to produce digital layer surfaces.
 - The converted depth section has to be interpreted in terms of the geological layering before it can be utilised.
 - For greatest accuracy the data should be calibrated against local borehole data. In areas where seismic data exists, but no boreholes have been drilled, the result will be highly uncertain.
- GIS data;
 - The Namoi catchment boundary (from the Namoi CMA on their soils mapping DVD, received November 2010).
 - An 'alluvial boundary', delineating the Lower Namoi, Upper Namoi, Peel Alluvium (Provided by NSW Office of Water as a shapefile named GWMacroWSPDraft, received October 2010).
 - Major stream systems and towns (geographical orientation purposes only), received from the NSW Geological Survey in October 2010.
- Geological images. Published reports and geological maps provide a very useful source of information and an independent check on modelling outcomes. These were either available electronically or were scanned and geo-referenced for the purposes of the Study. They were:
 - Digital whole of catchment surface geology provided by the NSW Geological Survey in October 2010 derived from the 1:250,000 geological mapping series.
 - Geological cross sections available from a number of sources:
 - Tadros (1993) provided the following:
 - Fig 6.10b (Pg 67) Section A-A1
 - Fig 18.4 (Pg 353) Section 2

- Fig 6.17 (Pg 76) Section C
- Fig 18.3 (Pg 352) Section 1
- From the following geological maps:
 - Gunnedah Coalfield (South) Regional Geology. Cross sections; A-A1, B-B1, C-C1, D-D1 (Pratt, 1996).
 - Gunnedah Coalfield (North) Regional Geology. Cross sections; A-A1, B-B1, C-C1, C1-C2. (Pratt, 1998).
 - Gilgandra (1:250,000), sheet SH 55-16. Cross Section A-B-C (Offenberg, 1968).
 - Walgett (1:250,000), sheet SH 55-11. Cross Section A-A1 (Meakin et al., 1996).
 - Narrabri (1:250,000), sheet SH 55-12. Cross Section A-B (Wallis, 1971).
 - Tamworth (1:250,000), sheet SH 55-13. Cross Section A-B (Offenberg, 1971).
 - Manilla (1:250,000), sheet SH 55-9. Cross Section A-B (Chesnut et al., 1973).
- Triassic basement and Volcanic basement elevations from Tadros (1993).
- Base of Narrabri Formation and base of alluvium in the Upper Namoi region from the Upper Namoi groundwater model as defined by the NSW Office of Water, Modelling Group (McNeillage, 2006).
- Well data:
 - Public datasets. Primarily the Pinneena 3.2 groundwater database which was received from the NSW Office of Water on 15 November 2010:
 - Drillers logs from 15,487 wells (Figure 5.1). This data consists of down hole intervals with descriptions of material type encountered during drilling (i.e. clay, gravel, rock, etc).
 - Coal and gas wells provided 576 formation 'picks' (a pick is an elevation, or depth down hole, at which the top or base of a geological surface has been identified).
 - Groundwater abstraction licenses were used to locate 2,349 boreholes with a recorded screen interval in the fractured rock aquifer to the east of the Hunter-Mooki Fault System (Figure 5.2).

- Private datasets (i.e. supplied by the Industry Partners). These generally consisted of formation picks but also included a number of geophysical logs. Both were loaded into Petrel, but only the formation picks have been used at this time. Geophysical logging is undertaken primarily to allow interpretation of formation picks (which were provided) but also to develop an understanding of hydraulic parameters within the target units (which were also provided, in summarised form). Therefore no benefit would result from duplicating this process. The following datasets were imported:
 - Eastern Star Gas, from December 2010 to June 2011, provided data from 178 wells (1,225 formation picks in total).
 - Whitehaven, in February 2011, provided data from 3,642 wells. This included information at a level of detail greater than the detail of the conceptual model and the expected resolution of the regional geological model. The data yielded 3,305 formation picks corresponding to the units modelled.
 - Santos, in March 2011, provided data from 52 wells (295 formation picks in total).
 - Dart Energy, in March 2011, provided in excess of 3,000 points for the 'top of basement'.
 - Well data from other coal operations and prospects (e.g. BHP Billiton (February 2011), Shenhua (March 2011), Idemitsu (March 2011) and Aston Resources (March 2011)) provided data at a high level of density and detail for local areas which is greater than the basin-scale geological model can replicate.
- Interpolated geological surfaces (Private). These are surfaces of geological units that have been interpolated by the various Industry Partners to support their operational or exploration activities. They will be based primarily on seismic surveys, physical well logs and downhole geophysical logs. They are limited to the areas where each of these companies is active. As these have been based primarily on formation picks (which were also provided) they have only been used in this study where formation picks were not partially or fully supplied. A summary of data used in the Petrel model is presented in the sub-sections below.
- The Gunnedah Bowen Basin SeeBase and Structural GIS Project (SRK, 2011). The SeeBase GIS Project has interpreted a regional structural / basin framework for the Gunnedah Basin and the southernmost extent of the Bowen Basin in NSW. This surface was produced by SRK Consulting for the NSW Department of Industry and Investment, and provides a top of the Boggabri Volcanics over most of the Namoi catchment west of the Hunter-Mooki Fault System (Figure 5.3).
- Topography from a compilation of 25 m and 90 m Digital Terrain Models created from *Shuttle Radar Topography Mission (SRTM)* as provided by NSW Department of Industry and Investment (Figure 5.4).

5.3 The Petrel model

5.3.1 *Introduction*

This sub-section describes the datasets that were used to interpolate the geological surfaces in Petrel, and to control the production of the resulting geological layers. These processes were undertaken within the following spatial extents:

- A top at ground surface.
- Horizontal extents at the Namoi catchment boundary.
- A base at the horizontal surface at -2,000 mAHD.

The Upper Namoi alluvial sediments have been divided into two distinct layers (the Narrabri and Gunnedah Formations). The Lower Namoi alluvial sediments have been modelled as a single unit at this stage.

5.3.2 *Base of alluvium and weathered zone*

The Pinneena dataset was used as the primary control on the base of alluvium throughout the Namoi catchment. This was based on drillers logs (the elevation of recordings of material that could be associated with hard rock, and therefore taken to indicate that the borehole had penetrated to the base of the alluvial sediments). From the 15,487 wells imported to Petrel, 277 did not have any drillers logs and a further 5,306 did not have an entry suggesting that hard rock had been reached. Of the remaining 9,904, only 2,195 were located within the conceptual alluvium boundary and these were used to generate the surface of the alluvial base.

The fact that there are a significant number of points outside of the conceptual alluvium boundary, which are distributed all over the catchment, suggests that there is a significant non 'hard rock' system in these locations too. This data was therefore utilised to create a 'weathered zone' surface. It is likely that this additional sub-surface unit may well represent several different lithological types (alluvium outside the conceptual boundary, soil zone, weathered zone, etc.), but it is warranted and will assist in developing the numerical model. Therefore the 6,110 'rock' picks outside the alluvium were used to generate this surface. These were filtered further by constraining the data to within a maximum thickness of 240 m and a minimum thickness of 10 m. This removed 1,599 'rock' picks, leaving 4,511 for use in surface generation.

5.3.3 *Base of Narrabri Formation*

Geological cross sections from the NSW Office of Water provided 108 formation picks for the base of the Narrabri Formation. These were manually picked from the data supplied and were used directly to define this surface.

5.3.4 *Fractured rock aquifer (east of Hunter-Mooki Fault System)*

The 2,349 boreholes with licensed abstraction and screen elevation information were used to define the base of the 'fractured rock aquifer'. Data which provided a thickness of less than 10 m was not used, but there was no maximum thickness constraint.

5.3.5 *Hard rock geology*

The interpolation of the geological units beneath the alluvium and above the Boggabri Volcanics was undertaken using a mixture of formation picks and previously generated surfaces from Industry Partners, formation picks from coal and gas resource bores from the NSW Government, and publically available geological cross sections.

The well formation picks were given highest priority in the modelling process so if there was a conflict between the two datasets the cross section data was not used or modified. This was judged and managed manually.

The following cross sections were used in assisting surface interpolation:

- From Tadros (1993): All cross sections identified in Section 5.2 of this report, apart from Fig 6.10b Section 2.
- From the Gunnedah Coalfield (South) Regional Geology map. Cross sections A-A1, B-B1, E-E1 were used; Cross Sections C-C1 and D-D1 were not. In this case the topographic DTM did not match the ground surfaces indicated on the cross section.
- From the Gunnedah Coalfield (North) Regional Geology map. All cross sections were used.
- From the Walgett, Manilla and Narrabri geological map sheets. These cross sections were used.
- From the Gilgandra and Tamworth geological map sheets. These cross section were not used due to a poor match between the sections and the more recent well formation picks.

The formation pick and surface data used to define the surfaces is summarised in Table 5.1. Duplications existed between the private data formation picks and public source formation picks. Of the 576 public formation picks, 16 were duplicated and removed. As mentioned previously, if significant formation picks existed in areas where digital surfaces also existed, the surfaces were not used (as they were essentially the same thing, but based on fewer data).

Table 5.1 Formation picks and digital surfaces used to generate the 'hard rock' geological model

Digital surface	Formation picks used	Digital surfaces used
Pilliga Sandstone Top	Eastern Star Gas - 58 Santos - 15 Whitehaven - 20 Public - 3	None
Purlawaugh Formation Top	Eastern Star Gas - 120 Santos - 16 Whitehaven - 115 Public - 3	None
Garrawilla Volcanics Top	Eastern Star Gas - 19 Santos - 24 Whitehaven - 315 Public - 3	None
Napperby Formation Top	Eastern Star Gas - 138 Santos - 39 Whitehaven - 132 Public - 11	None
Digby Formation Top	Eastern Star Gas - 161 Santos - 42 Whitehaven - 356 Public - 20	None
Black Jack - Top / Base of Triassic	Eastern Star Gas - 158 Santos - 44 Whitehaven - 356 Public - 60	None
Black Jack - Top of Hoskissons Formation	Eastern Star Gas - 142 Santos - 41 Whitehaven - 787 Public - 167	None
Black Jack - Base of Hoskissons Formation	Eastern Star Gas - 140 Public - 165 Whitehaven - 787	Shenhua - Base of Hoskissons BHP - Base of Hoskissons
Black Jack - Top of Melvilles Formation	Eastern Star Gas - 8 Whitehaven - 21 Public - 51	None
Black Jack - Bottom of Melvilles Formation	Eastern Star Gas - 7 Whitehaven - 21 Public - 51	Shenhua - Base of Melville
Top of Watermark/Porcupine Formations	Eastern Star Gas - 103 Santos - 33 Public - 14	Shenhua - Base of Black Jack
Top of Maules Creek Formation	Eastern Star Gas - 96 Santos - 11 Public - 10	None
Top of Leard / Goonbri Formations	Eastern Star Gas - 9 Santos - 10 Public - 2	None

5.3.6 *Basement / volcanic surface*

The top of Boggabri Volcanics is defined by the SeeBase GIS Project (SRK, 2011) surface. The SeeBase GIS Project is the most comprehensive surface dataset available in the Namoi catchment and has been constructed from several audited and distinct datasets. The surface is relatively smooth and covers almost the entire model domain west of the Hunter-Mooki Fault System, apart from a small portion to the far northwest. The surface defines a major system of basement lows with a central axis running in a roughly north-northwest direction and in the vicinity of the town of Gunnedah. The system comprises the four main troughs of the Gunnedah Basin; the Bellata, Bohena, Bando and Murrurundi Troughs. The Bohena Trough represents a major geological structure in the Namoi catchment (Section 4).

As confidence in the SeeBase surface is relatively high, the top of this surface was used to control the interpolation of overlying units up to the top of the Hoskissons seam within the Black Jack Group.

5.3.7 *Fault System*

The Hunter-Mooki Fault System was defined using two different data sources. The initial fault top was defined based on the surface geological maps SH 56-9 and SH 56-13. The dip of the fault and its intersection with the base of the model was defined using the digitised geological cross sections, specifically Gunnedah Coalfield (South) Regional Geology Section C/C1 and D/D1, Gunnedah Coalfield (North) Regional Geology Section A/A1, Manilla Section A/A1 and Tamworth Section A/A1.

The fault plane was constructed by linking the top and bottom traces. Once this was complete the fault was extended to the bottom (-2,000 mAHD) of the model domain and north and south catchment boundaries (Figure 5.5).

The model domain was divided into two blocks based on this fault delineation.

5.3.8 *Hard rock east of the Hunter-Mooki Fault System*

Due to the complexity of the geology in this region and the highly limited data density, attempts to correlate data to the east of the Hunter-Mooki Fault System into continuous stratigraphic units were unsuccessful. No refinement of the geological model in this area will be possible.

5.3.9 *Geological model construction*

Surfaces were interpolated based on the data described above. Where data was scarce for any particular surface the interpolation was controlled mathematically by trends in other surfaces for which more data was available. For example, the top of Boggabri Volcanics and top of Purlawaugh Formation were used as these trend surfaces (Table 5.2).

Layer thicknesses have been constrained based on the maximum thickness returned by the observed data. This does not apply to the GAB layer, which has been allowed to fill the gap between the top of Pilliga Sandstone and base of alluvium or weathered zone.

The layers were constructed using the relationships in Table 5.2. Surfaces have been defined in terms of their geological relationship to other surfaces in the model (erosional, conformable and base). These terms organise the layering in terms of priorities, such that conformable has the lowest priority and erosional has the highest. More specifically erosional surfaces will cut through any surface physically below them unless it is labelled 'base'.

Table 5.2 Layer relationships defined in Petrel

Horizon Number	Name	Horizon Type	Notes
1	Topography	Conformable	-
2	Bottom of Narrabri	Conformable	-
3	Bottom of alluvium / weathered zone	Erosional	Gunnedah and 'weathered zone' separated using zones
4	Bottom of fractured rock aquifer	Conformable	Only used in the east block, based on depth of groundwater boreholes
5	Pilliga Top	Conformable	Used Purlawaugh surface as trend
6	Purlawaugh Top	Conformable	Important data in the west block. Used as trend for other surfaces
7	Garrawilla Top	Conformable	Used Purlawaugh surface as trend
8	Napperby Top	Conformable	Used Purlawaugh surface as trend
9	Digby Top	Conformable	Used Purlawaugh surface as trend
10	Top / Base of Triassic	Erosional	Used Purlawaugh surface as trend
11	Top of Hoskissons seam	Conformable	Used SeeBase surface as trend
12	Base of Hoskissons seam	Conformable	Used SeeBase surface as trend
13	Top of Melvilles seam	Conformable	Used SeeBase surface as trend
14	Bottom of Melvilles seam	Conformable	Used SeeBase surface as trend
15	Top of Watermark/Porcupine Formations	Conformable	Used SeeBase surface as trend
16	Top of Maules Creek Formation	Conformable	Used SeeBase surface as trend
17	Top of Leard / Goonbri Formations	Conformable	Used SeeBase surface as trend
18	SeeBase GIS Project	Base	-
19	Model base	Base	-

5.4 The geological model

5.4.1 Domain and grid

The 3D domain of the geological model is displayed in Figure 5.6. The base of the model is set at a uniform value of -2,000 mAHD. The top of the model is set to the natural surface. The model is constrained laterally within the boundaries of the Namoi catchment, although this can be extended if numerical modelling requires. The geological model grid is irregular with grid cells of approximately 500 m x 500 m. The grid was also rotated to match the likely main direction of groundwater flow in alluvium (e.g. west-northwest).

The model coordinate system adopts the Map Grid of Australia (MGA) UTM Zone 55 projection which has been extrapolated into adjacent UTM zones occupied by the model. Some (projection) distortion near the model margins is therefore observed.

5.4.2 Faults

The Hunter-Mooki Fault System is postulated to cut through all of the Permian, Triassic and Jurassic strata that are present to the west (as indicated by the available geological cross sections). The Hunter-Mooki Fault trends north-northwesterly and dips at 43° to 48.5° northeast. The alluvial surfaces are not intersected by the fault and are continuous either side of it.

There are no other faults represented within the model domain.

5.4.3 Layers

The Petrel geological model is comprised of 18 layers. These layers represent 19 distinct geological units that are present in the sub-surface of the Namoi catchment and 2 inferred units of hydrogeological significance. The characteristics of the upper 17 model layers are described in Table 5.3 and below.

The 18th layer corresponds to the Boggabri Volcanics, but as its lower surface is defined as a uniform, and arbitrary, -2,000 mAHD, it is not discussed in detail.

Table 5.3 Characteristics of geological model layers

Model layer no.	Geological units	Average thickness (m)	Maximum thickness (m)
1	Narrabri Formation	19	73
2	Gunnedah Formation	36	200
	Weathered zone	15	252
3	Fractured rock aquifer	79	140
4	Great Artesian Basin	251	1,152
5	Pilliga Sandstone	101	333
6	Purlawaugh Formation	36	272
7	Garrawilla Volcanics	75	336
8	Napperby and Deriah Formation	104	436
9	Digby Formation	72	256
10	Upper Black Jack Group	94	586
11	Hoskissons seam	5	39
12	Middle Black Jack Group	35	184
13	Melvilles seam	2	30
14	Lower Black Jack Group	62	114
15	Watermark and Porcupine Formations	124	520
16	Maules Creek Formation	65	621
17	Goonbri and Leard Formation	104	695

Only the oldest sediments of the Great Artesian Basin (the Purlawaugh Formation and Pilliga Sandstone) are defined by the data to an extent that allows them to be modelled in this study. The material above them cannot be separated into constituent members and has been grouped into a single model layer, Layer 4, which is termed the 'Great Artesian Basin'.

5.4.4 Alluvial, fractured and weathered materials

The Narrabri Formation (Layer 1) is the uppermost layer in the Petrel model and is present only within the Upper Namoi Alluvium (Figures 5.7 and 5.8). It has a maximum thickness of 73 m and covers an area of about 3,700 km².

The Gunnedah Formation, Lower Namoi Alluvium, Peel Alluvium and an additional 'weathered zone' outside of the alluvial systems are all defined within Petrel model Layer 2 (Figures 5.9 and 5.10). These units have the following characteristics:

- The Lower Namoi Alluvium is modelled with a maximum thickness of about 130 m.
- The Gunnedah Formation is modelled with a maximum thickness of about 200 m.

- The Peel Alluvium is modelled with a maximum thickness of about 10 m.
- The 'weathered zone' is modelled with a maximum thickness of about 252 m. It extends over the entire model domain, with exception of areas covered by alluvium.

The fractured rock aquifer (Layer 3) is present to the east of the Hunter-Mooki Fault System (Figures 5.11 and 5.12). The definition of the fractured rock aquifer was based on the depth of groundwater abstraction boreholes in the area, thus delineating a zone of utilised aquifer resource. Its thickness is an average of 79 m with a maximum of up to 140 m, mostly associated with areas of higher topography. This layer extends over the entire portion of the model east of the Hunter-Mooki Fault System. It covers an area of approximately 12,200 km².

5.4.5 *Hard rock geology west of the Hunter-Mooki Fault System*

The Great Artesian Basin (GAB) sediments (Layer 4) increase in thickness towards the west, as result of the plunging of the top of the Pilliga Sandstone (which defines the base of GAB layer). The thickness ranges from 0 m in the east to over 1,000 m in the far western portion of the model.

The Pilliga Sandstone (Layer 5) extends mostly in the areas to the west of Gunnedah, where it presents a gentle dip angle towards the west. Its thickness ranges from 0 to 333 m with an average of about 100 m. Maximum thicknesses are found close to the southern catchment ridges and in the north close to the Hunter-Mooki Fault System.

The Purlawaugh Formation (Layer 6) presents a gentle dip to west, following the same trends of the Pilliga Sandstone. The average thickness is 36 m with maximum thicknesses of 272 m found in the western and southern portions of the catchment.

The Garrawilla Volcanics (Layer 7) presents an average thickness of 75 m and is located mainly within the central portion of the catchments around the Bohena Trough axis. Increasing thicknesses are found towards the south where maximum values are up to 336 m, while this unit pinches out towards the west. Its total coverage area is approximately 10,300 km².

The Napperby Formation and Deriah Formations (Layer 8) are considered jointly in the model due to lack of data to differentiate them. These units are located mostly to the west side of the Bohena Trough. This layer has an average thickness of 104 m, increasing to a maximum of over 430 m in the southern areas of the Liverpool Plains. The total coverage area is approximately 16,000 km².

The base of the Digby Formation (Layer 9) is erosional against the top of Black Jack Group. It is modelled with an average thickness of 72 m. Maximum thicknesses of 256 m can be found in southwestern portions. The Digby Formation is divided laterally into two distinct blocks. One is located close to the Bohena Trough and southern areas (where control data is available), and the second located to the western portion of the catchment where control data is lacking. This may indicate that the Digby Formation is pinching out towards the west. However, this will remain unclear unless additional data is acquired.

The Black Jack Group (Layers 10 to 14) hosts several of the coal seams that are subject to current coal seam gas exploration, and also present a coal mining resource when near surface. The coal seams within them, for which there is sufficient data, have therefore been delineated.

The layer configuration within the Black Jack Group is:

- The 'Upper' Black Jack (Layer 10) is defined by the top of Black Jack Group and top of Hoskissons seam. This layer extends over the majority of the Bohena Trough. Its thickness varies between 0 and 586 m, with an average of 94 m.
- The Hoskissons seam (Layer 11) forms a relatively continuous layer. The seam has an average thickness of 5 m and reaches a maximum of nearly 40 m.
- The 'Middle' Black Jack (Layer 12). The Middle Black Jack layer is defined between the base of the Hoskissons seam and top of the Melvilles seam. This unit has an average thickness of 35 m and a maximum thickness of nearly 185 m.
- The Melvilles seam (Layer 13) is modelled as a series of discontinuous lenses mostly within the Bohena Trough, with a combined (horizontal) coverage of approximately 4,400 km². Its thickness ranges between 0 and 30 m with an average of just 2 m.
- The 'Lower' Black Jack (Layer 14) is defined between the base of the Melvilles seam and Top of Watermark / Porcupine Formations. These sediments are modelled as several discontinuous lenses distributed mostly in the area of the Bohena Trough, with a combined (horizontal) coverage of approximately 10,100 km². Modelled thickness ranges between 0 and 114 m, with an average value of 62 m.

The Watermark and Porcupine Formations (Layer 15) are defined as a single layer in the geological model, as insufficient data exists to differentiate them. Their occurrence is restricted to the area of the Bohena Trough. They are modelled over an area of about 12,300 km². Their combined thickness ranges between 0 and 520 m with an average of 124 m. The greatest thickness values are found in the southern portion of the Bohena Trough in the area of Quirindi and the Liverpool Plains.

The Maules Creek Formation (Layer 16) is modelled as a single layer. There is insufficient data to define the individual coal seams (e.g. the Bohena seam) within this formation over the entire geological model, although this would be advantageous for the objectives of this study. The layer can be divided at a later date if additional data becomes available or if numerical modelling requires it. The Maules Creek Formation is present mostly within the Bohena Trough and covers a horizontal area of 7,200 km². It has an average thickness of about 65 m, but can reach a maximum of over 600 m.

The Goonbri and Leard Formations (Layer 17) are defined as a single layer in the model. The combined thickness of these units ranges between 0 and 695 m, with maximum values in the northern portions of the catchment. The extension of the layer is mostly restricted within the area of the Bohena Trough, which may indicate that these formations are pinching out towards the east.

The Boggabri Volcanics (Layer 18) are defined as the material beneath the top of this unit and have a fixed maximum depth (-2,000 mAHD). The modelled thickness of this layer is therefore not relevant. The average elevation of the top of the volcanics is about -570 mAHD, but it actually varies between -1,400 and 400 mAHD (Figure 5.13). The deepest elevations are found in the south of the catchment, in the area of the Liverpool Plains and the areas close to Pilliga.

5.4.6 *Hard rock geology east of the Hunter-Mooki Fault System*

The geological units to the east of the Hunter-Mooki Fault System are defined in the same layer as the Boggabri Volcanics. As there is no information to define any detail within this system, this layer occupies the entire volume from the base of the fractured rock aquifer to the base of the model (-2000 mAHD).

5.5 Assumptions

5.5.1 Introduction

The available data has been interpreted and interpolated to produce the digital geological model described above. There are many methods (algorithms) available to guide the interpolation process and they will produce significantly different results. However, the process and choices are guided by the conceptual understanding of the geology, which includes assumptions of the relationships between different geological units. The model presented is a preliminary output of this process, and will continue to be improved and audited as the Study progresses. Whilst this is unlikely to affect the underlying assumptions, it should reduce the uncertainties that are currently evident.

The assumptions and uncertainties associated with the current model are described below. They are generally associated with the data on which the model is constructed, or with the interpolation and construction methodology.

5.5.2 Assumptions

The data on which the geological model is based is described in full above. The data is spatially variable and of variable quality. The following assumptions and uncertainties therefore apply to the model:

- The formation picks provided by the Industry Partners and those contained within the public access Pinneena database are assumed to be the most accurate datasets in terms of defining geological surfaces.
- Where data is scarce, most obviously to the west of the catchment (Figure 5.14), the extension of geological surfaces is based on trends in other surfaces. This should improve the representation, but it is in these areas, and for these geological units, that the model is most uncertain. It is also the case that in these areas different approaches (e.g. numerical algorithms) are likely to produce significantly different results.
- As no continuity in geological units was observed to the east of the Hunter-Mooki Fault, this part of the model is assumed to be a single geological unit.
- In describing the base of alluvium, drillers logs have provided the key data. These are assumed to be accurate descriptions of the material (and depth) encountered during drilling, but there may be many reasons why the recording of 'rock' may not reliably define the base of alluvium. Inaccuracies in this will be passed directly into the geological model, but there are only limited ways in which this data can be audited.
- The raw data used to build the model is, in the case of the hard rock geology, concentrated in a relatively small area. There are vast areas within the model domain where no data is available and the surface elevations are based on trends in either those, or other surfaces in areas where data does exist. In these areas therefore uncertainty in the model is very high. However, the reliance on trends for surface interpolation is fundamental to the extension of the model to these data poor areas.
- The definition of a 'fractured rock aquifer' to the east of the Hunter-Mooki Fault is based on the assumption that the depth of water bores (specifically the screen interval) gives a good indication of this resource. There will be many uncertainties associated with this, but on the whole the result is credible.

- It is assumed that the 'western' hard rock geology and the eastern 'fractured rock aquifer' do not continue across the Hunter-Mooki Fault System. It is also assumed that the alluvium and weathered zones do. Whilst these assumptions are generally valid at a regional scale, at a more local scale the fault is more likely to be variable and will have an influence over many kilometres.
- The surfaces in the model are assumed to be either erosional or conformable, based on the understanding of these relationships gained from literature. These relationships will have a major bearing on the outcome of the geological modelling.
- Modelled surface elevations become averaged within model cells. The greater the cell size the greater the area averaged and loss of detail that occurs. However, the smaller the cell size the more cumbersome the model becomes. The current grid cell size for this model is 500 m². Given the volume that the model encompasses this is at the limit of what is currently possible, and demonstrates the 'power' of Petrel to handle this vast amount of data. It is also at the very limit of the resolution of the data.
- Apart from the Hunter-Mooki Fault System, data on smaller scale faults is scarce. It is therefore assumed that layers are continuous over the model domain (west of the Hunter-Mooki Fault System) and smaller scale faults, of which there will be many, have not been modelled and do not perturb the stratigraphy in these areas.
- It has been assumed that the maximum thicknesses of the geological units described in the data are representative of the maximum thickness of these units over the entire model domain. This may not be correct, but it does allow the thicknesses to be constrained against observed data, rather than allowed to vary independently of it.

Currently layers that pinch out or truncate are assigned zero thickness. This is contrary to the requirements of most groundwater modelling software such as MODFLOW. Layer thicknesses in this code must be greater than zero throughout the model domain and it is preferable if certain rules are obeyed in terms of how layer thickness varies from one cell to the next. The geological model could be modified to realise these requirements, rather than dealing with them at the numerical modelling stage. This is likely to be preferable.

5.6 Summary

The catchment aquifer systems are the primary water systems that can be impacted by coal mining and CSG developments. A fundamental step in developing any integrated regional numerical model of the water systems requires a comprehensive catchment-scale geological model; in essence a fundamental component of the Conceptual Model. A digital geological model is therefore required for two main reasons:

- To develop an understanding of the spatial relationship between the occurrence of coal both suitable for mining and gas extraction, and the water resources in the catchment;
- To provide a platform for numerical modelling of the aquifer systems in the catchment.

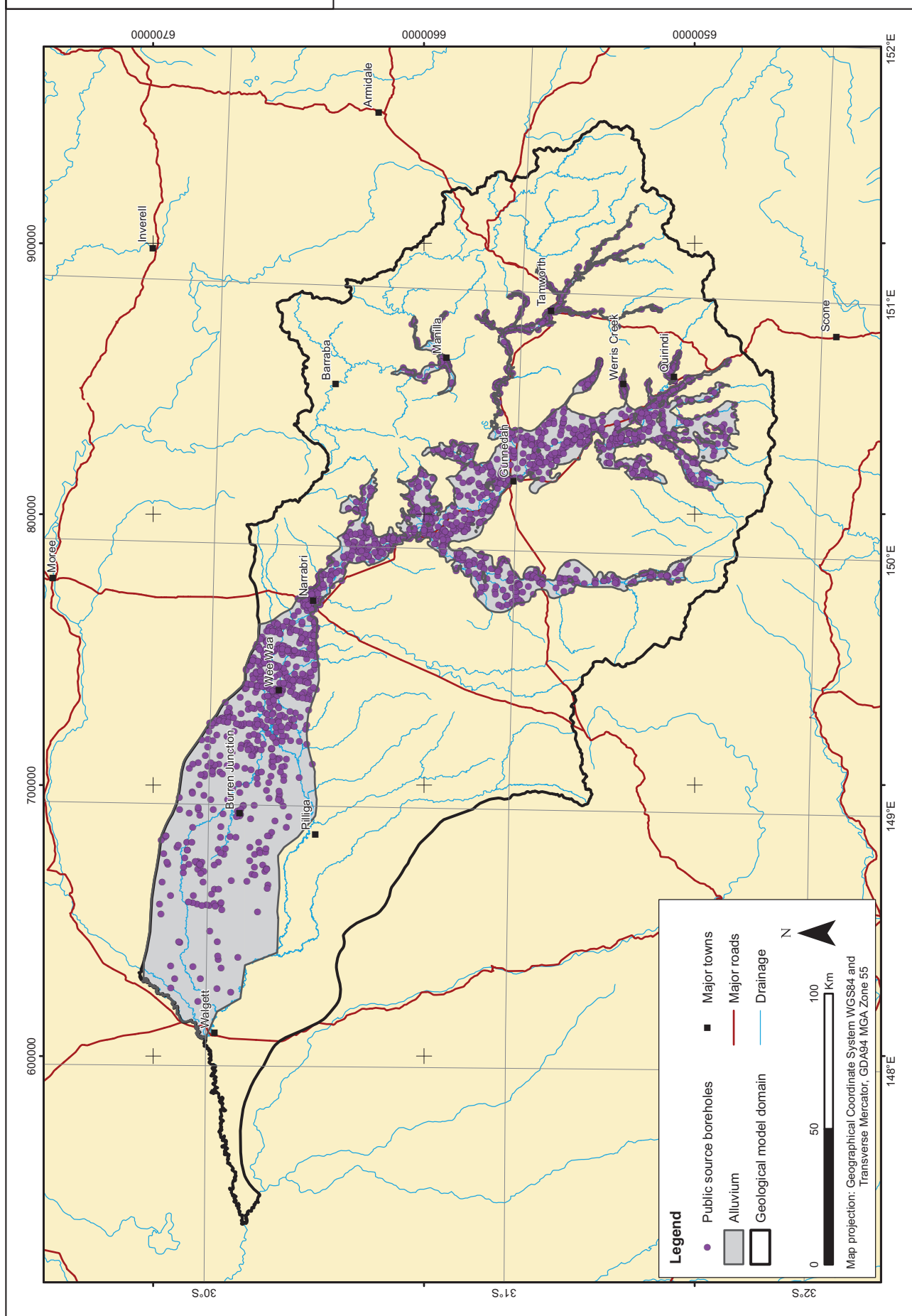
A digital model of the geological sequence in the Namoi catchment has been constructed using the Petrel software platform. The model has been based on a combination of private data (Industry Partner) and public source data and published geological cross sections. Alluvial layers and hard rock geology have been modelled in detail over the entire catchment to the depth of the top of the Boggabri Volcanics (at up to -1,400 mAHd). The model includes 18 layers representing 19 individual geological units. The major coal seams within the Black Jack Group (the Hoskissons and Melvilles seams) have been included as discrete layers in the model.

The model incorporates a representation of the Hunter-Mooki Fault System which cuts through the catchment from north to south. A detailed model of the geology to the east of the fault (dominated by metamorphic strata) has not been possible. 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 extrapolate geological surfaces to this region.

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

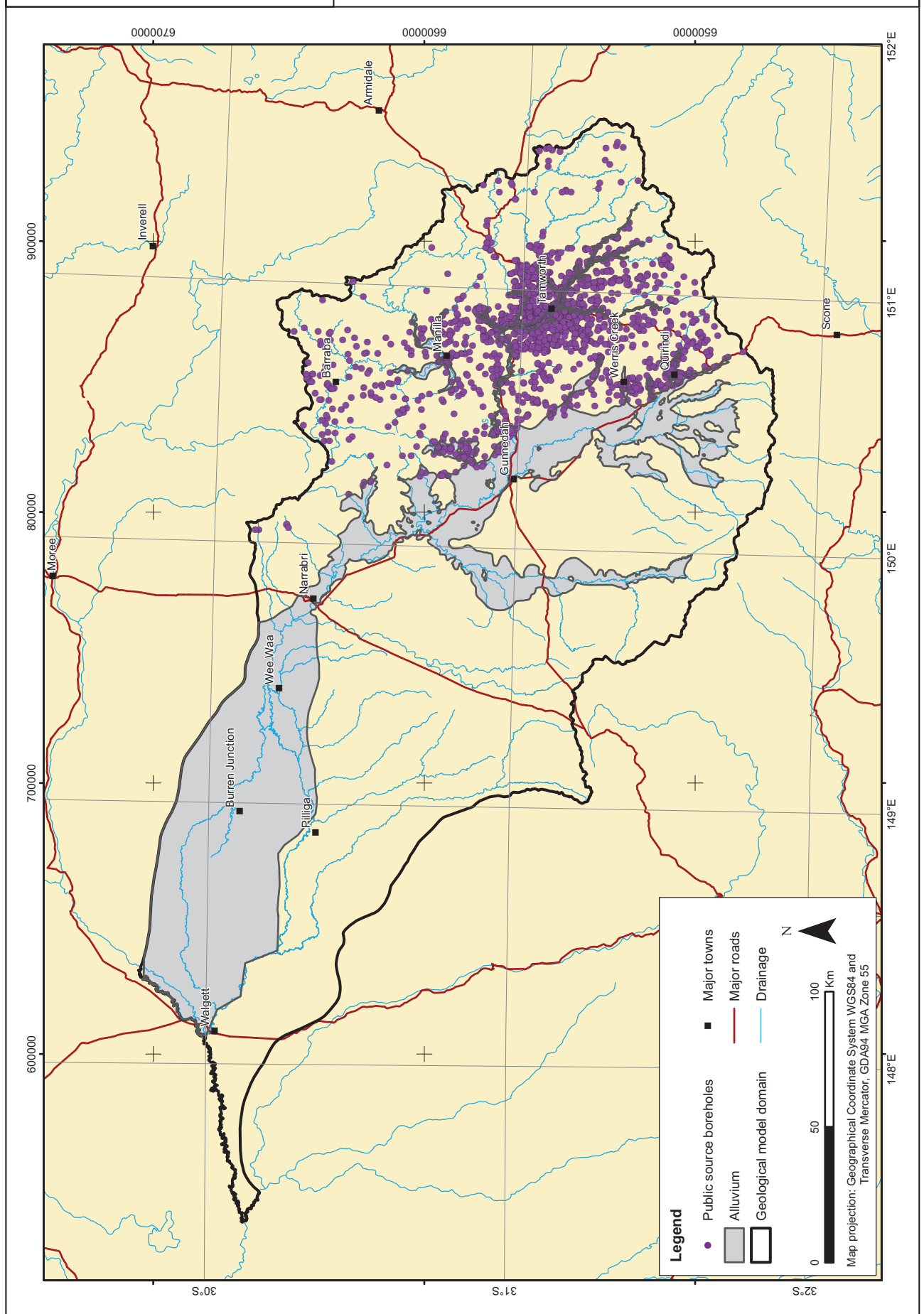
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Figure 5.1 Position of public source boreholes with drillers logs
(the information used to define the alluvium base)

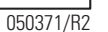


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Figure 5.2 Position of public source boreholes to the east of the Hunter-Mooki Fault System both licensed to abstract and with a recorded screen elevation

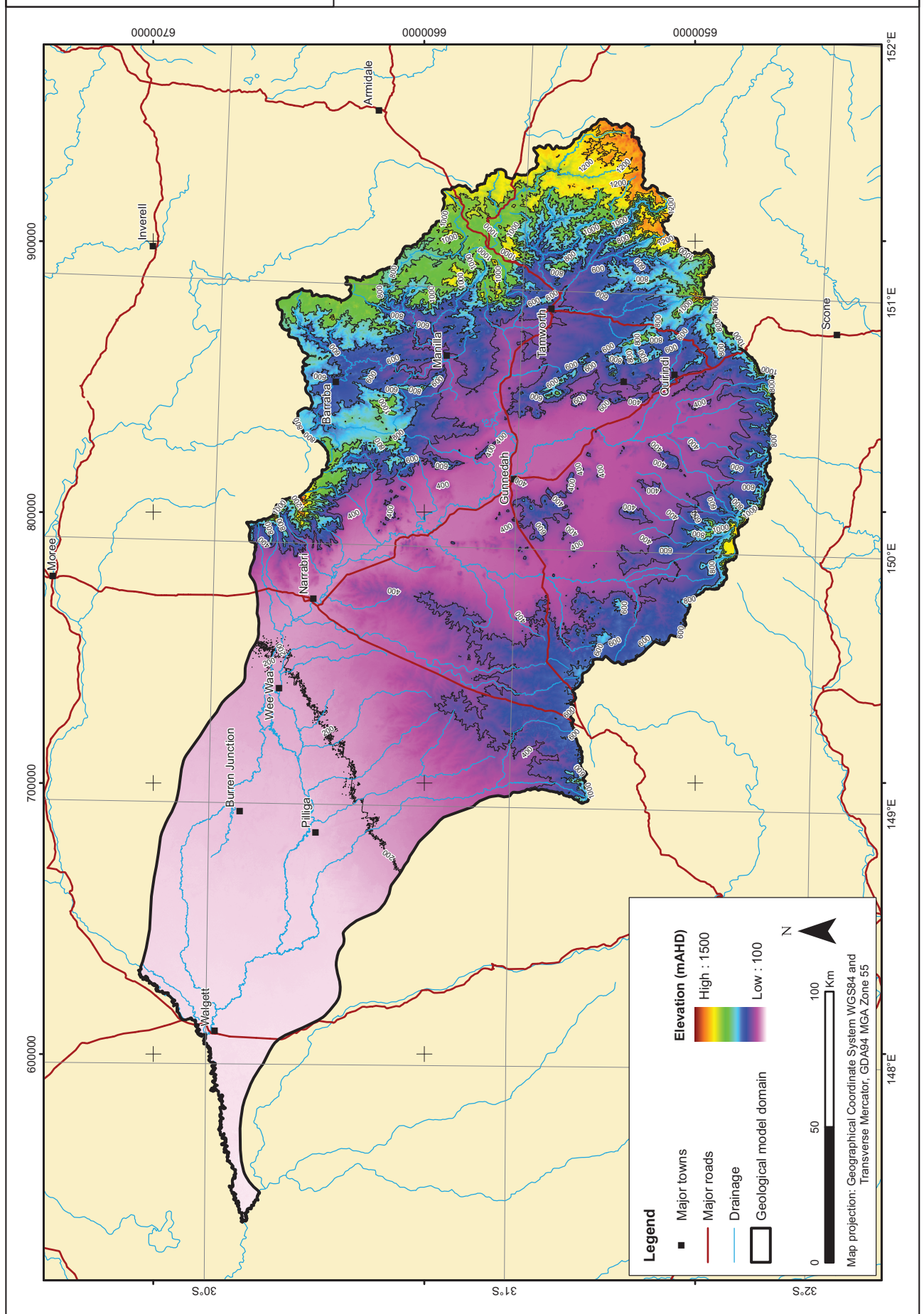


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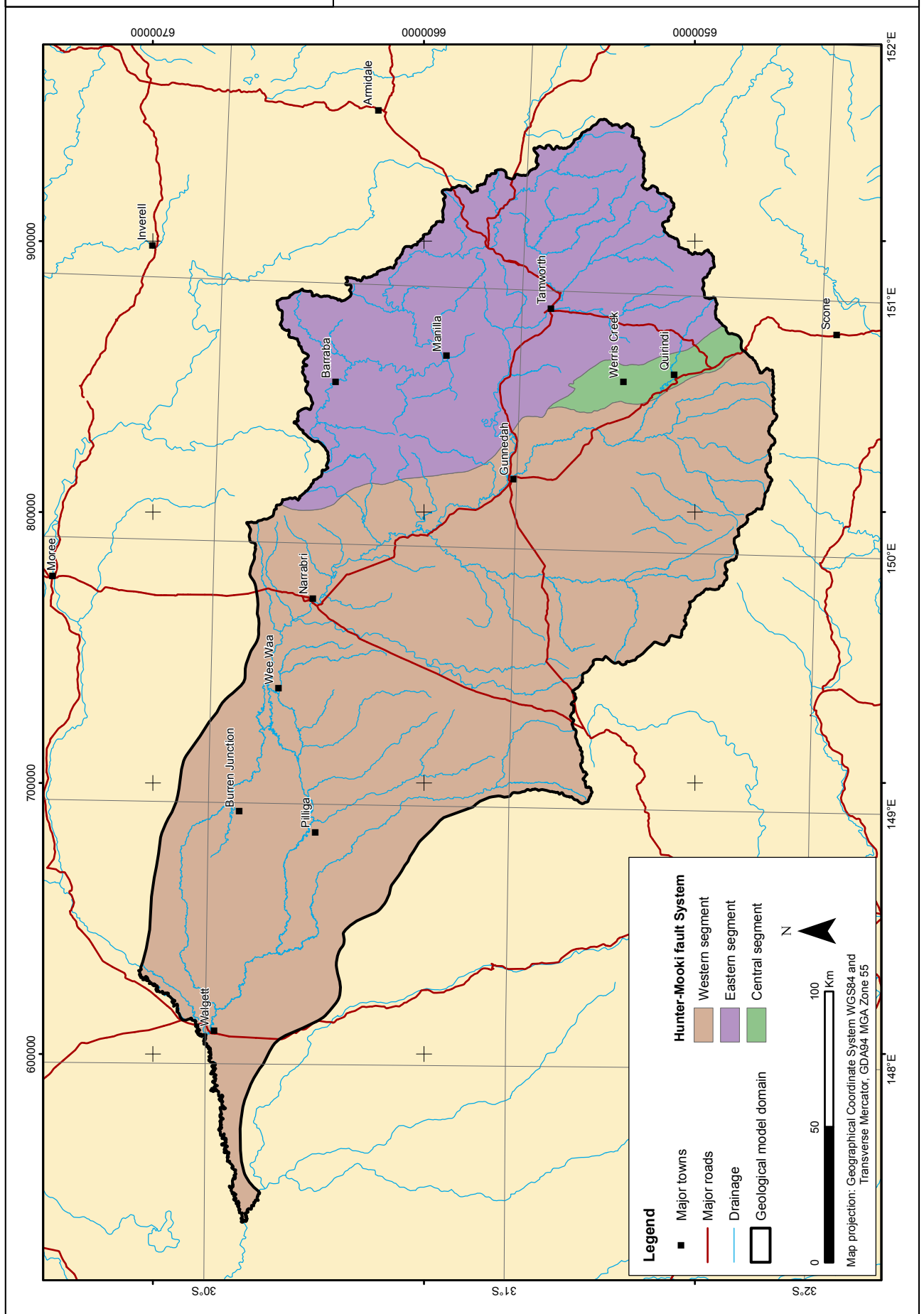
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Figure 5.4 Ground surface elevation Digital Terrain Model (DTM)



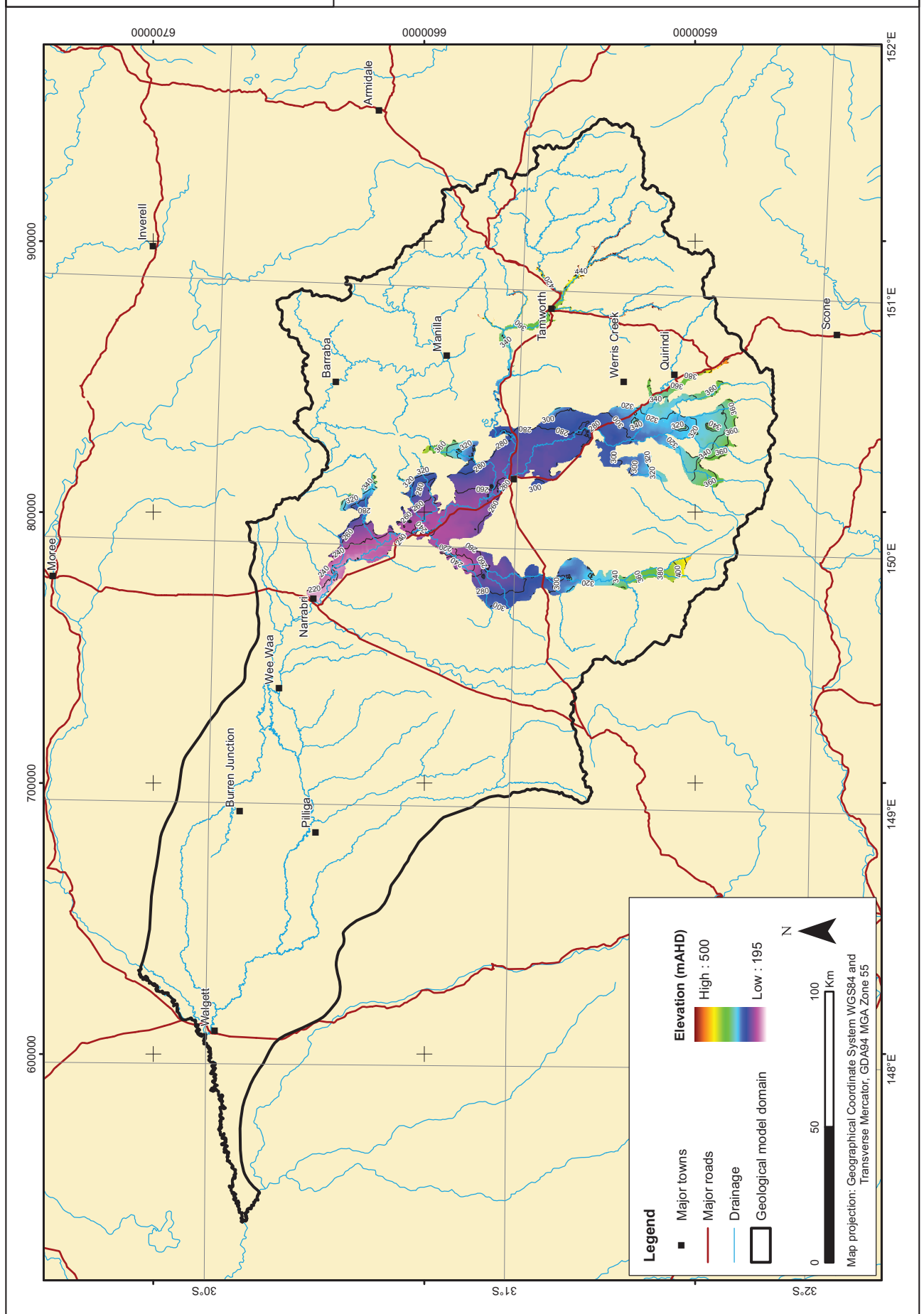
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Figure 5.5 The Hunter – Mooki Fault System; West, East and Central segments



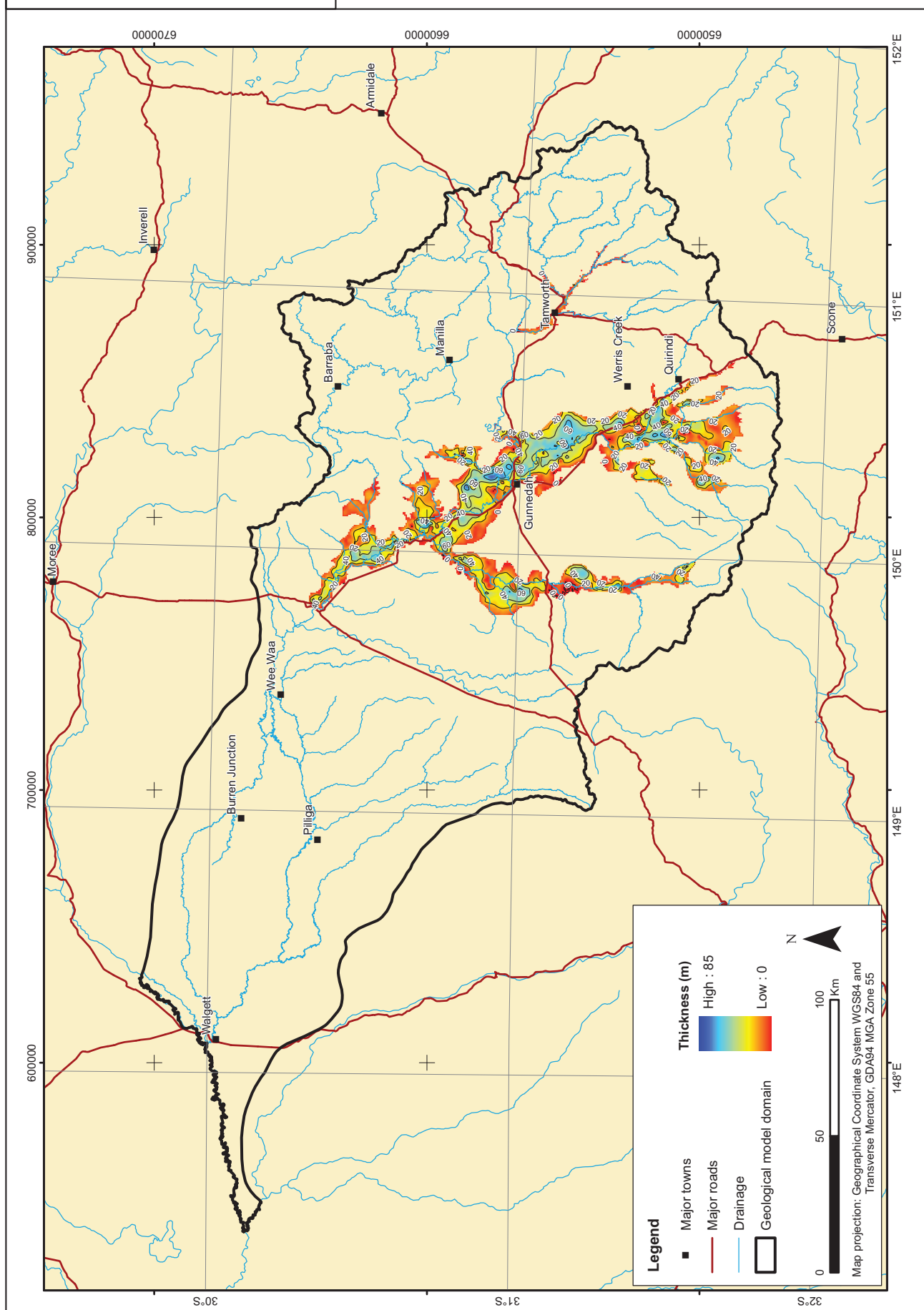
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Figure 5.6 The top elevation of the Narrabri Formation (model Layer 1)



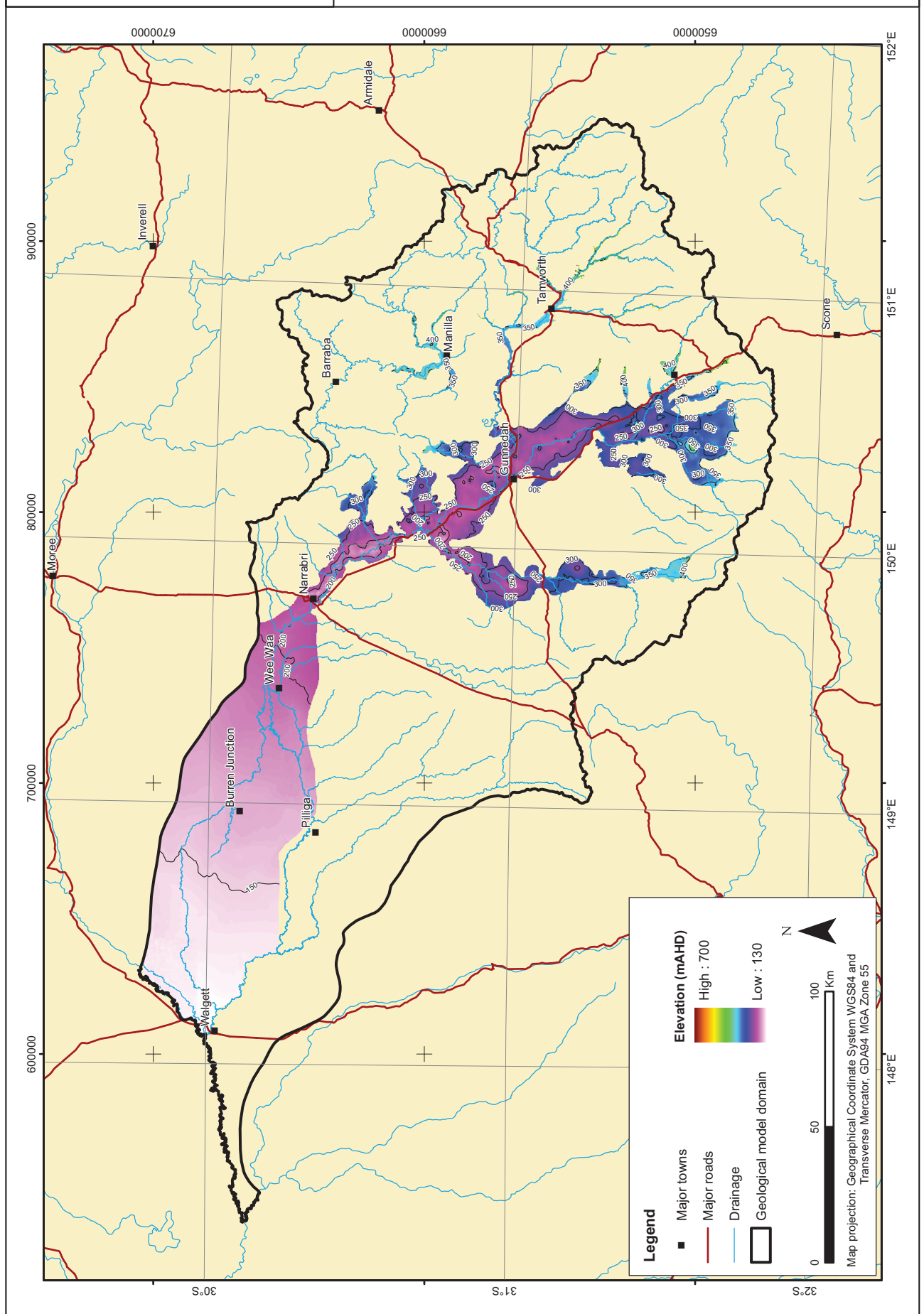
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Figure 5.7 The thickness of the Narrabri Formation
(model Layer 1)



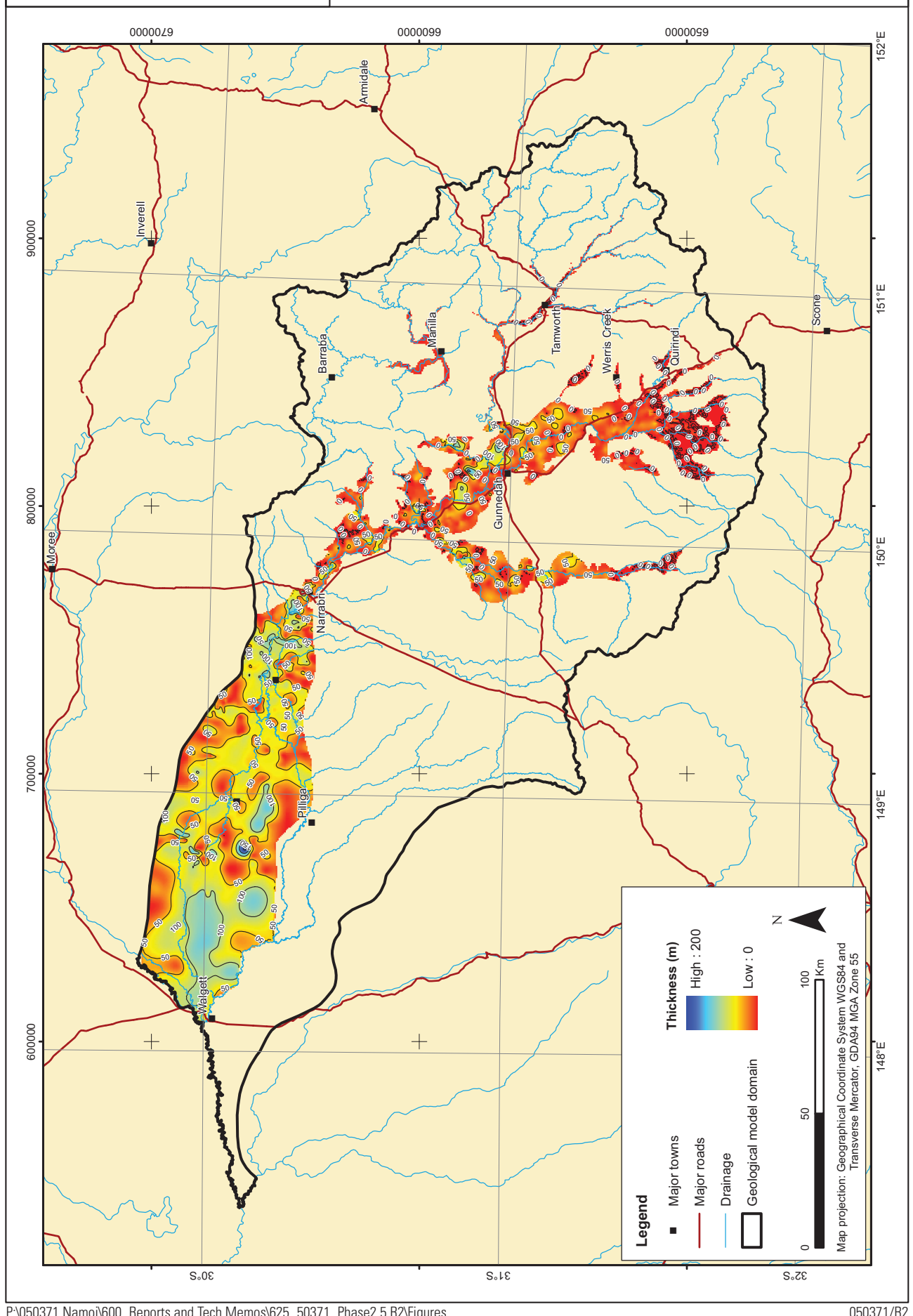
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Figure 5.8 The top elevation of the Gunnedah Formation, Lower Namoi Alluvium and Peel Alluvium (model Layer 2)



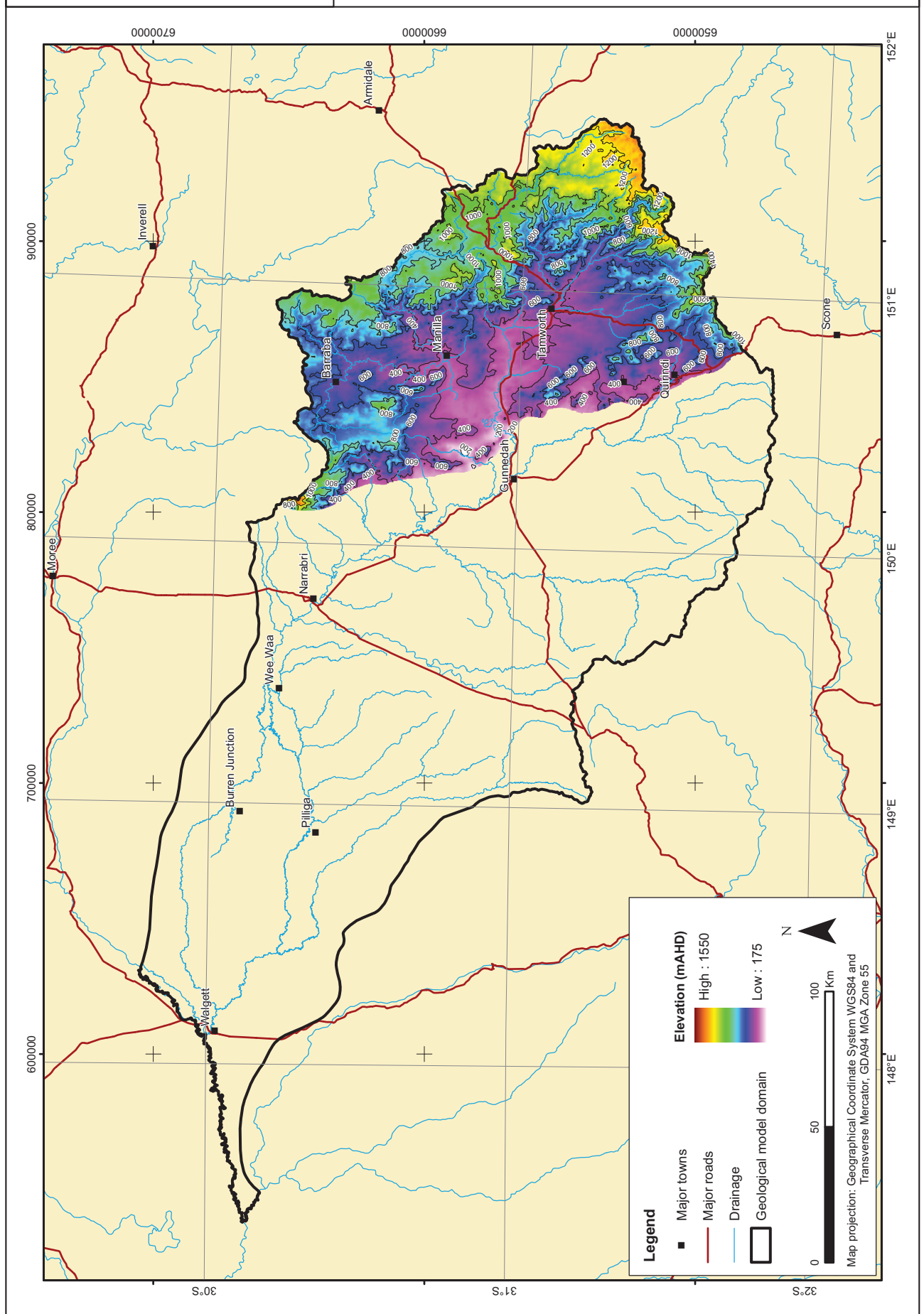
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Figure 5.9 The thickness of the Gunnedah Formation, Lower Namoi Alluvium and Peel Alluvium (model Layer 2)



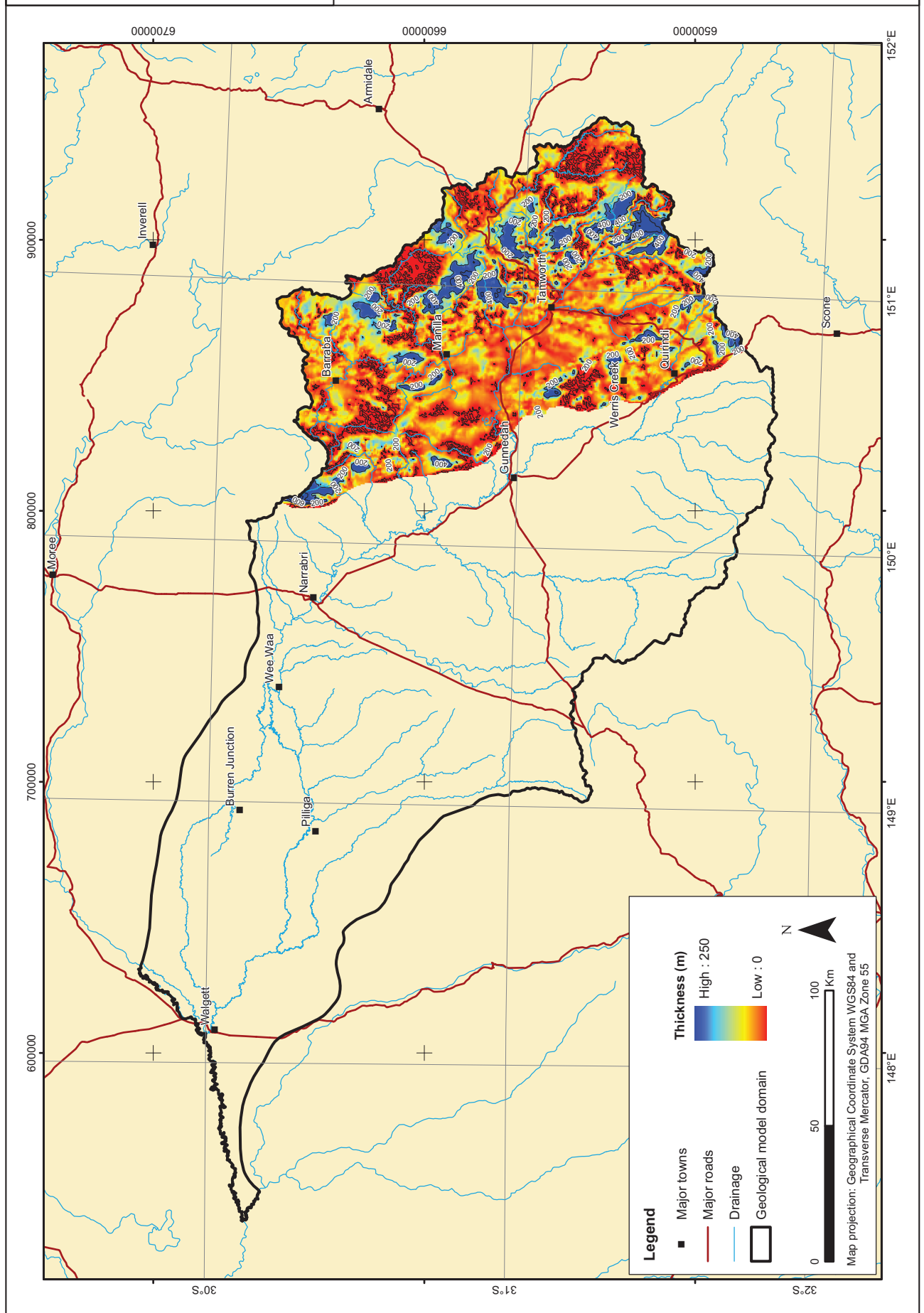
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Figure 5.10 The top elevation of the 'fractured rock aquifer' (model Layer 3)



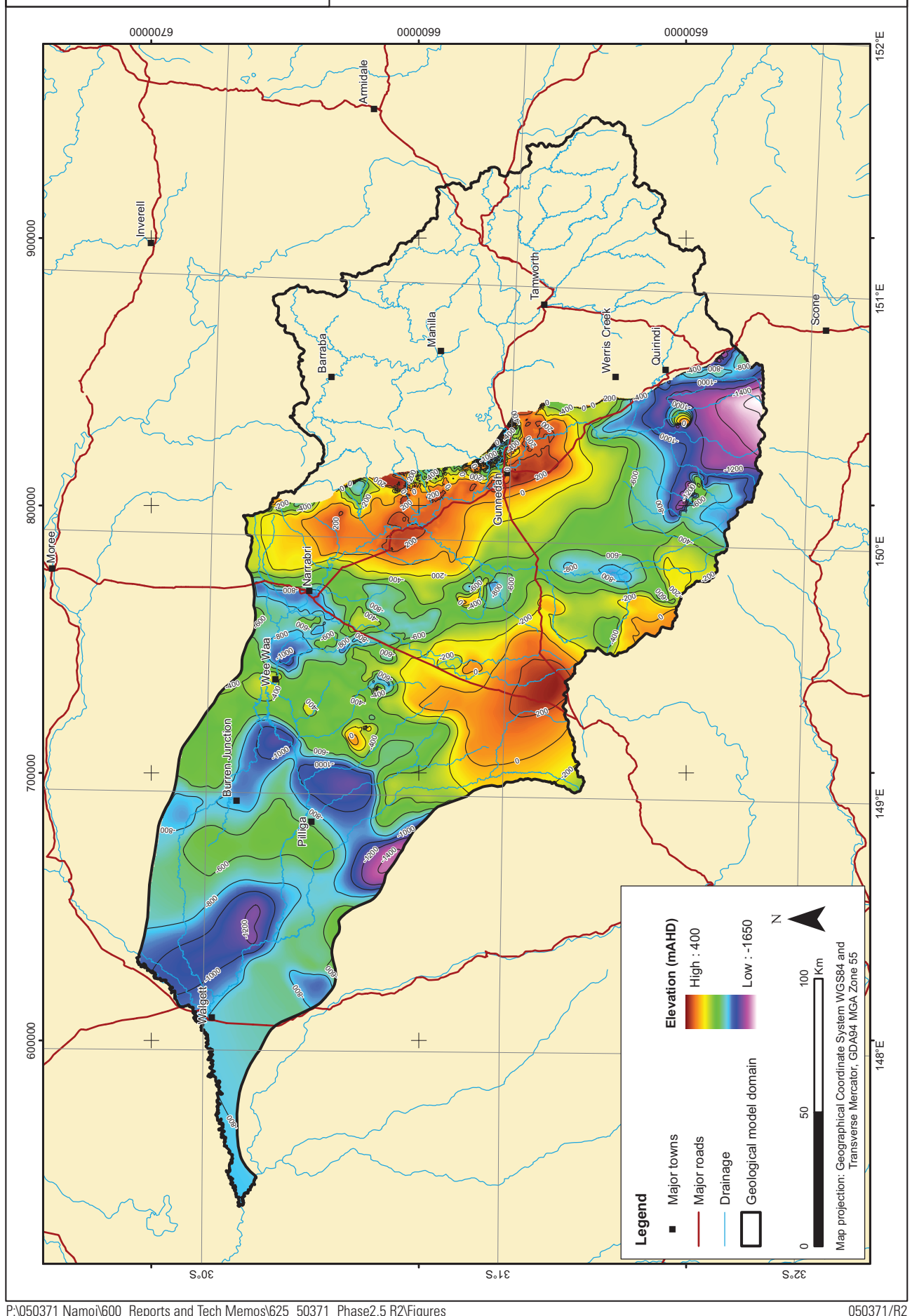
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Figure 5.11 The thickness of the 'fractured rock aquifer' (model Layer 3)



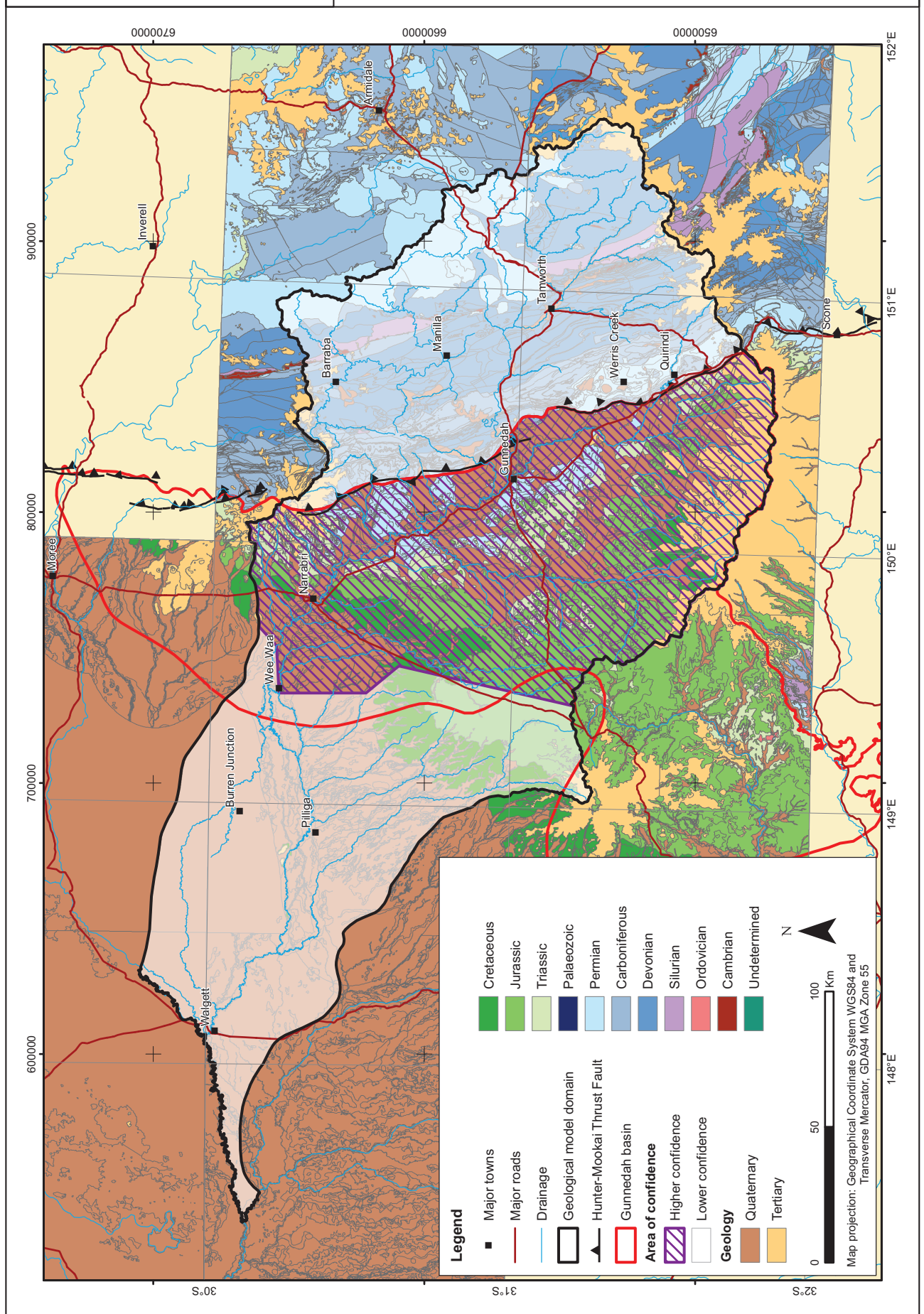
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Figure 5.12 The top elevation of the Boggabri Volcanics



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Figure 5.13 The area of highest data coverage within the geological model domain



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6 COAL AND GAS RESOURCES

6.1 Introduction

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 open-cut and underground operations with substantial developments planned or being investigated. The Gunnedah Basin is currently subject to a number of CSG developments in various stages of exploration, pre-development and exploitation.

6.2 Coal and gas extraction methods

6.2.1 *Coal mining*

The major mining method currently in use within the Namoi catchment is open-cut, but coal recovery may also involve underground mining techniques.

The various extraction methods are described by the NSW Mineral Council (2011), and a summary of this information is provided below.

Open-pit mines are generally developed when deposits of commercial minerals or rock are found relatively close to the surface, where the overburden (layer material covering the valuable deposit) is comparatively thin, where high rates of mining are planned, or the material of interest is structurally inappropriate for underground extraction (Greatmining, 2011). Open pit mining usually involves blasting and removing surface layers of soil and rock to reach the deposit. Walls of the pit are normally dug at angles of 25 to 70 degrees from horizontal to ensure pit-slope stability and lessen the probability of slope failure and rock falls (NSW Mineral Council, 2011). The angle of the walls relies most heavily on the mechanical strength and structural integrity of the wall rock and the water pressure behind the walls. Dewatering wells around the pit crest or within the pit can be used to control groundwater inflow and lower local groundwater levels (Greatmining, 2011). Drains are sometimes drilled horizontally directly into the pit walls to reduce pressures in the slopes to improve stability.

The main cost advantage of open-pit mining is that larger and more powerful shovels and trucks can be utilized as equipment is not restricted by the size of the opening it must work in (PT MMP Coal Mining, 2010).

The common factor for all forms of underground mining is the creation of tunnels extending from the surface into the mineral seam. 'Auger' mining and 'Longwall' mining are methods that may be used in the Namoi catchment, and they are described in more detail below. 'Bord and pillar' mining has also been used in several of the closed collieries, although this method has since fallen out of favour compared to other underground mining methods.

Auger mining is a method of highwall mining that involves the use of a remote controlled mining machine which is driven into a coal seam to extract the coal (NSW Mineral Council, 2011). Auger mines are operated on surface mine benches before they are covered up. This method is often used to access coal left behind from previous mining operations or when difficult geological conditions restrict the use of other mining methods. Coal is extracted from the base of a highwall (steep face) using horizontal drilling to create holes in the coal seam whilst pillars are left in place to support the roof from collapsing. The auger mining machine operates like a drill, with a cutter head rotating into the coal seam and creating circular holes to access the coal. The extracted coal is returned to the surface using the auger machine and a conveyor system (NSW Mineral Council, 2011).

Longwall mining involves the mining of an extended wall (normally about 250-400 m long) of coal in a single slice (generally 1-2 m thick) (Greatmining, 2011). The slice can be mined for several kilometres in this way. Mechanised shearers are used to cut and remove the coal at the face of the mine. After the coal is removed, it drops onto conveyors which take the coal to the surface. Temporary hydraulic-powered roof supports hold up the roof as the extraction process proceeds (Kentucky Geological Survey, 2011). The recovery rate is nearly 75%, but the equipment is expensive and cannot be used in all geological circumstances (Australian Coal Association, 2011). As mining continues, roof bolts are placed in the ceiling to avoid ceiling collapse. In longwall mining, only the main tunnels are bolted. Most of the longwall panel is allowed to collapse behind the shields, which hold the roof as coal is excavated.

6.2.2 *Coal Seam Gas*

Methods for the extraction of CSG vary depending on the type of resource. The Eastern Star Gas website (Eastern Star Gas, 2011b) provides the following fundamental information about CSG production techniques applicable to the Namoi catchment. 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 and the gas is extracted from the coal by means of wells that are drilled down (vertical wells) into seams and in some cases along the coal seams (lateral wells). 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.

CSG project development involves the drilling of a large number of wells to extract gas over wide areas. In general, production from a CSG well must be continuous. If production is halted water will typically re-enter the coal seam and the dewatering process must be undertaken again. 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 used in the Namoi catchment (Gas Today, 2009).

6.3 **Coal resources and development areas**

6.3.1 *Introduction*

Current coal mining exploration and activity prospects are limited to a zone through the centre of the catchment which closely follows the location of the alluvial deposits upstream of Narrabri. Table 6.1 provides a list of significant active (including active closure phase) coal mining operations within the Namoi catchment and summary details about each. The mine locations are illustrated in Figures 6.1 and 6.2. In the subsequent sections each of these operations is discussed in more detail with a focus on water resource use and management.

Table 6.1 Summary of coal mines within Namoi catchment

Site name and mine lease (ML) number	Operator	Location	Resource	Production rate
Tarrawonga ML1579	Whitehaven /Idemitsu	16 km east of Boggabri	78.1 Mt resources (open-cut), 33 Mt marketable reserves	1.5 Mtpa. 2006. Production started in 2006. Truck and excavator method. Export market.
Werris Creek ML1563	Whitehaven	4 km south of Werris Creek	37.4 Mt resources, 32.0 Mt marketable reserve	1.5 Mtpa. 2005. Raw coal. Truck and excavator method. Export market.
Rocglen (Belmont) ML1620	Whitehaven	28 km north of Gunnedah	20.1 Mt resources, 11.1 Mt marketable reserves	1.5 Mtpa, Production started late 2008. Truck and excavator method to Gunnedah CHPP
Sunnyside ML1624	Whitehaven	15 km west of Gunnedah	91.1 Mt resources, 27.6 Mt marketable reserve	1 Mtpa. 2008. Raw coal. Production started in late 2008. Open-cut and highwall auger
Narrabri ML1609	Whitehaven /Idemitsu	28 km south of Narrabri	Narrabri North 475.4 Mt, Narrabri South 379.2 Mt resources Narrabri North 133.4 Mt, Narrabri South 66.5 Mt marketable reserves	0.7 Mtpa to 5.3 Mtpa once phase two production starts. Continuous miners. Production started mid 2010. Raw coal until washery built.
Boggabri	Idemitsu	15 km northeast of Boggabri		1.4 Mtpa saleable coal, 2008 1.55 Mtpa coal exported, 2009
Canyon (Whitehaven) ML1471, ML1464	Closed Whitehaven	15 km east of Boggabri		Up to 1 Mtpa. 2000. All exported. Last coal mined in July 2009. Rehabilitation by end of 2010. Environmental monitoring for additional five years

(Whitehaven, 2011b)

The expected lives of the coal mines are approximately twenty years but vary from one mine to another. At the end of exploitation, the final voids are expected to reach a depth between 200 mAH and 300 mAH. A summary of this information for each of the existing mines is provided in the Table 6.2.

Table 6.2 Coal mines expected life and final depth

Mines	Mining methods	Expected final depth	Expected mine life
Tarrawonga	Open-cut	265 mAHD (Whitehaven, 2010c)	2006 -2016 (excluding a proposed 13 years extension) (Whitehaven, 2010c)
Werris Creek	Open-cut	190 m below ground level (Werris Creek Coal, 2011)	2005 – 2025 (Business Spectator, 2011)
Rocglen	Open-cut	220 mAHD (Namoi CMA, 2011b)	2008 – 2020 (Whitehaven, 2008)
Sunnyside	Open-cut + auger mining	295 mAHD (GeoTerra, 2008)	2008 – 2013 (OEC, 2008)
Narrabri	Underground (longwall mining)	East 160 – 180 mAHD West 380 mAHD (Whitehaven, 2011a)	2010 – 2070 (NSW Narrabri Council, 2007)
Boggabri	Open-cut	285 mAHD (AGE, 2010)	2006 – 2031 (Idemitsu, 2009)
Canyon Mine (recently closed)	Open-cut	Void backfilled to 25 m below ground level (Whitehaven, 2009a)	2000 – 2009 (Whitehaven, 2009a)

In the context of water use and the impact on water resources, even those mines that do not wash their product through a preparation plant need significant quantities for dust management, drilling, human consumption and numerous other uses. Current corporate reports provide statistics showing that approximately 0.2 m³ of fresh water can be consumed for every tonne of coal produced, although that can vary both upwards and downwards according to operating practice and circumstances. The transformation of this fresh water to dirty water which must then be managed through the mines systems and storages generates additional challenges for the mine operators (Evans et al., 2003).

Detailed water balances and water requirements for the mines can be found in Appendix C.

6.3.2 Coal mines operated by Whitehaven

Whitehaven Coal Limited is the sole operator of 3 coal mines (2 open-cut mines and a single combined open-cut / underground mine). An additional open-cut mine was decommissioned in 2009. The mines are described in detail below.

Canyon mine (recently closed)

A closure plan for the Canyon open-cut mine was submitted in July 2009. The closure plan aims to return the mine lease area to uses that existed pre-mining, principally agriculture, grazing, and native vegetation. The base of the void will be backfilled to 25 m below ground level to cover any exposed coal seams (Whitehaven, 2009a and 2009b). It is hoped that this will reduce the amount of groundwater interaction within the void. The final void has been designed as a surface water storage facility. If monitoring shows high salinity due to excess groundwater inflows, which would render the site unsuitable for agricultural or grazing, closure plans suggest it could be lined with clay.

According to Whitehaven (2009b), from 2001 to 2009 the annual water requirement from the mine was between 110 and 230 m³/d. This was sourced from a combination of licensed groundwater abstraction, groundwater and surface water flow into the pit, and surface flows (runoff) to sediment basins and storage dams. Generally about 50% of the water was derived from the latter.

Rocglen

The Rocglen open-cut mine, formerly known as the Belmont Coal Project, is located 28 km north of Gunnedah. The open-cut pit covers an area of 1.1 km². Rocglen production started in late 2008 with an initial production rate of 1.5 Mtpa (NSW DPI, 2011c) and a resource estimation of 20.1 Mt (Whitehaven, 2011b). In the future, open-cut mining may be supplemented by auger mining, to a distance of 200 m beyond the western limit of the open-cut (Whitehaven, 2010d). The Rocglen coal deposit is contained within the Early Permian Maules Creek Formation (Whitehaven, 2010d).

Operational water requirements are preferentially sourced from dirty water run-off collected on site, together with any surface water and groundwater which accumulates in the open-cut, and is pumped to designated pit dewatering dams (Whitehaven, 2009c). Any shortfall is supplemented by harvested clean water. The total water requirement of this operation is reported to be about 280 m³/d (Whitehaven, 2009c).

Table 6.3 shows the predictions of inflow to the open-cut pit provided by numerical modelling (Whitehaven, 2009c). Combined with inputs from other sources, e.g. surface run-off, the figures suggest that the mine receives more water than it uses (Appendix C).

Table 6.3 Rocglen Mine - Groundwater inflows

Years	Average Inflow of Groundwater (m³/d)
2008 to 2011	1,643
2012 to 2013	223
2014 to 2015	1,813

(Whitehaven, 2009c)

Sunnyside

Sunnyside open-cut coal mine is located 15 km west of Gunnedah. The pit covers an area of approximately 0.4 km² and production started late in 2008. The current production rate is 1 Mtpa (NSW DPI, 2011c) and the resources estimation is 91.1 Mt (Whitehaven, 2011b). Additional coal resources may be accessed by auger mining from the southern highwall within the open-cut area (NSW DPI, 2011c).

Two major coal seams occur beneath the project site, namely the Hoskissons seam and the underlying Upper and Lower Melvilles seam. However, it appears to be only economic to extract from the Hoskissons seam. The depth of weathering extends approximately 30 m below surface, with the depth to the top of the Hoskissons seam extending up to approximately 65 m below surface in the open-cut pit area (Corkery and Co Pty Ltd., 2008).

The operational water requirement for the Sunnyside Coal Mine is in the range of 205 to 274 m³/d, depending on seasonal conditions. Combined with inputs from other sources the figures suggest that the mine receives more water than it uses (OEC, 2008).

A FEFLOW groundwater model was constructed to simulate the interaction of the open-cut pit with the groundwater system (GeoTerra, 2008). The model predicts that drawdown (reduction in groundwater levels) will not exceed 1 m in bedrock formations outside of the immediate Sunnyside open pit area. Pit inflows were predicted to vary between 175 and 290 m³/d (Table 6.4).

Table 6.4 Sunnyside Mine - Groundwater inflows

Years	Modelled Pit Inflows (m³/d)
2008	260
2009	270
2010	285
2011	220
2012	190

(GeoTerra, 2008)

Werris Creek

Werris Creek coal mine is an open-cut mine adjacent to an old underground mine called Werris Creek Colliery, which was active from 1925 to 1963. Werris Creek coal mine is located 4 km south of Werris Creek and is operated by Whitehaven. The open pit covers an area of approximately 0.7 km² and is up to 150 m deep. Production started in 2005 at 1.5 Mtpa (Whitehaven, 2011c). The resources estimation is 37.4 Mt (Whitehaven, 2011b). Seven mineable coal seams have been identified with a combined thickness of 130 m.

The site water requirement is about 300 m³/d (Werris Creek Coal, 2005). Generally the site intercepts sufficient water to meet this demand. In particularly dry years, however, groundwater extraction from the underground workings of the former Werris Creek Colliery and other licensed groundwater bores will be used to make up the shortfall (Werris Creek Coal, 2005).

6.3.3 *Whitehaven and Idemitsu joint venture coal mines*

Whitehaven Coal Ltd and Idemitsu Australia Resources Pty Ltd are joint operators of 2 coal mines (1 open-cut and 1 underground (longwall)). The operations are described in detail below.

Tarrawonga

Tarrawonga Coal Mine, also known as East Boggabri project, is located 16 km east of Boggabri. Coal mining by open-cut mining methods is defined over an area of approximately 1.6 km². Tarrawonga production started in 2006 with an initial production rate of 1.5 Mtpa (NSW DPI, 2011). The resources estimation is 78.1 Mt (Whitehaven, 2011b).

Coal seams within the Boggabri Project area are hosted by the Maules Creek Formation. A total of 16 seams have been formally identified and correlated. Of these, 8 seams have been targeted for open-cut operation (Whitehaven, 2010a). Additional coal seams are not amenable to open-cut mining but have potential for future underground development (Whitehaven, 2010a). The estimation of Tarrawonga underground mine resources is 40.2 Mt (Whitehaven, 2011b).

About 240 m³/d of water is required on the mine site primarily for dust suppression, with minor quantities required for potable and toilet/ablutions purposes (Soil Services, 2005). The amount of water intercepted by the mine is greater than this. Groundwater modelling (Soil Services, 2005) has shown for example that the inflow to the pit may vary between 500 and 700 m³/d during the life of the mine (Table 6.5).

Table 6.5 Tarrawonga Mine – Predicted groundwater inflows

Years	Groundwater inflows (m³/d)
2007	650
2009	640
2011	700
2013	520

(Soil Services, 2005)

Narrabri

The Narrabri coal mine is an underground (longwall) operation located 28 km south of Narrabri. The resources estimations are 475.4 Mt for Narrabri North and 379.2 Mt for Narrabri South (Whitehaven, 2011b). The coal resource of the Narrabri Coal Mine is contained within the Hoskissons seam, which is 8 to 10 m thick in this area.

The mine is being developed in two stages (Whitehaven, 2010b). Stage 1 of the project was approved in late 2007 and commenced in June 2010. Initial production (under Stage1 approval) is approximately 0.5 - 0.7 Mtpa with a limit of 2.5 Mtpa.

According to Whitehaven (2010b), Stage 2 was approved in July 2010. It involves the installation of additional coal processing and handling infrastructure to increase the annual production rate from 2.5 to 8 Mtpa. The longwall for Stage 2 was ordered in September 2009 to commence delivery in early 2011 Whitehaven (2010b).

The Narrabri Coal Mine lies within the catchment of the Namoi River. Locally, and within proximity of the project site, Kurrajong Creek and Pine Creek provide flows to the Namoi River during runoff events (Narrabri Coal, 2009). Sediment detention basins within the disturbed area of the pit top area have been designed to limit the opportunity for uncontrolled discharge of runoff from the mine-disturbed area (Narrabri Coal, 2009).

Within the Narrabri Coal Mine area, surface water resources are limited to a number of ephemeral drainage lines which flow for a short period after substantial rainfall, farm dams, and newly constructed water storage dams and groundwater sources (Narrabri Coal, 2009). Water is required on the mine site in Stage 1 primarily for dust suppression purposes, with minor quantities required for potable and toilet ablutions purposes (Narrabri Coal, 2009). Where practicable, water collected on-site is retained or reused, with water for dust suppression sourced from a combination of on-site water harvesting, inflows from the overburden during drift development, and groundwater extraction (Narrabri Coal, 2009). Water for potable, toilet and ablutions purposes is trucked to the site from Narrabri (Narrabri Coal, 2009).

Based upon operational experience during Stage 1 of the mining, consideration of water requirements at similarly sized underground mines and the completion of a water balance analysis, the predicted water requirements for Stage 2 development total about 3,000 m³/d (Whitehaven, 2011a). Water requirements will be met from groundwater inflow, surface water runoff and water extracted from the Namoi River (licensed).

Active dewatering of the groundwater system will undertaken to support development of the underground mine. Whitehaven (2011a) suggests that the dewatering rates will be about 200 m³/d in 2011 and 3,900 m³/d by 2028. Dewatering rates are expected to fall after 2028 as a significant volume of the inflowing water can be retained in completed areas which are down-dip of the active panels

A detailed water balance for the mine is presented in Appendix C.

The groundwater that would be encountered by the underground workings is reportedly saline with an average total dissolved solids (TDS) concentration of between 6,000 mg/L and 8,000 mg/L expected (Whitehaven, 2011a). The saline water will be treated by ultra-filtration and reverse osmosis. The treated water will be re-used underground for dust suppression and equipment cooling purposes, or if surplus to operational requirements, discharged from the pit top area to the Namoi River (Whitehaven, 2011a). A by-product of the water treatment would be the generation of significant volumes of brine, i.e. saline water, with approximately 20,000 m³ generated for every 100,000 m³ of raw water treated (Whitehaven, 2011a). The current proposal for managing this brine is to store it at surface for the life of the mine before progressively pumping it back into the underground workings (Whitehaven, 2011a).

6.3.4 *Idemitsu operated coal mines*

Idemitsu Australia Resources Pty Ltd are sole operators of a single mine in the Namoi catchment (the Boggabri mine).

The Boggabri coal mine is located 15 km northeast of Boggabri. Production started in 2006. The mine currently produces 2.8 Mt of thermal and pulverized coal injection (PCI) coal annually, which is exported through the Port of Newcastle (Idemitsu, 2011). Approval has been received to increase production to 4.3 Mt annually by 2013. A total of approximately 210 Mt are mineable by open-cut methods. The initial mine plan targets approximately 100 Mt of this resource. The mine extracts coal from the Maules Creek Formation (Idemitsu, 2011).

Parsons Brinckerhoff (2010) provided a water assessment for the continuation of Boggabri coal mine. Water requirements were predicted to increase from about 600 m³/d in 2006 to nearly 3,000 m³/d in 2027. From the available data it is not clear how much groundwater is expected to flow into the pit, although it could be about 1,200 m³/d (based on the water balance for a dry year – as provided in Appendix C).

Three aquifer systems exist in the region: the alluvial aquifer associated with the Namoi River floodplain and tributaries; the weathered bedrock near the ground surface; and the coal seams of the Maules Creek Formation (Whitehaven, 2010c).

Modelling demonstrates that the cones of depression from the existing Tarrawonga mine and Boggabri mine may be interacting (Whitehaven, 2010c). The zone of influence is simulated to migrate to the boundary of the Namoi Valley alluvial aquifer to the south within the first five years of the project (Whitehaven, 2010c). The simulated higher recharge rate from slope wash runoff and the presence of the Boggabri Volcanics prevents further propagation of the zone of influence (Whitehaven, 2010c). The project is predicted to result in the reduction in the rate of the groundwater flow from the Permian coal seam aquifers to the base of the Namoi Valley alluvial aquifer (Whitehaven, 2010c). This reduction in water level in the alluvial aquifer is predicted to be less than one meter (Whitehaven, 2010c).

6.3.5 *Potential areas for future mining development*

Coal operations are expected to expand in the Gunnedah Basin over the coming decade (ACIL Tasman, 2009). The Gunnedah Basin presently produces 11 Mtpa (in 2009) of coal and this is projected to increase to 55 Mtpa by 2021 (ACIL Tasman, 2009). Significant mining projects currently in the exploration and pre-development phase are discussed in the following subsections.

Maules Creek

Maules Creek, operated by Aston Resources, is located in the heart of the Gunnedah Basin approximately 20 km northeast of Boggabri and 16 km from the main railway line servicing the coal terminals at the Port of Newcastle. The Project has estimated resources of 679 Mt and coal reserves of 362 Mt (Aston Resources, 2011). The resource is expected to sustain a potential project life in excess of 30 years.

Aston has developed a detailed 20 year mine plan and expects first coal in the second half of 2012, with saleable production exceeding 10 Mtpa from 2014 (Aston Resources, 2011). The project will target coal seams within the Maules Creek Formation, with the expected base of the pit at approximately 50 mAHD (AGE, 2010).

Watermark

Shenhua was granted the Watermark Exploration Licence (EL 7223) in October 2008 over an area of 195 km² area, approximately 30 km south of Gunnedah (Shenhua, 2009). The Watermark deposit is expected to contain shallow resources of domestic and export quality thermal coal, with in situ coal resources expected to exceed 1 billion tonnes. Should a viable mine be identified, Shenhua anticipates construction of the mine to commence in 2012, with mine production commencing in 2013 (subject to the issue of all necessary environmental planning and mining approvals) (Shenhua, 2009).

Shenhua has identified potentially significant deposits of thermal coal contained in the Hoskissons and Melvilles seams (Shenhua, 2009). Additional coal is present in seams overlying the Hoskissons seam and in the Maules Creek seam at depth (Shenhua, 2009). Shenhua have undertaken drilling to depths from 35 m to 411 m to reach the three different coal seams: Hoskissons, Melvilles, and Maules Creek (Shenhua, 2009). Exploration and analysis of the deposit is expected to be completed within three phases. Each phase is planned over a nine month period that could partly be run in parallel so that the total program will be aimed for completion over one and a half years (Shenhua, 2009).

Caroona Coal

BHP Billiton commenced exploration activities in the Caroona Exploration Licence Area (ELA), approximately 22 km west of Werris Creek, in April 2006 as part of a five year program to determine the extent of the coal resource and potentially develop a mine proposal (BHP Billiton, 2008). The regional exploration and the targeted exploration have been completed and the project assessment phase should end in 2011. The Caroona deposit is estimated to contain more than 500 Mt of in situ potentially mineable underground coal that may produce a high quality exportable thermal coal (BHP Billiton, 2008).

After two years of exploration, BHP Billiton has identified areas within the Exploration Licence Area (ELA) for further targeted exploration. These areas are generally located under the ridge country of Doona Point (including Doona State Forest), Nicholas Ridge and George's Island. These areas are being targeted for further exploration because they represent a significant coal resource that has the potential to be efficiently extracted by underground longwall mining (BHP Billiton, 2008). The targeted exploration area represents approximately 126 km² of the 350 km² ELA.

The parts of the ELA that are excluded from the targeted exploration area are generally the floodplain and where the deep alluvial aquifers are located. The Mooki River and Quirindi Creek are outside the area to be targeted for further exploration. BHP Billiton is not considering open-cut mining on any part of the Caroona ELA (BHP Billiton, 2008).

Goonbri

Exploration License (EL) 7435, which is held by Goonbri Coal Company, covers an area of 984 ha 18 km east-northeast of Boggabri and expires on December 2014 (NSW DRE, 2011). It is possible that a future open-cut or underground coal mine will be developed within EL 7435 (Goonbri project) under a new project approval which may be made at some time in the future. There have been no approvals issued or applications made for this proposal to date that are publically available (NSW DRE, 2011).

6.4 Infrastructure development within the catchment

According to PriceWaterhouseCoopers (2009) the current rail network through the Liverpool Range will require upgrading if coal output continues to increase. Whitehaven and Idemitsu have already sponsored investments to increase capacity to meet their needs (15 Mtpa in 2010). Further track upgrades which would increase the carrying capacity to 18 Mtpa have been identified, but additional capacity above this volume would require substantial investment (PriceWaterhouseCoopers, 2009). Coal producers within the catchment have formed a project group with Australian Rail Track Corporation (ARTC) to define and cost this upgrade (PriceWaterhouseCoopers, 2009). Another study is looking at creating a new inland freight rail line between Melbourne and Brisbane passing through the Namoi catchment. The benefits to the catchment have not yet been identified (PriceWaterhouseCoopers, 2009).

6.5 Potential impacts of coal mining on water resources**6.5.1 *Open-cut mining***

Smith (2009) provides a description of the potential impact of open-cut mining on water resources. Through excavation and dewatering, open-cut mining may have impacts on streams, aquifers and alluvial soils. The associated pit infrastructure intercepts then captures rainfall and runoff. Mining below the water table can have an impact on groundwater resources due to dewatering inducing local changes of groundwater gradients and flow directions. Pit runoff water can be contaminated water with suspended solids and/or dissolved minerals and metals, and needs to be treated before discharge into the local drainage system (Smith, 2009).

6.5.2 *Underground mining*

Underground mining induces groundwater flow just as open-cut mining does. This water needs to be managed, preferably by intercepting it before it reaches the void (via dewatering wells). This will have an impact on the local groundwater system. The direct effect of underground mining on surface water features is generally less than open-cut mining, due to the smaller surface expression of the mine and reduced area of surface water management.

However, a significant aspect of underground mining, particularly from longwall methods, is surface subsidence (Smith, 2009). As the longwall progresses through the seam, the cavity behind the longwall increases and eventually collapses under the weight of the overlying strata (Smith, 2009). This collapsing causes surface subsidence, which can affect surface drainage patterns and water quality (Smith, 2009).

Underground mining can also induce connective cracking 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).

6.5.3 *Water quality*

Operations in either underground or open-cut mines have the potential to cause the discharge of often poor quality groundwater to surface water and groundwater systems. According to the NSW Department of Environment and Conservation (NSW DEC, 2004) minewater can be highly saline, and high in metals and acidity.

A significant challenge to the mining industry is to manage large site storages of dirty water of varying quality so as to minimise discharges to the local environment, while at the same time allowing any existing drainage processes to continue with as little disturbance as possible.

6.6 Coal Seam Gas resources and development areas

6.6.1 *Introduction*

Eastern Star Gas (ESG) and Santos are the two main operators of CSG projects within the Namoi catchment area.

Before undertaking any activities, companies or individuals wishing to explore for CSG in New South Wales must first apply to the Minister for Mineral Resources for one of the licences issued under the Petroleum Act (NSW Department of Industry and Investment, 2011b). There are three main types of permits issued under the Petroleum Act; the Petroleum Exploration Licence (PEL), the Petroleum Assessment Lease (PAL) and the Petroleum Production Lease (PPL).

A PPL allows commercial extraction or production of petroleum resources. If exploration reveals significant resources, the titleholder may make a separate application and go through an assessment process before petroleum production is allowed, as required by the Petroleum Act (NSW Department of Industry and Investment, 2011b). A PPL is initially granted for up to 21 years and allows the operator exclusive right to conduct petroleum extraction and production on an area no larger than four adjoining five minute graticular blocks, equating to less than 3% of the original maximum exploration area (NSW Department of Industry and Investment, 2011b). There is only one PPL in the area of Namoi catchment; PPL 3 has been granted to ESG for the development of the Coonarah conventional gas field, located about 20 km west of Narrabri. The field was fully appraised by drilling in 2001 and the '2P' (proven and probable) reserves of 11.3 PJ (10^{15} Joules) natural gas are currently being produced from the Maules Creek sandstone reservoir to fuel Wilga Park Power Station (Eastern Star Gas, 2011d).

PAL 2 has been granted to ESG for the development of the Bohena gas field, located about 21 km west of Narrabri. The Bohena gas prospect is sometimes known as the 'Narrabri CSG Project'.

The rest of the CSG projects within Namoi Catchment are under PEL at the present time (NSW Department of Industry and Investment, 2011b). Figures 6.3, 6.4a and 6.4b show the current extent of petroleum exploration leases (PEL, PAL and PPL) within the catchment.

6.6.2 *Narrabri Coal Seam Gas Project (PAL 2)*

PAL2 represents a small portion of PEL 238 which covers most of the Pilliga State Forest. ESG holds a 65% interest in PEL 238 and PAL 2 and is the operator (NSW Department of Industry and Investment, 2011b). The remaining 35% interest has been held by Santos since 2009 (NSW Department of Industry and Investment, 2011b). The targeted coal seams for the project are primarily located in the Maules Creek Formation (Eastern Star Gas, 2010). The gas reserves, as reported in 2010, are presented in Table 6.6.

Table 6.6 PEL 238 Coal Seam Gas reserves

PEL 238 Gas Reserves		
Proven reserves	Proven and probable reserves	Proven, probable and possible reserves
115 PJ	1520 PJ	2797 PJ

(Eastern Star Gas, 2010). PJ= 10^{15} Joules

The Narrabri CSG project includes two areas of development: the Bohena CSG pilot and the Bibblewindi CSG pilot. Twenty three wells have been drilled by ESG: eight vertical wells in the Bohena CSG pilot, and nine vertical wells and six lateral wells in the Bibblewindi CSG pilot. Eight appraisal wells were drilled before ESG became operators of the PAL.

Three of the vertical wells have been hydraulically fractured to enhance the production, two in the Bohena CSG pilot and one in the Bibblewindi CSG pilot. Lateral wells can be oriented to maximise reservoir connectivity, therefore significantly enhancing production rates relative to vertical wells (Eastern Star Gas, 2011b). According to Gas Today (2009), ESG are using the lateral technique because of the unique structure of the coal seams, which are characterised by vertical fractures running through the entirety of the coal parallel to each other. The wells are drilled perpendicular to the fractures in order to maximise the CSG production. Five to ten times more production is expected from a multilateral well than from a vertical well, even with fracture stimulation (Gas Today, 2009). ESG have drilled lateral wells approximately 1 km through the coal seam. Lateral wells are used in conjunction with vertical wells and ESG have drilled lateral wells which intersect vertical wells 1 km deep and over 1 km away from the drill site (Gas Today, 2009).

Groundwater abstraction is a necessary by-product of CSG production and is known as 'produced' water or 'associated' water. The gas production mechanism consists in drilling wells into the coal seam in order to dewater it and release gas. Water production modelling by ESG indicates the maximum rates of water production that can be expected from each CSG well in the Narrabri CSG Project will be about 160 m³/d (1,000 barrels per day) (Eastern Star Gas, 2006). This wellfield is currently proposed to contain 550 wells which will be drilled over a 20 year period (Eco Logical, 2011). ESG pipes the water produced to Bibblewindi where the company has water handling facilities (Eastern Star Gas, 2006). Their water management plan includes evaporation in lined ponds, with reverse osmosis (RO) treatment to reduce the overall storage volume (Eastern Star Gas, 2006). Seventy percent of the production water passed through the treatment unit will be recovered as low to zero solute concentration (pure) permeate for reuse and discharge and the remaining 30% as concentrate for storage and further evaporation (Eastern Star Gas, 2006).

6.6.3 Exploration areas

One hundred and twelve exploration wells have been drilled in the Namoi catchment. With the exception of the Narrabri gas field, the other CSG projects are still at an exploration stage. ESG holds 65% interest in PEL's 434 and 433 and is the operator (Eastern Star Gas, 2011c). The remaining 35% interest is held by Santos. Future development would be constrained by a number of factors which are currently unquantified due to the current level of exploration.

Santos holds a 100% interest in PEL 450, 452 and 162 as well as 25% interest in PEL 1 and PEL 12 and a 15% interest in PEL 456, covering an area of 20,000 km². These permits include the districts of Gunnedah, Coonabarabran, Scone, Quirindi and Boggabri. Exploration of these permit areas is underway and in 2011 included single point hole testing. Santos' reserves as of December 2010 in the Gunnedah Basin consist of 739 PJ (10^{15} Joules) of proven and probable reserves (Santos, 2011) and 951 PJ of contingent resources as of December 2009 (Santos, 2010a).

Exploration has been ongoing since 2008. To date over 400 km of seismic survey have been undertaken by Santos along the existing road network. In addition, environmental studies have been implemented and core holes have been drilled and tested. As of 2011 a detailed drilling and testing stage is still ongoing, with 5 exploration core holes completed or scheduled in PEL 1. Core holes in PEL 462 and PEL 433 are due for completion in the third quarter of 2011 (Santos, 2010b).

Testing of the Longlea core hole groundwater has indicated that total dissolved solids (TDS) in the Black Jack Group at this location is approximately 2,600 mg/L. The rate of groundwater extraction during full scale production has not been published by Santos and estimates are not available at this time (Queensland Government DME, 2011).

6.6.4 Potential impacts of CSG extraction on water resources

There are several pathways by which the process of CSG extraction can affect water resources, including the management of the water when it is pumped out of the coal seam. The main potential impacts are introduced below.

Impact on surface water and groundwater quantity

The extraction of CSG involves pumping the available water from the coal seam aquifer in order to reduce the water pressure that holds the gas in the coal seam (Parsons Brinckerhoff, 2004). This will have an effect on the groundwater system surrounding it, as groundwater will then flow towards the zone of dewatering (Parsons Brinckerhoff, 2004). The activity may have an impact on groundwater and surface water resources, but this 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).

Operational water management

Large quantities of water are normally an inevitable 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 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 (which varies depending on the use). The most common treatment is by reverse osmosis (RO). RO involves pushing water through membranes with pores small enough to filter out most dissolved ions such as salt, resulting in a product that is suitable for operational use such as drilling and dust suppression, and can be used for irrigation through water blending or nutrient supplementation. This water treatment process is currently in use for Narrabri CSG project (Eastern Star Gas, 2006).

Effects of Coal Seam Gas extraction processes

CSG extraction may require hydraulic fracturing in order to increase the gas recovery (Queensland Government, 2011). The process involves pumping fluid and sand, under pressure, into a coal seam. This action fractures the coal seam, which provides a pathway that increases the ability of gas to flow through the coal (Queensland Government, 2011). This activity may result in fracturing beyond the target coal seams resulting in increased connection between the seams and the surrounding groundwater systems. The chemical make-up of the fluid may also have an impact (Queensland Government, 2011).

6.7 Spatial relationship to water resources

The digital geological model has been used to assess the spatial relationship between water resources (primarily the alluvial systems and rivers) and formations hosting coal seams and, based on the depth to these formations from the ground surface, the potential areas that are prospective to coal mining versus those that are prospective to coal seam gas extraction. The analysis has been based on the full thickness of both the Black Jack Group and Maules Creek Formations, rather than the modelled Hoskissons or Melvilles seams as these are not the only coal seams found within these formations. The actual definition of prospective coal resources (whether coal or coal seam gas) will be based on numerous factors, including grade, gas composition, geological constraints, etc. None of these factors are taken into account in this purely spatial analysis.

The result of the spatial relationship analysis is displayed in Figure 6.5 and illustrates the extent of the Black Jack Group and Maules Creek Formations in the catchment, and the location of those areas where either of these units come within 400 m of the ground surface. Whilst the distinction is by no means fixed, this provides an appreciation of the areas prospective for open pit and underground coal mining (i.e. anything within 400 m of the surface). The areas prospective for coal seam gas extraction may overlap significantly with the coal mining areas and CSG extraction should be considered possible at fairly shallow depths (potentially 200 m or less).

The figure illustrates that the location with highest potential for coal mining is beneath and adjacent to the Upper Namoi Alluvium, stretching from Narrabri in the north to south of Quirindi to the southeast. 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 targeted in this manner. The geological model also suggests that these formations come to within a few hundred metres of the surface in an area around the Pilliga State Forest. The data that delineates this zone is much more limited than the data to the east, and this result should be considered more uncertain.

The figure also shows that the potential areas for coal seam gas development cover a far greater area than the prospective coal mining localities. However, to the west of the catchment this analysis is also based on sparse data and the result is more uncertain than the interpretation to the east.

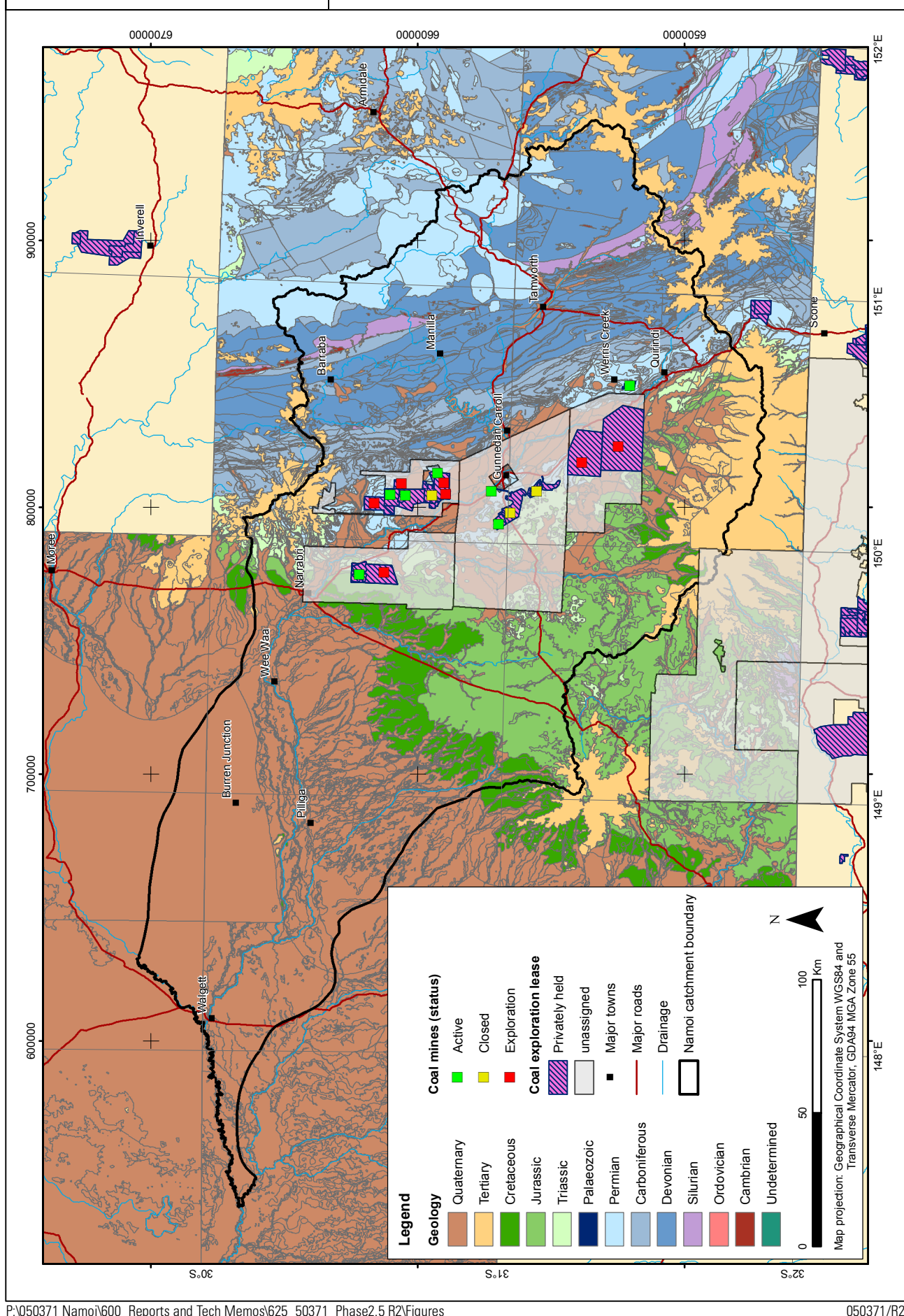
6.8 Summary

The coal seams of the Namoi catchment are mined for both coal and coal seam gas (CSG). The coal industry has been active for many years, but the CSG industry is in its infancy. Coal seams within both the Black Jack and Maules Creek Formation present economical resources.

There are currently 6 active coal mines in the catchment, and 2 major projects are in exploration phase. Both open-cut and underground mining is undertaken. These methods target coal at up to about 300 m below ground level. The mines generally produce more water than they use with the greatest component of use usually for dust suppression. Most of this water is derived from surface water runoff and groundwater inflows to the pit. The mining process may directly impact the flow and quality of both surface water and groundwater. Underground mining may also cause subsidence of the ground surface.

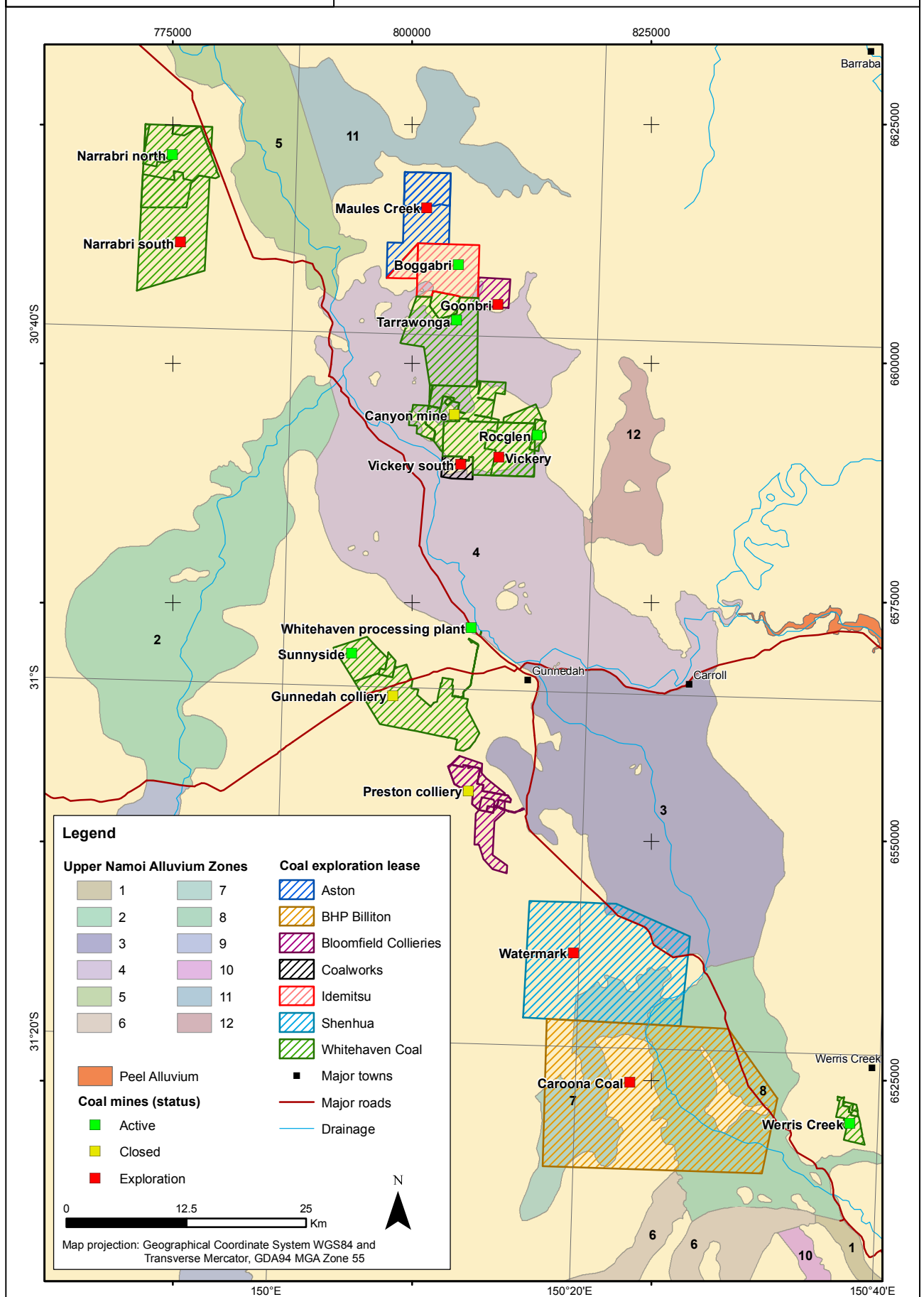
A relatively small number of boreholes have been drilled by the coal seam gas industry in the catchment. These wells target coal seams at depth and up to 1 km below ground surface. Both vertical and lateral pilot production boreholes have been trialled. In order to produce gas from these boreholes, groundwater pressure must first be reduced. In this process groundwater is removed from the coal seams and brought to the surface. The direct impacts of coal seam gas on the water resources are from the depressurisation of the coal seams and the migration of this depressurisation into the groundwater system. Wells can be stimulated by enhancement processes such as hydraulic fracturing, which may be used to increase the seam permeability and therefore flow. The management of the water at surface may also be problematic.

Figure 6.1 Location of coal mining development and exploration areas in the Namoi catchment



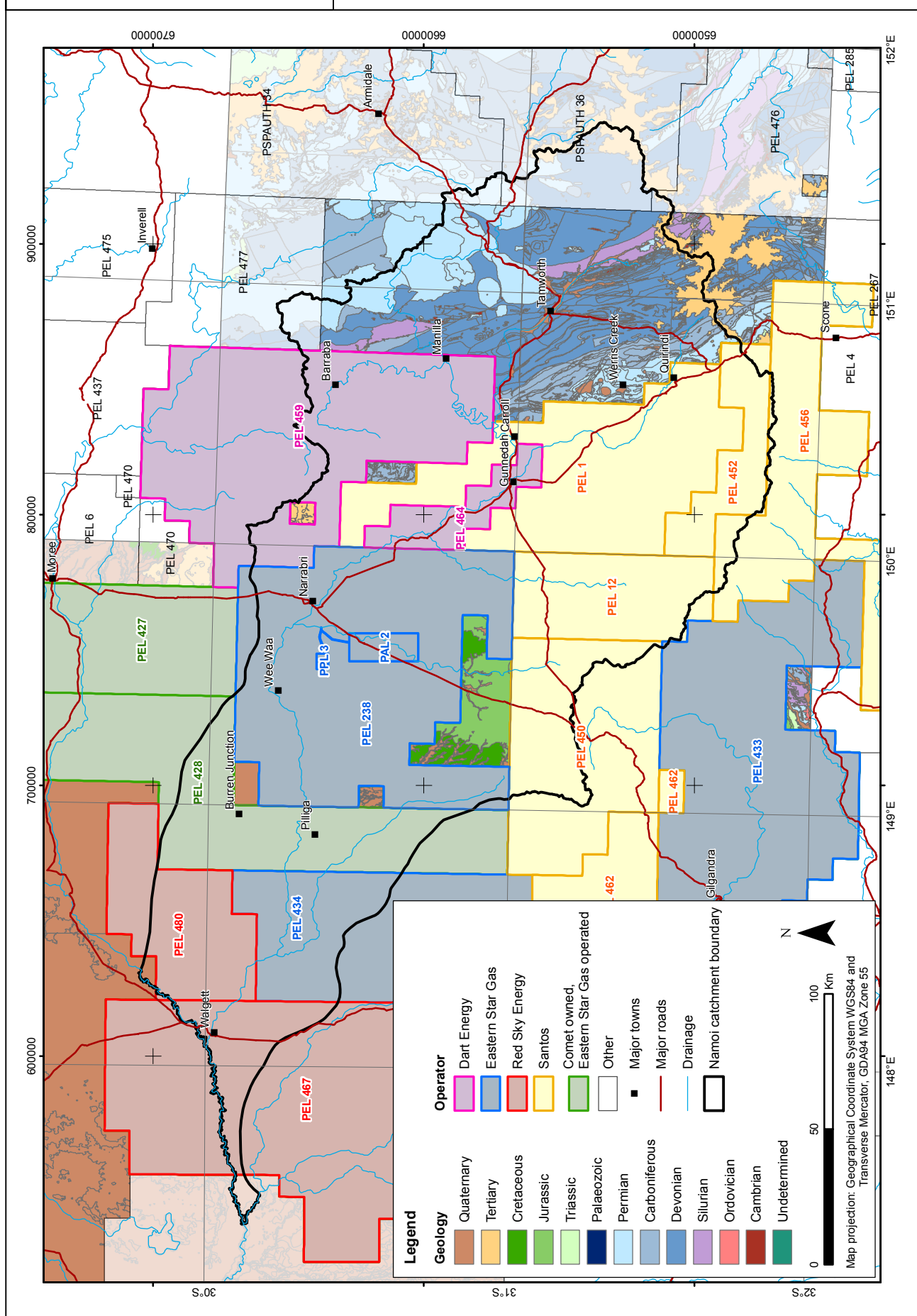
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Figure 6.2 Details of coal mining development and exploration within the Namoi catchment



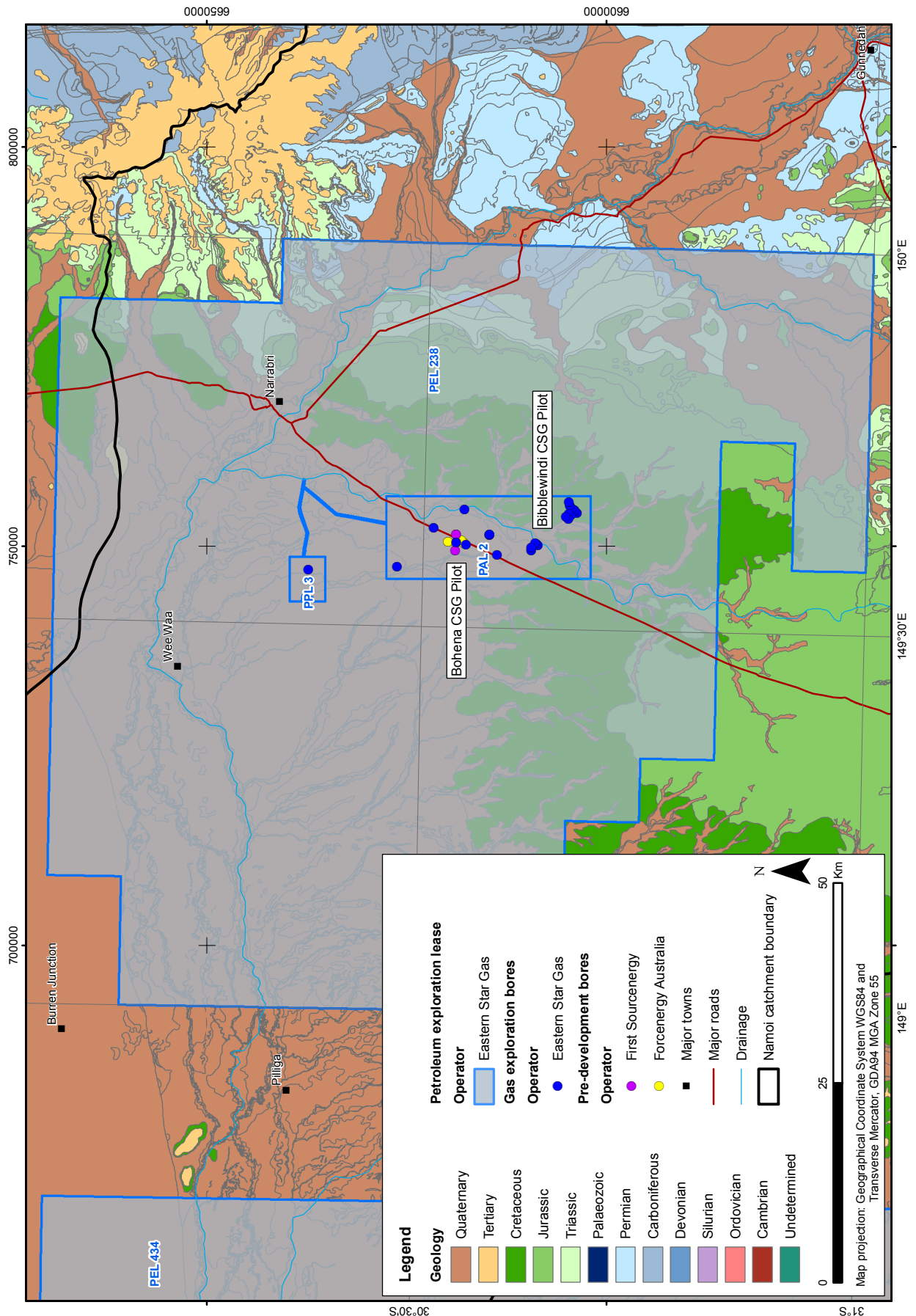
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Figure 6.3 Location of Petroleum Exploration Licences (PEL) in the Namoi catchment



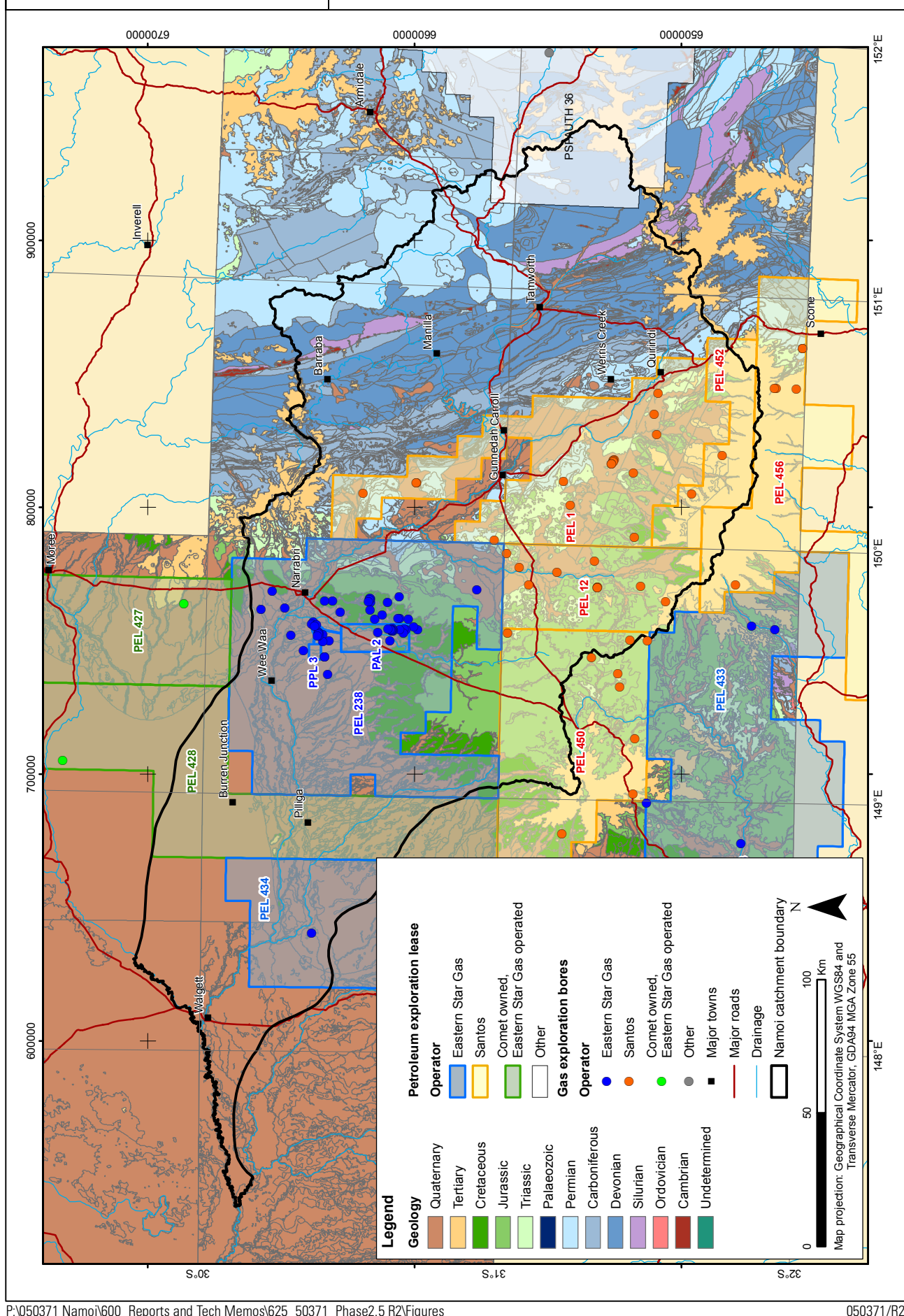
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Figure 6.4a Location of Petroleum Assessment Leases (PAL) and Petroleum Production Leases (PPL) in the Namoi catchment



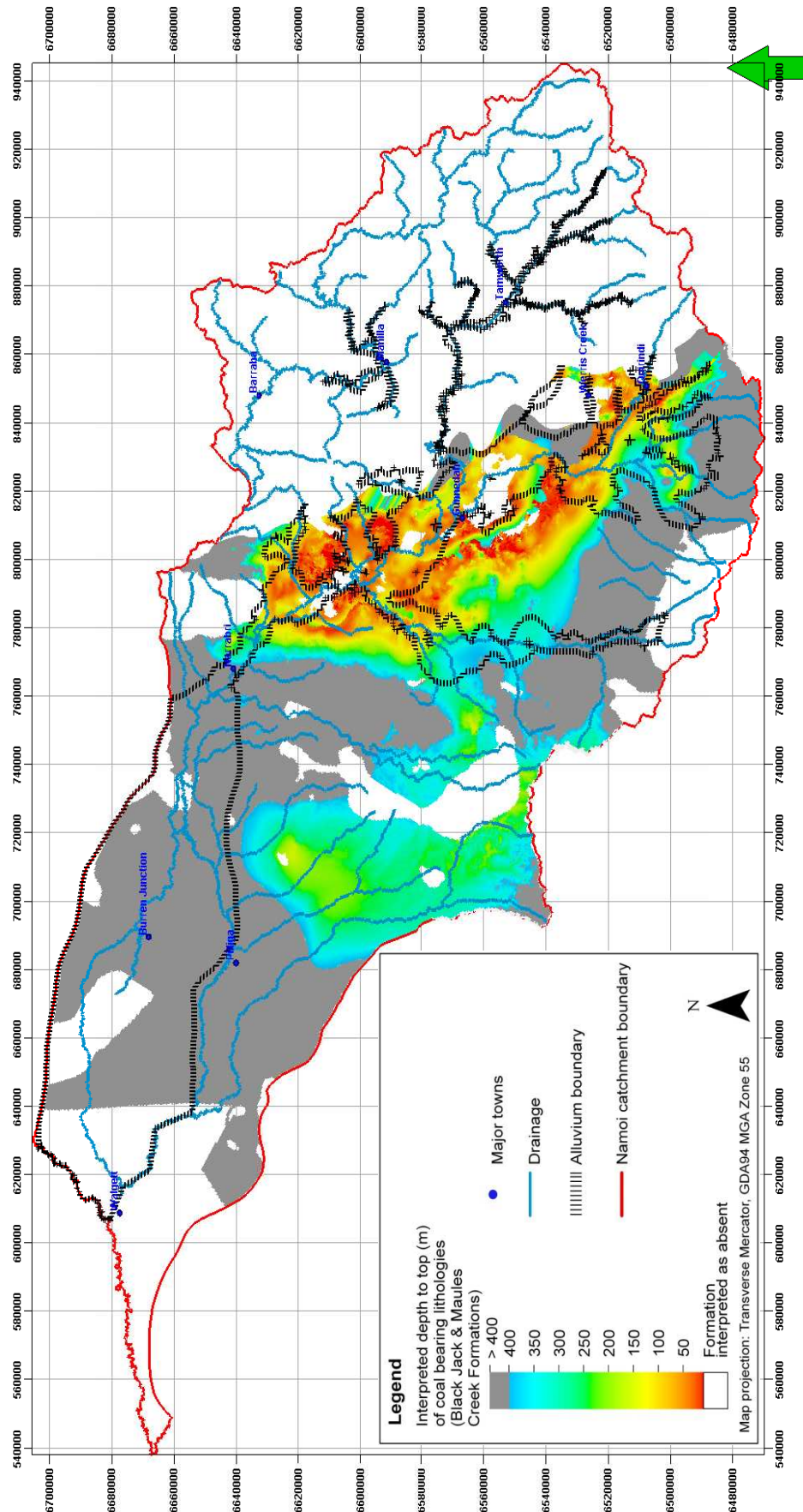
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Figure 6.4b Location of appraised Petroleum Exploration Licences (PEL) in the Namoi catchment



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Figure 6.5 Interpreted depth to coal bearing formations and relationship to water resources



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7 HYDROGEOLOGICAL CHARACTERISATION

7.1 Background

Groundwater resources in the Namoi catchment are highly developed. Extraction occurs primarily from the alluvial aquifers associated with the main rivers and their major tributaries, although 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 regions:

- 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) areas in the northwest of the catchment.
- Volcanic basement underlying the Gunnedah Basin and GAB deposits.

Abstraction from the alluvial deposits is greatest from the deeper areas of the alluvium, i.e. the Gunnedah Formation in the Upper Namoi alluvial areas, and the Gunnedah and Cubbaroo Formation in the Lower Namoi area. The alluvial deposits in the Lower Namoi area extend beyond the boundary of the Lower Namoi groundwater model (Merrick, 2001) to cover the whole of the floodplain. The Lower Namoi alluvium is underlain by Jurassic shales, sandstones and mudstones that form the edge of the Great Artesian Basin. These in turn are underlain by Triassic and Permian Gunnedah Basin deposits, as discussed in Section 4.

The catchment to the east of the Hunter-Mooki Thrust is part of the New England Fold Belt. These are moderately to highly deformed Silurian to Permian rocks overlain by Carboniferous sediments. To date no coal seams have been identified in these materials. Whilst water supplies can be obtained from these deposits they are regarded as poor aquifers that are only suitable for local small-scale supply.

7.2 Groundwater management areas

The Namoi catchment has been divided into 8 Groundwater Management Areas (GMA). The areas have been defined by the NSW State Government in accordance with the Murray Darling Basin Plan and are based on geology as well as groundwater and surface water catchment divides. The individual areas are discussed below and are listed in Table 7.1.

The descriptions of the groundwater management areas given below are based on information taken from the MDB Water Sharing Plan report cards for each groundwater source unless otherwise referenced. These report cards were downloaded from the NSW Office of Water website (NSW Office of Water, 2011).

Four of the areas have been split further to give a total of 12 separate management areas, as shown on Figure 7.1.

Table 7.1 Summary of groundwater management areas

Management area	Approximate area (km²)
New England Fold Belt	7,843
Peel Valley Fractured Rock	4,489
Peel Valley Alluvium	186
Gunnedah Basin	3,534
Oxley Basin	3,230
Great Artesian Basin	7,010
Great Artesian Basin Alluvium	4,099
Liverpool Ranges Basalt	1,716
Galarganbone Tertiary Basalt	80
Upper Namoi alluvium	3,786
Lower Namoi alluvium	5,866
Miscellaneous alluvium of Barwon Region	210
Total area	42,049

New England Fold Belt GMA

The New England Fold Belt fractured rock GMA is of Silurian age and is an eroded ancient mountain range. The basement geology consists of folded phyllites, jaspers, greywackes and interbedded basic volcanics while the overlying geology consists of carboniferous mudstones, sandstones, limestones, conglomerates, tuffs and interbedded rhyolites.

The sequence extends beyond the Namoi catchment boundary to the east and is bounded by the Hunter-Mooki Thrust to the west. Three groundwater management zones lie in the GMA of which one ('Namoi') is within the Namoi catchment. The others are the Border River Management zone and the Gwydir Management zone.

Peel Valley Fractured Rock GMA

The Peel Valley Fractured Rock GMA includes the sedimentary and metamorphosed sedimentary rocks in the Peel catchment, excluding the alluvium. It is bounded by the Great Dividing Range in the east, the confluence of the Peel River and the Namoi River to the west, the Moonib Range to the north and the Melville Range to the south.

The lithologies within the area consist of cherty argillaceous shale, limestones, sandstones and mudstones of the Yarramine and Baldwin Formations. There is a strong regional northwest to southeast lineation with dip to the southwest.

The groundwater is used extensively for stock water although it is occasionally exploited for small scale commercial and irrigation purposes. The water quality is generally suitable for stock and domestic purposes only.

Peel Valley Alluvium GMA

The Peel Valley Alluvium GMA includes the unconsolidated alluvial deposits associated with the Peel River from Chaffey Dam to Namoi and also the unregulated tributaries of the Attunga, Moore, Cockburn, Dungowan, Duncans, and Goonoo Goonoo rivers and creeks.

The aquifer is generally less than 1.5 km wide and less than 15 m thick except between Tamworth and Attunga where it is up to 20 m thick and 3 km wide (Beale, 1970a). The top 1 to 4 m of the aquifer is a clay rich layer. Recharge is from rainfall infiltration or leakage from streams and rivers, and the stored groundwater is used for stock, domestic, irrigation and town water supply purposes.

Gunnedah-Oxley Basin GMA

The Gunnedah-Oxley Basin includes the Permo-Triassic Gunnedah Basin sediments and the overlying younger Jurassic and Cretaceous rocks of the Oxley Basin. These areas are shown as two different groundwater management zones on Figure 7.1, although they are combined into one unit for management purposes as they are extensively hydraulically connected. The Gunnedah-Oxley Basin is bounded by the Mount Coricudgy Anticline (SW from Muswellbrook), the Hunter-Mooki Thrust to the east, the Lachlan fold belt to the west, and a structural high north of Narrabri.

Great Artesian Basin Alluvium GMA

The Great Artesian Basin (GAB) Alluvium GMA includes the unconsolidated and consolidated sediments overlying the NSW GAB Surat Groundwater Source but exclude the Upper and Lower Namoi Alluvium. The GAB groundwater source is bounded by the surface water catchments of the Castlereagh River to the south, Barwon River to the west, and Gwydir River to the north.

The alluvium consists of unconsolidated sediments deposited in floodplain and marshy environmental conditions, located over the Rolling Downs Albion age unconformity. The alluvium is anything up to 60 m thick and is underlain by a consolidated confining layer of the GAB Surat water source. This consists of claystone, mudstone, calcrete, shales and the minor conglomerates and sandstones of the Rolling Down Group.

Recharge to the alluvial aquifer is mainly rainfall infiltration although secondary recharge due to infiltration from the Namoi River and tertiary recharge through upward leakage from the GAB Surat water source are also present.

Liverpool Ranges Basalt GMA

The Liverpool Ranges Basalt GMA includes the alkali basalt of the Barrington tops Volcanic Plateau. The basalt extends 100 km to the west and forms the northern boundary of the Hunter Valley. Elsewhere it forms a component of the Great Dividing Range, and in the west it merges into the Warrumbungle Range. Three groundwater management zones exist within the GMA, only the Namoi zone exists within the catchment.

Upper Namoi Alluvium GMA

The Upper Namoi Alluvium GMA covers an area of c. 3,786 km² and extends approximately 175 km south of Narrabri. The area includes the unconsolidated sediments associated with the Namoi River and a number of its tributaries including the Mooki River, Maules Creek, and Cox's Creek. The area has been divided into 12 groundwater management zones by the NSW Government based on basic hydrogeology such as aquifer framework, facies variations, or features such as bedrock constrictions (NSW Office of Water, pers. comm., March 2011). These zones are shown on Figure 7.2.

Lower Namoi Alluvium GMA

The Lower Namoi alluvium GMA extends approximately 160 km west from Narrabri although the downstream limit of the alluvial body is poorly defined (ANRA, 2011). The alluvium is up to 120 m deep (CSIRO, 2007) but may not be continuous with adjacent units except at shallow depths (ANRA, 2011). Some areas of the GMA contain brackish or saline water (ANRA, 2011). The Lower Namoi Groundwater Source is underlain by the GAB Surat GMA.

7.3 Aquifer properties

7.3.1 Alluvium

Alluvial deposits cover a large percentage of the central and western catchment area and a small percentage of the uplands to the east. The principal alluvial aquifers are the Upper Namoi and Lower Namoi groundwater management areas as shown on Figure 7.2. The water resources of these units have been extensively developed as sources for both small scale stock and domestic licences, and also larger scale irrigation and town supplies.

Whilst there are small areas of upland alluvium developed in the eastern area of the catchment these are significantly smaller than the floodplain alluviums and are considered to be minor aquifers that are suitable for smaller abstractions only. It is understood that in times of drought the Peel alluvium cannot be relied on as a groundwater resource as it has a tendency to dry out (Beale, 1970a).

A number of groundwater studies have been completed to assess the main alluvial aquifers within the Namoi catchment. Some of these studies have included or focused on numerical modelling to aid in water resources evaluation and management. These previous studies are summarised below and present the main sources of tested or assumed aquifer parameters. Where the studies have also included an investigation of the hard rock aquifers below the alluvium they are summarised in following sections.

The Upper Namoi model

The Upper Namoi numerical groundwater model (McNeilage, 2006) encompasses alluvial Zones 2, 3, 4, 5, 11 and 12 of the Upper Namoi GMA, as shown in Figure 7.3. An additional model iteration is currently in the early stages of development by the NSW Office of Water at Parramatta (pers. comm., March 2011). This new iteration will include additional zones within the Upper Namoi alluvium as the current upgradient boundaries are not reflective of current use patterns. These were previously included in the Mooki groundwater model. The updated model iteration is expected to be completed after the water Study has been delivered.

The Upper Namoi model comprises two layers that represent the two formations that can often be recognised within the alluvium. The Narrabri Formation occurs from the ground surface to a maximum 70 m depth. It comprises overbank clays with channels of sand and gravel resulting in low yielding aquifers. The lower Gunnedah Formation varies in thickness reaching a maximum of 115 m and contains a higher fraction of sand and gravel, creating a higher yielding aquifer. The most productive areas generally lie within the deeper palaeochannels (CSIRO, 2007) although numerous shallow bores are also used for water supply.

The present numerical model assumes that the degree of connection between the bedrock and alluvium is low and the bedrock is relatively impermeable. This reasoning was justified on the basis that there is likely to be more than two orders of magnitude difference between the alluvium and bedrock permeability (McNeilage, 2006). Broughton (1994) indicates that in parts of the model area there is significant potential for leakage from the bedrock to the overlying alluvium or vice versa if either is stressed.

Calibrated parameters for the whole Upper Namoi model area are shown in Table 7.2. Distributions of each parameter appear to be very patchy with little order to hydraulic zoning, as shown in Figure 7.4.

Table 7.2 Calibrated aquifer parameters for the Upper Namoi model area

Model area	Horizontal hydraulic conductivity (m/d)		Inter layer leakage (1/d)	Specific yield (-)	Specific storage (1/m)
	Layer 1	Layer 2	Layer 1/2	Layer 1	Layer 2
Minimum	0.1	0.05	1.7×10^{-6}	0.005	1.0×10^{-7}
Maximum	30	30	3.7×10^{-2}	0.1	5.0×10^{-4}
Mean	6.3	7.1	3.0×10^{-4}	0.04	1.6×10^{-4}
Median	5.0	5.0	9.5×10^{-5}	0.03	1.0×10^{-4}
Std Deviation	6.1	6.1	1.3×10^{-3}	0.027	1.7×10^{-4}

(McNeilage, 2006)

Lower Namoi model

A similar numerical model exists for the Lower Namoi GMA (Figure 7.3). The model has been through various stages of development and recalibration since it was initially constructed. The most recent model was developed in 2001 although it is understood that this model is also being reviewed and updated by NSW Office of Water (pers. comm., 16 March 2011), with the report expected in 2012/13. The model splits the Lower Namoi alluvium into three separate layers, the Narrabri, Gunnedah, and Cubbaroo Formations. There is very little specific information publically available for the 2001 model, although a report with model results (Merrick, 2001) and selected model input files have been provided to the Study (by the NSW Office of Water on 19 April 2011 and 21 July 2011 respectively). With the limited data provided it has not been possible for SWS to fully appreciate all aspects of the conceptualisation, construction and results of the Lower Namoi modelling, but the information that has been provided will be used to assist the development of the impact assessment tools produced as part of the Study.

The Lower Namoi model does not cover the whole of the alluvial area in this section of the catchment and the extent to which the Lower Namoi alluvium and GAB alluvium are hydraulically connected is expected to be high. The Lower Namoi model also includes upwards groundwater flow from the underlying GAB materials.

Maules Creek model

This model represents a section of the alluvial aquifer in the Maules Creek catchment, which lies within Zone 11 of the Upper Namoi GMA. Hydraulic parameters were assigned based on 3D geological modelling work completed for the catchment. The geological units were designated as either sand or clay for the purposes of the model. Parameter values used in the model are shown in Table 7.3 (Giambastini et al., 2009).

The model suggests that the reduction in stream flow as a result of groundwater abstraction in this catchment is 20%, and during the irrigation season the groundwater abstraction changes the river from a gaining to a losing stream.

Table 7.3 Parameters used in the Maules Creek model

Parameter	Value
Horizontal hydraulic conductivity	Sand = 86.4 m/d, Clay = 6.9 – 0.09 m/d
Anisotropy	0.1
Specific yield	Sand = 0.1, Clay = 0.01
Specific storage	1.0×10^{-5} 1/m

(Giambastini et al., 2009)

Gins Leap Gap Project

This project was commissioned to investigate groundwater movement through Gins Leap Gap, which marks the boundary between the Upper Namoi Groundwater Zones 4 and 5 (KLC, 2010). The report concludes that groundwater movement through The Gap is constricted by a horizontal narrowing of the valley floor to approximately 1 km width, and also a vertical thinning of the aquifer to approximately 40 m depth due to the presence of a basement high. Groundwater flow was estimated to be approximately 1 ML/d at the time of the study (2009-2010). Deep drainage to Upper Namoi Zones 4, 5, and 11 was calculated as contributing 67,000 ML/yr to groundwater recharge, and potential runoff contributions to groundwater recharge were estimated at 30,000 ML/yr, or approximately 20% of total runoff (KLC, 2010).

A pumping test of 4 L/s on a production bore in the alluvium which had several monitoring bores indicated a range in hydraulic conductivity from 1.5 m/d at the production bore to 70 m/d at one of the monitoring bores, and a transmissivity range of 23.4 to 1,471 m²/d (KLC, 2010). Drawdown at the pumping well was 5.4 m. Calculated storativity values ranged over two orders of magnitude, from 9.0×10^{-5} to 4.4×10^{-3} . There is also a low hydraulic gradient within the alluvium of 0.00055 (0.5 m/km) (KLC, 2010).

Isotope studies

Collated information from isotope studies undertaken on water from the alluvium is reported in Kelly et al. (2007) and is summarised in Table 7.4. Using these values a flow rate of 9 m/yr along the Mooki catchment was estimated.

Table 7.4 Summary of dating information provided in Kelly et al. (2007)

Area	Age	Method
Mooki catchment	Recent in the south to 12000 years near the outlet	Not given
Eastern Lower Namoi	Recent	Tritium
Western Lower Namoi	Greater than 25000 years	Carbon - 14

Isotope and radiocarbon dating is also reported in the work undertaken at Gins Leap Gap (KLC, 2010). Shallow alluvial groundwater was shown to be 'modern' i.e. less than 50 years old, with recharge from the nearby river systems being the most likely source of this modern water.

Investigations in other areas of the catchment

Investigations of groundwater flow through the thick clay sequence at the top of the alluvial sequence on the Liverpool Plains showed a vertical hydraulic conductivity of 0.00024 m/d and a specific storage of 3.7×10^{-5} /m (Timms and Acworth, 2005). Monitoring of groundwater levels using data loggers showed rapid increases in pressure in shallow holes after rainfall events, followed by responses in the deeper holes after a time delay of several weeks.

Stauffer et al. (1997) suggested that flow to the Narrabri Formation occurs through upward leakage from the pressurised Gunnedah Formation alluvial aquifer. Stauffer et al. (1997) justified this assumption by noting that the hydraulic conductivity in the Gunnedah Formation was 1000 times higher and the specific yield was up to 100 times lower than in the overlying Narrabri Formation. Salinity investigations by the University of NSW-Water Research Laboratory group have shown that upward discharge of water is extremely slow with water possibly moving only about 5 m in 10,000 years (LPLMC, 2006).

Upland alluvium to the east of the Hunter-Mooki Fault

While the main alluvial units are located to the west of the Hunter-Mooki Fault there are also smaller areas to the west of the fault.

The principal upland alluvial areas are those surrounding the Peel River. The Peel Valley alluvium is sourced from a wide range of basement rocks and the hydraulic properties are therefore heterogeneous along the different tributaries and the main valley. The distribution of water bearing gravels within the alluvium is highly variable, and the spatial extent is heavily restricted by the surrounding hard basement rocks. The alluvium is most extensive in the area between Tamworth and Attunga, reaching a maximum width of 3 km and thickness of no more than 20 m before it narrows again. Irrigation supplies of between 6.3 and 50 L/s were obtained from bores at various locations along the main river although the yields from these bores fell significantly during dry periods once groundwater storage became depleted (Beale, 1970a). Since then the Peel River has become regulated in its lower sections but it is not known how these abstraction bores respond to the stabilised base flows. Interpretation of monitoring bore hydrographs from within the alluvium suggests that there has been little change in the groundwater regime.

Water supplies can also be obtained from the alluvium along tributaries to the Peel such as the Cockburn River and Attunga Creek to the north, the Dungowan Creek to the east, and the Goonoo Goonoo Creek to the south, although the smaller extent of the alluvium in these areas has prevented major development. Bores located within the alluvium are reported to respond rapidly to changes in rainfall runoff, and during drought periods the supplies can fall to minimal values (Beale, 1970a).

There are only minor areas of alluvium in the remaining upland areas and they have not been highly developed for groundwater supplies. The alluvium along the Namoi and Manilla rivers is not expected to be greater than 15 m thick but bores can yield up to 25 L/s. Alluvium along the Halls Creek and Upper Manilla River is able to support more intensive abstraction on at least a short timescale (Beale, 1970b).

Within the upland alluvial systems groundwater discharges typically to drainage lines, local changes in soil texture, around the break-of-slope and at the base of terraces. Salt storage in the finer grained units of these systems is high and groundwater salinity is variable from fresh to saline with lower salinity levels being characteristic of the coarser sediments. The response of these systems to a change in the water balance can be relatively fast (CSIRO, 2007).

7.3.2 Gunnedah Basin sediments

The Gunnedah Basin sediments underlie the central part of the Namoi catchment and it is this area of the catchment which is the focus of the coal mining and CSG exploration. Coal seams occur within the Permian Black Jack and Maules Creek Formations that occur both at depth and as surface outcrops.

The target coal seams for coal and CSG extraction vary across the basin. In the Maules Creek area there are a large number of seams from within the Maules Creek Formation that are being targeted by coal operators (NSW DPI, 2009). Many of these can be correlated across adjacent mine sites.

In the main Gunnedah Basin there are fewer target seams. The principal seams for CSG exploration are the Hoskissons seam, which lies within the Black Jack Group; and the Bohena seam within the Maules Creek Formation (See Section 6). The Hoskissons seam, and associated minor seams, are also being targeted by both open-cut and underground coal operators where they occur nearer to the surface (NSW DPI, 2009).

The coal beds within the Gunnedah Basin have a low hydraulic conductivity when compared to the hydraulic conductivities characteristic of the main alluvial aquifers. Groundwater moves through the coal seams via fractures (cleats) caused by structural changes within the basin. Depending on fracture orientation, CSG operators can exploit these natural fractures by drilling horizontal wells along the coal seams to improve the efficiency of gas extraction with fewer production wells at the surface (Australian Pipeliner, 2009).

Despite the large volume of work completed on the alluvial systems within the Namoi catchment there is very little published information relating to the properties of the underlying hard rock aquifers. The focus has been on the major alluvial systems which have mostly been treated as discrete and isolated bodies in numerical models. Hydraulic values are therefore limited to either published values for the formations in other areas or testing work completed by the coal mines and CSG companies.

Narrabri mine

Whitehaven have completed a numerical model for their Narrabri underground mine (Aquaterra, 2009) and have used the following hydraulic parameters for each geological unit (Table 7.5).

Table 7.5 Hydrogeological units and parameters, Narrabri Mine model

Model Layer	Formation	Adopted horizontal hydraulic conductivity, Kh (m/d)	Adopted vertical hydraulic conductivity, Kv (m/d)
1	Alluvium	0.265 – 5	0.0005 – 0.005
2	Pilliga Sandstone	0.004 – 0.265	1.5×10^{-5} – 0.0002
3	Purlawaugh Formation	0.004 – 0.02	1.5×10^{-5} – 0.001
4	Garrawilla Volcanics	0.001 – 0.04	6.0×10^{-6} – 0.001
5	Napperby Formation (above sill)	0.001 – 0.04	6.0×10^{-6} – 0.001
6	Basalt Sill	0.004 – 0.12	6.0×10^{-6} – 0.001
7	Napperby Formation (below sill)	0.004 – 0.021	6.0×10^{-6} – 0.001
8	Digby Formation	0.004 – 0.04	6.0×10^{-6} – 0.001
9	Hoskissons seam	0.005 – 0.04	6.0×10^{-6} – 0.001
10	Arkarula Formation	0.0005 – 0.04	1.0×10^{-6} – 0.001
11	Pamboola Formation	0.04	0.001

(Aquaterra, 2009)

Sunnyside mine

The Sunnyside mine lies adjacent to the old Gunnedah Colliery where the Hoskissons seam was mined by bord and pillar methods. There is the potential for a hydraulic connection to exist between the old workings and the open-cut pit if the former are saturated. Recent investigations (Beckett, 2007) have shown that these workings only contain 31.2 ML of stored water in an isolated downthrown block, with an estimated void space of 1523 ML of the workings still being dry. A FEFLOW model of the mine site was constructed to represent the alluvium, Digby Formation, and Black Jack Group in the study area (Golder Associates, 2008). Hydraulic testing of the Hoskissons seam showed hydraulic conductivity values of up to 4.0 m/d from bores containing 8 m of screen within the range 32 – 79 m below ground level (mbgl). Yields from these bores were < 0.38 L/s. The Hoskissons seam is unconfined where it subcrops under the alluvium but becomes more confined as the beds dip deeper towards the west (OEC, 2008). Hydraulic parameters used in the groundwater model are shown in Table 7.6.

Table 7.6 Hydraulic parameters used in the Sunnyside groundwater model

Formation	Horizontal hydraulic conductivity (m/d)	Vertical hydraulic conductivity (m/d)	Specific storage, Ss (1/m)	Specific yield, Sy (-)
Alluvium	21.8 – 26.2	3.5 – 7.2	1×10^{-4}	0.15
Formations above Hoskissons seam	4×10^{-4} – 2×10^{-4}	1×10^{-4} – 5×10^{-4}	1×10^{-4}	0.1
Hoskissons seam	0.33 – 3.3	2×10^{-4} – 2.2×10^{-3}	1×10^{-4}	0.2
Shallow Marine facies and Lower Delta Plain facies	0.02	5×10^{-3} – 0.4	1×10^{-4}	0.1

(Golder Associates, 2008)

Boggabri and Tarrawonga mines

Estimates of hydraulic conductivities in the Maules Creek sub-basin have also been calculated by the coal mining companies. The Jeralong seam in the Boggabri mine is estimated to have a hydraulic conductivity of approximately 0.4 m/d, with the interburden being an order of magnitude lower (RCA Australia, 2005). Packer testing of other coal seams and interburden at this site, also in 2005, resulted in a range in hydraulic conductivity from 0.005 to 0.68 m/d (Parsons Brinckerhoff, 2005), with an average of 0.21 m/d.

The Nagero and Merriown seams at the Tarrawonga mine showed similar values to those in the Boggabri mine, with a hydraulic conductivity estimate of 0.5 m/d (RCA Australia, 2005). Interburden values are again at least an order of magnitude lower than those in the coal seams. A specific yield of 0.05 has been adopted for the coal seams in the numerical model for this mine, where they become confined the specific storage has been taken as 1.0×10^{-5} 1/m. Interburden specific yield has been estimated as 0.02.

The combined numerical model for the Boggabri and Tarrawonga mines splits the Maules Creek Formation into two units which form combined layers of coal and interburden. This approach was adopted as there was little data available on the regional structure of the Maules Creek Formation (AGE, 2010). The model did not include any faults other than the Hunter-Mooki Fault and also did not include the intrusive material in the area. The model demonstrates that the cones of depression from the existing Tarrawonga mine and Boggabri Coal mine are interacting and that the zone of influence will migrate to the boundary of the Namoi Valley alluvial aquifer to the south within the first five years of the project. The higher recharge rate from slope wash runoff and the Boggabri Volcanics prevents further propagation of the zone of influence. The groundwater simulation indicates that the maximum void inflow rate of brackish water from the Permian coal seam aquifers will be 1 ML/yr by 2025 (AGE, 2010). Although hard to isolate from other pit inflows an estimate of 0.5 ML/d was calculated for actual groundwater inflow to the Boggabri Mine (Parsons Brinckerhoff, 2008).

Investigations undertaken for the Boggabri mine project also showed a narrow band of alluvium along Nagero Creek. This was generally consistent with that of the Namoi River alluvium, suggesting a possibility of hydraulic interconnection (Hansen Bailey, 2010).

Groundwater inflows from the Namoi River alluvial aquifer to the mine void are predicted to increase to a maximum void inflow rate of 0.2 ML/yr by 2025 (AGE, 2010). The project is also predicted to result in the reduction in the rate of the groundwater flow from the Permian coal seam aquifers to the base of the Namoi Valley alluvial aquifer. This reduction in water level in the alluvial aquifer is predicted to be less than one metre which is noted as being undetectable from seasonal cycles (AGE, 2010).

Post-closure the groundwater inflows to the pit will decrease as the mining void and adjacent aquifers recover. Rainfall and groundwater seepage will take approximately 15 – 20 years to fill the backfilled void to an equilibrium level. Assuming that the final void is backfilled to 285 mAHD it is predicted that the groundwater levels will stabilise at about 283 mAHD. This is apparently consistent with the pre-mining groundwater levels and the reported conclusion that the final void will not act as a permanent sink for groundwater (AGE, 2010).

Rocglen mine

Aquifer parameters for the Rocglen (formerly Belmont) mine show a slightly lower hydraulic conductivity for the Glenroc seams of 0.06 – 0.07 m/d, with interburden again being an order of magnitude lower (RCA Australia, 2007). Storativities were calculated as being 0.01 for the seams and 0.001 for the interburden (RCA Australia, 2007). Groundwater levels were approximately 34 mbgl in the vicinity of the mine in 2007.

A numerical model was built for the site in 2007 (RCA Australia, 2007). Calibrated hydraulic parameters are shown in Table 7.7. Calibrated vertical permeability values are almost always an order of magnitude lower than the horizontal values shown in the table. Specific yield and porosity data was taken from generic published literature (RCA Australia, 2007).

Table 7.7 Hydraulic permeability values for the Rocglen model

Strata	Horizontal permeability adopted for the slopes (m/d)	Horizontal permeability adopted for the valley (m/d)	Range of field measured data (m/d)
Overburden	0.015	Midslope - 0.004 Valley - 6.04	0.0138 – 0.077
Glenroc seam sequence and interburden	0.015	0.518	0.0008 – 0.002
Interburden between Lower Glenroc and Belmont seams	0.015	0.0004	0.013 – 0.077
Belmont seam	0.015	0.0005	0.060 – 0.432
Sandstone Floor	0.0015	0.043	0.034 – 0.051

(RCA Australia, 2007)

The groundwater model predicts groundwater inflows of between 305 and 719 m³/d throughout the life of the mine. The inflows would be removed from the pit by evaporation (RCA Australia, 2007).

Water levels are predicted to fall by 2 m up to 5 km from the limit of open-cut mining as a result of mining (RCA Australia, 2007). Two bores outside the mine lease boundary could apparently be affected by more than 10% of their current saturated thickness as the drawdown spreads outwards from the void (RCA Australia, 2007).

Werris Creek mine

The Werris Creek opencast coal mine is located in the Werrie Basin, which is a small closed basin east of the main system at the southern extent of the current Gunnedah Basin Coal Fields. The coal bearing layers are underlain by low permeability claystones and weathered Werrie Basalt. Flow velocities within the coal measures have been estimated as 1 m/yr, and within the basalt as approximately 3 m/yr. The weathered basalt is thought to provide a barrier to flow between the coal measures and the unweathered basalt. A decrease in water level of 0.1 m is predicted within bores on adjacent landholdings (RCA Australia, 2010). To the south of the mine the Quipolly Creek alluvium forms a minor aquifer, with flow rates estimated to be 150 m/yr (RCA Australia, 2010).

The current site is next to the underground workings of the Werris Creek colliery. It has been estimated that there is approximately 200 ML of groundwater stored in these old workings (Corkery and Co Pty Ltd, 2010). This would need to be managed during the current mining phase as the coal seam mined in the colliery is also to be extracted in the open-cut mine.

Hydraulic parameters used in the site groundwater model developed by RCA Australia (2005), are given in Corkery and Co Pty Ltd (2010) and are reproduced in Table 7.8. The coal seams, interburden and alluvium have the highest permeability values. The surrounding materials have properties that are at least an order of magnitude smaller. Vertical anisotropy is also present in most layers.

Table 7.8 Werris Creek groundwater model hydraulic parameters

Strata	Horizontal hydraulic conductivity (m/d)	Vertical hydraulic conductivity (m/d)
Coal seams and interburden	0.086	0.086
Claystone (underlying lowest coal seam)	0.0004	0.0004
Basalt	0.0034	0.00034
Fractured basalt	0.069	0.0069
Alluvium	0.864	0.0864
Sandstone/conglomerate	0.005	0.0008
Volcanics	0.001	0.0001

(RCA Australia, 2005)

Kahlua CSG

Santos has also completed a numerical model for their pilot well site at Kahlua (Golder Associates, 2010). Many of the parameters used have been taken from generic values found in existing literature. Coal seam pressures collected during exploration drilling were used to estimate the hydraulic conductivity of the Hoskissons seam at depth. These estimates showed a range from 0.33 to 3.3 m/d (Golder Associates, 2010). Adopted parameters used in the numerical model are shown in Table 7.9. The report also indicates that the Napperby and Upper Digby Formations, as well as the Clare Sandstone within the Black Jack Group are considered by Santos to be the only potential aquifers within the hard rock geological sequence.

Table 7.9 Adopted parameters for the Kahlua model

Formation	Horizontal hydraulic conductivity (m/d)		Vertical hydraulic conductivity (m/d)		Specific storage (1/m)	Specific yield (-)
	Max	Min	Max	Min	Best case	Best case
Narrabri Fm	6	0.008	0.00024	0.000024	---	0.1
Gunnedah Fm	31	8.6	7.2	3.5	---	0.15
Napperby/Digby Fm	1.5	0.08	0.71	0.62	0.00001	0.1
Upper Black Jack Group	1.1	0.0003	0.59	0.19	0.00001	---
Hoskissons seam	3.3	0.13	0.002	0.00022	0.0001	---
Lower Black Jack Group	0.047	0.0015	0.0004	0.0004	0.00001	---

(Golder Associates, 2010)

Simulations run using this model assumed a maximum extraction rate of 160 m³/d from each pilot well and assumed that this rate would be sustained for a period of 2 years (Golder Associates, 2010). The numerical model predicted that after the 2 years of pumping the water levels within the Hoskissons seam would be affected by more than 0.1 m within a 3.6 km radius of the test wells. The predicted drawdown in the alluvial aquifers was less than 20 cm, although this was not considered significant given the inherent level of accuracy of the model (Golder Associates, 2010).

A more general discussion of the water resource potential of the Gunnedah Basin is given by Beale (1970b). The Permian rocks within the catchment include the coal bearing strata in addition to sandstones, shales, volcanics and intrusives. Water supplies for stock are generally found between 30 and 60 m depth although this, and bore yields, can vary greatly depending on the type of strata encountered. Water quality within the Permian rocks is often poor (Beale, 1970b).

There is a high probability of drilling an unproductive bore within the limited extent of the Triassic strata (Napperby and Digby Formations) (Beale, 1970b). A large number of unsuccessful bores have been drilled into shales and sandstone. The shale beds are often thick and the sandstone units are often of low permeability and are comparably discontinuous and thinner (Beale, 1970b).

Sedimentary Jurassic and Cretaceous rocks comprising sandstones, shales, and conglomerates cover a large area in the centre and western areas of the catchment and include the Pilliga Sandstone which is a recognised aquifer and intake bed to the GAB. These bores are mostly utilised for stock water supplies. The depth of these bores varies depending on the distance from the outcropping areas of the intake beds to the GAB. The water quality of these beds limits the use of this water as the beds dip deeper (Beale, 1970b). Yields of 8.8 to 34 L/s have been recorded for areas of the sandstone to the north of Narrabri (Beale, 1970b).

In general terms the existing studies complement each other, with similar values being obtained for several of the coal seams and the interburden immediately surrounding them. There is still very limited information available on the hydraulic properties of the remaining strata, especially at depth.

7.3.3 Ridge deposits

Zhang et al. (1997) consider the fractured rock aquifers of ridges areas to be of very low conductivity and do not consider them to be significant in terms of regional groundwater flow. The low transmissivity within this material leads to enhanced shallow movement of potential groundwater recharge towards alluvial areas where it is able to recharge into the adjacent alluvial aquifers.

7.3.4 Great Artesian Basin

The GAB comprises a very large multi-layered aquifer system. The GAB was first drilled in the 1880's (Herczeg, 2008), with the first recorded bores in the Namoi catchment being noted in the 1890's. Historically bores were left uncapped, allowing water to freely leave the system and causing a decrease in pressure. Data recorded within the Pinneena 3.2 database shows that groundwater levels in bores near Pilliga, close to the Namoi recharge zone, fell from around 200 mAHD in 1915 to c. 170 mAHD by the late 1980's. Other GAB bores within the catchment have recorded a much larger change in head. 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.

The basal GAB aquifer units in the Namoi catchment comprise the Jurassic Purlawaugh and Pilliga Sandstones. These units are present over a large section of the catchment and form the intake beds to the GAB where they outcrop to the west of the Rocky Glen Ridge. According to the NSW Department of Water and Energy (NSW DWE, 2009), in this area they form part of the Southern Recharge Groundwater Source, as defined in the NSW Great Artesian Basin Groundwater Sources Water Sharing Plan. The latest estimate of recharge rates into these intake areas is approximately 6 mm/yr (Herczeg, 2008), although estimates vary by over two orders of magnitude. The GAB lying within the Namoi catchment forms part of the larger Coonamble Embayment. This is widely believed to be isolated from the main areas of the GAB (Herczeg, 2008).

Hydraulic conductivities of GAB sandstones, including the Pilliga, range from 0.1 to 10 m/d, and the majority of tests are at the lower end of the range (GABCC, 2010). Transmissivities vary considerably, depending on the geology of the individual formations and the thickness of each layer. Bulk hydraulic parameters for the GAB are given in Table 7.10.

Table 7.10 Bulk hydraulic parameters for the Great Artesian Basin

Bulk hydraulic parameter	Value
Transmissivity	10 – 2,000 m ² /d
Hydraulic conductivity	0.1 – 10 m/d
Porosity of main aquifer	17 – 19%
Average storage coefficient	1x10 ⁻⁴ to 1x10 ⁻⁵
Average groundwater velocity	1 – 5 m / yr

(GABCC, 2010)

Flow systems within the fringes of the GAB have been age dated using ³⁶Cl dating (Radke et al., 2000). This shows waters of less than 5,000 years old in the recharge zones to greater than 200,000 years in the deeper confined areas. Horizontal flow rates have been inferred as 4 m/yr in the alluvial fans of the Great Dividing Range, to less than 1 m/yr as the groundwater gets deeper and more confined (Herczeg, 2008).

Flood events are thought to be insignificant sources of recharge to the GAB due to the upwards vertical gradients present in the majority of the area (Herczeg, 2008). The recharge areas are most likely to be located on hillslopes where the effects of flooding would be minor.

Great Artesian Basin model

A transient groundwater flow model of the Great Artesian Basin (GAB) was constructed by the Bureau of Rural Sciences (Welsh, 2006). The shallowest artesian (Cadna-owie – Hooray) aquifer is modelled over the entire on-shore extent of the Basin south of the Gilbert River in north Queensland.

Conceptually, water within the model is treated as predominantly meteoric origin entering the aquifer where it is shallow or exposed around the elevated basin margin and travels down slope through the aquifer from which it may exit via a bore or a natural spring. The groundwater is pressurised and leaks vertically from higher-pressure to lower-pressure aquifers. Because deeper aquifers are recharged from higher on the western side of the Great Dividing Range (the main recharge area) than shallower aquifers, leakage is dominantly upwards (Welsh, 2006).

The Lower Namoi River model developed for the Water Sharing Plan estimates that the GAB provides an average flow of 8.3 GL/yr to the Lower Namoi surface water system (Herczeg, 2008). It is understood the Lower Namoi model area is being reconceptualised by CSIRO and it is possible that this rate will be adjusted as part of this process.

7.3.5 *New England Fold Belt*

The catchment to the east of the Hunter-Mooki Fault is part of the New England Fold Belt. The area contains moderately to highly deformed Silurian to Permian rocks that include phyllites, cherts, jaspers and greywackes with interbedded basic volcanics. These are overlain by Carboniferous shallow marine sediments comprising mudstones, sandstones, limestones, conglomerates and tuffs with interbedded rhyolites (NSW Office of Water, 2010).

Groundwater can be obtained from the fractured bedrock along the Peel River. The majority of bores have been drilled to depths of less than 80 m, with over 50% being less than 40 m deep. The water is most commonly used for stock supplies although there are occasional wells which yield enough water for irrigation.

There are few bores recorded in the Silurian rocks within the Fold Belt area. The majority of supplies are obtained along the lower elevation stream lines, with bores sunk in upland areas being less successful (Beale, 1970a and Beale, 1970b).

Bores drilled into Devonian rocks also have variable success rates, with those located in hard rock or elevated sites being more inclined to be unproductive. Successful supplies can usually be obtained in bores sunk to between 15 and 60 m depth (Beale, 1970a).

Carboniferous rocks occur in both the west and east of the catchment. Bores into these rocks are almost always successful, although the quality of the water can render it suitable for stock watering only. The depths of successful bores are an average of 10 m, although bores of 80 m depth are also known (Beale, 1970a).

Lavas and intrusives are also present in some areas. Stock supplies can be obtained from the lavas and granites if they are sited carefully (Beale, 1970a).

7.3.6 *Hydrogeological basement*

The hydrogeological basement to the Namoi catchment has been taken as contiguous with the regional geological volcanic basement in all areas to the west of the Hunter-Mooki Fault. The volcanic basement varies in depth, forming a series of north-south trending ridges and troughs. The Boggabri Ridge separates the Maules Creek Sub-Basin in the east from the main Gunnedah Basin. A second ridge, the Rocky Glen Ridge, separates the Gunnedah Basin from the Gilgandra Sub-Basin to the northwest.

A depth to economic basement map has been defined by SRK under the SeeBase Project (SRK, 2011). This defines the base of the Permian sedimentary material, below which lie the basement volcanics.

Little data exists on the hydraulic properties of the basal volcanics. Where the basement is close to the surface the volcanics have weathered, often to depths of 30 m and any testing of these areas will therefore be unrepresentative of the materials in the deeper unweathered areas.

Typical hydraulic properties for unweathered volcanic materials are expected to be in the range of 1.0×10^{-5} m/d to 1×10^{-9} m/d. Typical hydraulic properties for weathered volcanic materials are would be expect to be within the range of 1 m/day to 1.0×10^{-5} m/d (Freeze and Cherry, 1979). Volcanic basement in the Tarrawonga mine was estimated to have a hydraulic conductivity of 0.03 m/d (RCA Australia, 2005). This is comparable with several estimates from the coal seam gas explorations within Australian basins.

7.3.7 *Summary of parameters for each geological unit*

Table 7.11 summarises the hydrogeological understanding of the different geological units based on the information above, with any gaps filled using literature values. The values shown in the table will be used as a starting point in any parameterisation of the numerical models, although these are likely 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 7.11 Summary of parameters for each geological unit

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)

7.4 Structural constraints

It is likely that in the upland margins of the catchment, such as the area to the east of the Hunter-Mooki Fault and along the top of the Liverpool Range Volcanics, the groundwater divide follows the surface water divide. The complex stream networks in these areas support the theory that these areas are dominated by surface water runoff processes rather than groundwater infiltration. There are no major aquifers in these areas and groundwater flow is expected to be dominated by fracture flow within the bedrock.

There are no structural constraints to groundwater flow in the northwest of the catchment where the topography becomes much flatter, and the groundwater divide between the Namoi catchment and the adjacent areas becomes more arbitrary.

Within the centre of the catchment the Hunter-Mooki Fault marks a distinct break in the bedrock geological formations. It is unknown whether there is significant groundwater flow across the fault to any great depth and the deep groundwater connection has therefore been assumed to be minimal given the nature of the geological strata involved and the lack of data to suggest otherwise.

Several of the Upper Namoi alluvial groundwater management zones partially overlie the Hunter-Mooki Fault. Contouring of the alluvial basement shows that these form continuous units across the fault. Given the high conductivities and storage within the alluvium these areas are likely to have the greatest potential for groundwater movement over/across the fault.

More localised fault structures occur within the Gunnedah Basin sediments. Some of these have been estimated to have displacements of up to 120 m (Tadros, 1993) and therefore have the potential to cause a large disconnection across geological units. This 'minor' faulting within the catchment cannot be captured at a regional scale. Where adequately defined, it is anticipated that some of these faults may have a significant effect on groundwater flow characteristics and will need to be assessed in model simulations.

7.5 Catchment wide yields and other hydraulic data

Bore yields (L/s) are available within the Pinneena 3.2 GW database (obtained in November 2010). Figure 7.5 shows the locations of these tests along with the resulting yield obtained from each bore. With the exception of boreholes that penetrate the GAB aquifer the remaining high yielding bores are almost exclusively located within the alluvial aquifers or along major river valleys. Bores drilled within the fractured rock aquifers surrounding the alluvium rarely have yields of over 2 L/s, whereas there are numerous bores within the alluvium with yields over 50 L/s. However, within the Lower Namoi alluvium there are also a large number of bores with very low yields. These are most likely completed in areas of thick clay deposits.

Records are also available showing the depths at which water bearing zones were encountered during drilling (Figure 7.6 and 7.7). Where more than one zone was encountered the circles appear stacked at the relevant point. Whilst these do not record the flow rates of water encountered at each depth they give an indication of where noticeable inflows were encountered. Of the >14,000 entries recorded, over 95% of zones are at less than 100 m depth, and 50% of zones were encountered at less than 30 m depth.

The deepest water bearing zones were encountered in the GAB aquifers. Water bearing zones were not recorded in many of these wells above 100 mbgl. It may simply be that although flows were encountered they were minimal compared to those that were expected from deeper layers and they were therefore not recorded.

Within the Lower Namoi alluvium water bearing zones have been encountered from near surface to over 100 m depth. The depth to the initial water bearing zone increases from east to west along the catchment. This may be related to the depth of the unsaturated zone rather than lower productivity of the upper alluvial layers.

In the Upper Namoi alluvium water bearing zones are encountered at shallow depths along the current stream channels. Many of the bores only record one shallow water bearing zone but these are believed to be shallow wells that were not drilled beyond these points. There are also areas of the alluvium where water bearing zones have been encountered at much deeper levels. These are most likely drilled to intercept groundwater from the deeper Gunnedah Formation in the palaeochannels in addition to striking water in the shallow zones.

In the Peel Groundwater Unit and the remaining New England Fold Belt area bores either strike water at shallow or deep levels but there are fewer bores with more than one water bearing zone recorded. This is true for both the alluvial and fractured rock areas.

Within the other hard rock areas in the Namoi catchment the initial water bearing zones are usually deeper than in the alluvial areas. This is especially true in the area to the west of Narrabri.

7.6 Groundwater monitoring data

7.6.1 Introduction

Water resources monitoring for groundwater level and quality 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 have also confirmed the existence of baseline monitoring programs for water resource management. Industry partner data has been received and reviewed for all active mines and several of the more advanced exploratory coal mine leases.

Long term monitoring of groundwater levels and quality can provide information such as:

- the degree of connection between different aquifer/aquitard systems;
- the mechanisms by which water moves through these systems;
- the influence of abstractions on nearby boreholes;
- a review of whether regional water resources are being over exploited or are stable/recovering.

Previous reports have indicated that although there is a large volume of data available in several areas of the catchment there are large areas, such as the Barwon Highlands, with very little data. There also appears to be a lack of long-term hydrochemical sampling (Ife and Skelt, 2004).

7.6.2 Groundwater levels

The most widespread dataset available comes from the Pinneena 3.2 GW database. The database contains single measurements of water levels from when bores were drilled and also time variant groundwater levels at a large number of monitored bores within the catchment. Several of these are multi level installations, giving a total of 1,510 individual measuring points.

Figure 7.8 shows the locations of all of the time variant monitoring bores in the catchment. Bores which intersect the Great Artesian Basin are distinguished from those that monitor the shallower groundwater units. 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, and there are very few time variant monitoring bores located in the remaining hard rock aquifers. Many of the bores within the alluvial areas were installed as dedicated monitoring sites in the 1970's and 80's and several transects can be seen across the Upper and Lower Namoi alluvium. Figure 7.9 summarises the number of data points available for each of these monitoring bores.

Figure 7.10 shows the number of sites with data recorded in each month. There are fewer than 20 bores with data available prior to 1968. These bores are all located within the northwest of the catchment within the artesian area of the GAB. After 1968 the number of sites with data increases rapidly as government monitoring bores are installed.

Table 7.12 groups the Pinneena GWL monitoring sites by the number of data points available. The majority of the sites with over 250 readings are located in the alluvial deposits of the Lower Namoi valley, with a few sites reaching as far upstream as Boggabri.

Table 7.12 Groundwater monitoring sites grouped by the number of readings taken

Number of readings	Number of sites
>300	273
>250	438
>200	646
>150	907
>100	1,091
>50	1,200
>0	1,510

Great Artesian Basin

The locations with data available prior to 1968 all show strong artesian heads when they were first drilled (Figure 7.11). The earliest heads are recorded in 1905 for bore GW004186. When it was drilled the artesian head was 87.2 metres above ground level (magl), over the next 70 years the groundwater head fell by 78 m to 8.6 magl and the last reading from the bore, in 1989, was 7.6 magl. Heads appear to have stabilised since the early 1980's.

Spatial coverage of the GAB boreholes and the changes through time are shown on Figure 7.12 as both magl and mAHD. Groundwater levels for the years 1914-15 and 1988-90 have been plotted as these dates have a high number of readings and are at either end of the available monitoring period. It can be seen that the reduction in head is across the whole of the GAB in the Namoi catchment and is not limited to a particular area. Heads have remained slightly higher adjacent to the recharge zone in the southeast.

Lower Namoi

As mentioned above there are a large number of monitoring bores located within the Lower Namoi groundwater area. It has not been possible to analyse each hydrograph individually so hydrographs for a number of transects across the alluvium have been extracted and analysed. Several of these boreholes were then chosen to represent the larger scale characteristics of the area.

Monitoring group GW021412 is completed at three depths within the alluvium and has a record going back to 1968 (Figure 7.13). Static groundwater levels have remained relatively stable through time although the effect of groundwater abstraction on the lower two installations is highly noticeable even from the beginning of the record. The shallowest installation is largely unaffected by groundwater abstraction but does appear to show a response to changes in stream flow, with a number of sharp rises followed by recession curves. The unsaturated zone at this site has historically been less than 10 m, and the potential for interaction with surface flows is high if the river is incised significantly below ground level.

Since 2000 the stable rest levels within all three bores have fallen slightly. This most likely reflects the effects of the extended dry spell on the catchment combined with a continuation of groundwater abstraction during this time. Other nearby bores also show this falling trend although the apparent interaction with surface water is not as pronounced in those at a greater distance from the river.

All three bores in bore group GW025144 show similar water levels at the start of the record in 1968, indicating that major abstraction started later in this area of the catchment (Figure 7.13). The hydrographs do not start to show a significant response to abstraction until 1978. All three bores respond to abstraction, with the deeper screens showing the greatest range in levels. All bores show similar rest levels outside of the irrigation season indicating a low transmissivity or storage in the deeper aquifer.

There is a long term water level fall in all three holes. From 1978 to 2004 rest water levels dropped by approximately 9 m. After this date the data for the shallow bore becomes very patchy as water levels drop below the screened section. Levels in the two deeper holes show an additional 4 m fall after 2004. Water levels currently lie at approximately 38 mbgl, from a start level of c. 25 m in 1968.

Bores further towards the west of the Lower Namoi alluvium are influenced even less by groundwater abstraction. Bore group GW036387 shows a relatively stable rest water level throughout the period of record in all holes and the hydrographs only start to diverge frequently due to abstraction after 1990 (Figure 7.14). There is still a downwards vertical hydraulic gradient through the alluvium but it is not as pronounced as in the east of the catchment. Rest water levels are considerably deeper than in the far east of the catchment, with an unsaturated zone of over 23 m.

Upper Namoi – Lower and Central area

Bore pair GW036096 is located at the upstream end of Zone 5. The bores show similar water levels from 1975 until 1984 (Figure 7.15). The deeper bore then appears to start showing a small response to groundwater abstraction. The response is minor until 1997 when there starts to be large annual cycles. The bore levels remain slightly below those for the shallow bore even after periods of groundwater level recovery at the end of each abstraction season. Water levels appear to respond to surface events in the early years, when water levels are less than 8 m below the surface. This response is lost as water levels start to decline. Rest levels are now approximately 12 m below ground level.

Bore group GW030232 is located down gradient of bore pair GW036096. These bores also show similar responses to each other at the start of the record, although there does not appear to be the same connection to surface events (Figure 7.15). The deeper bore starts to show a response to abstraction in 1984. Unlike the previous bores the deeper bore shows much stronger drawdown effects from 1984 onwards, most likely indicating that early abstraction was closer to this bore group. Bore levels have varied through time but show an almost continual fall in level since 1998. Bore levels have fallen by the same amount as the other bores in the area, and rest water levels are also a similar distance below ground level.

Upper Namoi – Upper area

Bore group GW030431, located in Zone 3 of the Upper Namoi area, is completed at three depths: 20-21 mbgl, 54.3-57.3 mbgl, and 81.7-84.7 mbgl. All three bore hydrographs show the same groundwater elevations in 1985 but then start to diverge (Figure 7.16). The shallow bore falls by 4.5 m between 1985 and 2009. The fall is not constant and the bore appears to be responding to long term climatic cycles, with peaks in 1984, 1991, and 2001 which correlate with periods of above average rainfall. However, these cycles may also be a response to abstraction from the underlying aquifer systems as agricultural irrigation will also produce this type of groundwater pattern.

The two deeper bores appear to be well connected to each other and show a much steeper falling trend than the shallow bore, with a fall of 11 m over the length of record. Annual cycles of 2-3 m can be observed in most years, probably due to nearby alluvial abstractions. Bores at the edges of the alluvium, such as GW036011 (screened at 18.3-21.3 mbgl and 54.9-59.4 mbgl), do not have the large annual variations but do show the longer term quasi-climatic cycle (Figure 7.16).

Bore group GW030063 lies within Zone 8 of the Upper Namoi alluvial area. The shallow bore is screened in the range 24.4 - 27.4 mbgl, and the deeper bore is screened at 50.3 – 53.3 mbgl. Both hydrographs show very similar water levels trends, indicating that there is a strong hydraulic connection between the two screens (Figure 7.17). The drillers log suggests that both bores are completed in a thick layer of fine gravel. Water levels mirror seasonal and longer term rainfall patterns, with a c. 2 m range in most years. This range is extended after prolonged wet and dry periods, but the overall trend is a falling water level. Between January 1975 and January 2010 the water level has fallen by 10 m. Other boreholes within and adjacent to this groundwater management unit show a similar trend.

Upper Namoi - Cox's Creek

Bore group GW036499 is located next to Cox's Creek. Prior to 1992, the bore levels are all similar and show very minor fluctuations (Figure 7.17). After 1992 there appears to be a change in the groundwater use within this area of the catchment, with abstractions beginning to dominate annual groundwater patterns in the deeper aquifer and water levels beginning to fall. The shallow bore shows rising levels until 2001, after which there is a steady decline until present day. Large groundwater level spikes can be seen in all three bores in 1983 and 2007. This is likely to be a result of surface water flooding. Similar groundwater patterns are seen in other bores within this catchment.

Peel Valley

There have been two phases of groundwater monitoring in the Peel catchment. A small group of bores were monitored in the 1970's and 1980's but after this time monitoring stopped. A second major phase of monitoring started in 2000 and has continued until the present day. The majority of monitoring bores in the Peel catchment are shallow, with between 1 and 6 metres of screen located between 2 and 22 metres below ground level. Absolute water levels within the catchment vary from 522 mAHD to 291 mAHD and bores are located in both the regulated and unregulated sections of the river.

There are four bores which cover both periods of monitoring. These all lie within the now regulated section of the river. The early years cover the period when Chaffey Dam was being constructed but there is little difference in groundwater levels before and after this time.

Bores in the Peel catchment generally show a steady water level through time. There are no bores which show an unmistakable response to groundwater abstraction as seen in the main alluvial areas in the Namoi valley. There are three bores that show variable water levels which may be a result of local groundwater abstractions. Two of these are located on the Goonoo Goonoo Creek (GW093016, GW093017) close to a high density of groundwater abstraction licences. The hydrographs fall a number of times by up to 7 m but return to the same initial base levels. The third bore (GW93019) is located up a minor tributary valley to the east of the Goonoo Goonoo Creek and is also adjacent to a number of groundwater abstraction sites. This bore shows a fall in levels of 10 m between 2000 and 2005 followed by a stable lower level since that date. Selected borehole hydrographs are shown on Figure 7.18, bore locations are shown on Figure 7.8.

Liverpool Ranges

There are few government groundwater monitoring bores located away from the alluvial areas.

Bore pair GW040832 is located above the Upper Namoi Zone 6 alluvium, at the base of the Liverpool Ranges. The bores show less than 1 m of groundwater head variation over the 7 year monitoring period, and these appear to be annual cycles. The shallow screen at 5-7 m and deep screen at 18-21 m depth show very similar water levels, indicating that there is a good connection between them. The geological units that these bores are installed in is unknown but they are located in an area marked as basalt on the geological map.

The degree to which groundwater level variations are caused by abstractions or natural seasonal changes in all of the GMAs is uncertain. The early records for boreholes in several management zones show similar rest water levels in bore groups completed at different depths under pre abstraction. Agricultural bores are likely to abstract minimal volumes during the wet season, when there is sufficient rainfall to water crops. This will lead to potential increases in groundwater levels from both rainfall recharge and recovering water levels around bores. Conversely, during the dry season there will be falls in groundwater levels as a result of agricultural borehole abstractions and also reduced rainfall recharge to the aquifer.

7.6.3 Groundwater level contours and flows

Groundwater monitoring was active in the majority of sub-catchments by 1980, which was also a year with relatively high groundwater levels in relation to the long term trends. Figure 7.19 presents depth to water table for all of the bores that recorded water levels in that year. The plot includes water levels taken from any bores at the time of construction. To try and minimise the influence of irrigation pumping the highest water level record in the year was taken for the plot, as this is more likely to give a representative rest water level for the aquifer. For multi-pipe bore groups the shallowest bore was chosen for the plot as this was also less likely to be influenced by nearby abstraction and also would give a better reflection of the shallow groundwater system.

In 1980 the shallowest water levels are encountered along the Peel River valley and in the Upper Namoi alluvium, with water levels of less than 10 mbgl in most places. Levels in the higher elevations of Upper Namoi Zone 8 are slightly deeper, at around 12 mbgl. There are also deep water levels recorded within the fractured rock aquifers in the Peel catchment.

Water levels in the Cox's Creek sub-catchment are between 10 and 20 m despite the almost natural groundwater levels observed, indicating that these levels are naturally deeper levels. Deeper water levels are also seen in Zone 12, which is also at a slightly elevated position from the main floodplain.

Within the Lower Namoi there are shallow levels in the east of the catchment near Narrabri, and deeper levels moving towards the west. Again these deeper water levels are most likely natural as there has been no significant change in the hydrographs in these western areas by this time.

Absolute groundwater levels, converted to mAHD, are shown on Figure 7.20. Despite the different depths to water observed in the water level records the absolute levels show that these are all consistent with a topographic hydraulic gradient from east to west.

Figure 7.21 shows the relative change in the shallow water levels between 1980 and 2000. The year 2000 was also a relative high point in the longer term natural climatic cycle of the shallow bores. For areas of the Upper Namoi Zone 4 catchment and the Cox's Creek catchment there were no bores that were being monitored in both years and the comparison has been made between 1986 and 2000. These bores are shown with slightly smaller markers on the plot. Over the chosen periods rising water levels are shown as green shaded markers, and falling water levels are shown as red shades. The deeper the colour the larger the difference observed.

A small degree of natural variation in water levels would be expected over this length of record, and the majority of water levels show a change in level of less than 2.5 metres. However, there are areas within the catchment which have recorded much larger changes. There are two areas within the Upper Namoi where water levels have fallen by over 8 metres. Water levels also fell noticeably in the Lower Namoi close to Narrabri although these falls are seen next to a small water level rise. Conversely, water levels rose in the highest elevation areas of the Upper Namoi.

Between 2000 and 2010 water levels have fallen in the majority of the recorded bores (Figure 7.22). There are a large number of bores with only minor falls which are likely to be reflecting the effects of the long term drought on the catchment. In the highly stressed areas of the catchment, where there are significant abstractions from groundwater, the effects of the drought are more pronounced, and there are further falls of up to 8 metres in the shallow groundwater levels.

A catchment wide water level contour map has been produced using average water levels for any non-GAB site that had a groundwater level recorded after 1950 (Figure 7.23). The few hard rock sites available with time variant water level readings do not show a large variation in water level over time, it was therefore felt that water levels obtained from hard rock bores during construction would still be representative of water levels on a regional scale. A total of 7,480 points were available for regional water level contouring, data points are least dense around the Pilliga Forest and GAB alluvial areas. Figure 7.23 shows that groundwater levels follow a similar pattern to topography, with projected flow paths mirroring the surface water systems.

7.6.4 Groundwater quality

For a catchment this size there is very little groundwater quality data available from government sources such as the Pinneena 3.2 database. This lack of information in a long term government dataset has also been commented on by authors of previous studies, as noted in Kelly et al. (2007). A larger amount of data has been collected for various private studies, and it is possible to obtain an enhanced understanding of catchment water quality from these reports.

Water quality records start in the Pinneena 3.2 database from 1991 onwards. There are no bores with long records of water quality that would help to establish the variation in major ion chemistry over time. In locations with multiple pipes and one hole number there is nothing in the database to distinguish which pipe the measurement was taken from.

Salinity and electrical conductivity

The greatest range of water quality data has been collected to look at 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). Salinity measurements from when many of the bores were drilled are recorded in Pinneena. The records are either grouped into numerical classes or are descriptive rather than numerical, with waters described as fresh, brackish, salty, etc.

These descriptive records were correlated subjectively with salinity classes taken from Fetter (1994) (Table 7.13) to allow them to be plotted spatially. It is not known whether the descriptions in the database adhere to these classes or are simply subjective based on tasting the water but they allow for an understanding of trends across the area (Figure 7.24). The majority of bores produced water with low total dissolved solids (TDS) when drilled. It can be seen that the hard rock aquifers outside the alluvium have always been more saline than the alluvium, with electrical conductivity (EC) values that are suitable for stock watering rather than irrigation or domestic use. The western area of the Lower Namoi alluvium is also of high salinity, which explains why there is less abstraction pressure observed in the borehole hydrographs.

Table 7.13 Standard salinity classes and description groupings

Salinity class	TDS (mg/L)	Pinneena descriptions
Fresh	<1,000	Excellent, very good, good, potable, fresh, domestic
Slightly brackish	1,000 – 3,000	Good stock, stock, fair
Brackish	3,000 – 10,000	Brackish, very brackish
Saline	10,000 – 100,000	Poor, slightly salty, salty
Brine	>100,000	---

Time variant TDS values are limited within the database to two small areas of the catchment. There are however a larger number of sites with multiple data readings for electrical conductivity (EC), which can be approximately correlated to TDS using the formula:

$$EC (\mu S/cm) \times 0.67 = TDS (mg/L)$$

Data in the Pinneena 3.2 database shows that there have been two periods where there have been groups of bores monitored for EC. One period in the early 1990's (~ 3-4 dates per bore), and one in 2003-04 (~ 10 dates per bore). The data is focussed on one area in the Lower Namoi, and one area in the Zone 3 of the Upper Namoi GMU. When these EC results are plotted it is apparent that the samples are most likely obtained from different depths within the aquifer although this is not noted in the database. An example of this is bore GW036320, located in the Lower Namoi. The bore number has three distinct salinity trends, at 15,000, 8,000, and 3,000 $\mu S/cm$, with samples taken on the same day for each point. The depths at which these samples are taken from is unknown. The results from previous studies, reported in Kelly et al. (2007), appear to indicate that the alluvial aquifers are often fresher at depth.

Timms et al. (2010) report on the salinity of samples collected from irrigators in the Namoi catchment during 2009. A summary of results for each GMA are provided in Table 7.14. These samples are all relatively fresh compared to the values observed in some of the monitoring bores. This is to be expected as the irrigators would preferentially abstract from lower salinity sources if the option is available.

Table 7.14 Irrigators samples electrical conductivity (EC) results (µS/cm)

GMA	Zone	Min	Max	Average
GAB alluvial	---	594	1420	1144
GAB	---	64	954	488
Gunnedah Basin	---	504	4200	1850
Liverpool Ranges Basalt	---	889	2310	1599
Lower Namoi Alluvium	---	252	7590	1176
Misc alluvium of Barwon Region	---	1130	1870	1500
New England Fold Belt	---	798	2250	1131
Oxley Basin	---	1140	1220	1180
Peel Valley Fractured Rock	---	548	1880	1025
Upper Namoi Alluvium	2	580	2560	1773
Upper Namoi Alluvium	3	452	758	574
Upper Namoi Alluvium	4	340	2230	798
Upper Namoi Alluvium	5	960	2470	1715
Upper Namoi Alluvium	6	853	2000	1426
Upper Namoi Alluvium	7	1270	1270	1270
Upper Namoi Alluvium	8	693	1240	947
Upper Namoi Alluvium	11	674	674	674

(Timms et al., 2010)

Groundwater chemical composition

There are few samples within the Pinneena 3.2 database that have the full analyses of major ions required for water typing. A comprehensive review of published water quality reports is given in Kelly et al. (2007). All samples will have originally started out with the chemical signature of local rainfall. A representative rainfall chemistry for the Wee Waa / Narrabri area is shown in Table 7.15 (Ransley et al., 2010) and any changes that develop to the water after that time will reflect the interaction with different soils and geological units.

The rainfall signature contains all of the major ions in extremely low concentrations, and has a TDS concentration of < 6 mg/L which is significantly lower than the TDS of any of the groundwater samples.

Table 7.15 Rainfall chemistry Wee Waa / Narrabri area (mg/L) as noted in Ransley et al. (2010)

	TDS	Ca	Na	Mg	K	Cl	SO₄	HCO₃
Blackburn and McLeod (1983)	5.5	0.2	1.3	0.1	0.3	1.4	0.6	1.6
Ransley et al. (2010)	4.8	0.2	0.8	0.2	0.5	1.2	0.7	0.7

Lavitt (1999) analysed water samples from the Mooki catchment and found that groundwater samples from the shallow alluvium had a very variable composition but were more similar to river water than the deeper alluvial aquifers. This implies a limited vertical connection within the alluvium under natural conditions. Samples from the deeper alluvial units were found to be more similar to the surrounding hard rock units, which suggested that the deeper alluvium and shallow hard rock aquifers are hydraulically connected. However, this may also be related to the source rock of the basal alluvium being similar to the hard rock aquifers, or the water in the deeper alluvium being much older and more chemically evolved than in the shallow alluvium. Many of the shallow samples were of high salinity, with the chemistry being dominated by Na and Cl ions.

Less saline samples from the shallow aquifer had a greater spread of cations and a higher percentage of bicarbonate as the major anion. The review found that water samples from the hard rock Gunnedah Basin, Liverpool Range volcanics, and Werrie Basalt and New England Fold Belt formed distinct groupings when plotted (Figure 7.25). Groundwater samples from the wider Gunnedah Basin sediments show a larger degree of ion exchange, with several locations showing cation concentrations trending to sodium dominated.

Water samples taken from a site in the extreme upper reaches of the Mooki catchment, within Upper Namoi Zone 6, also showed a similarly disconnected system, with only very slow vertical leakage between the shallow and deeper alluvial layers being observed (Timms and Acworth., 2002). The water chemistry of the alluvium was found to overlap with that of the Liverpool Ranges Volcanics and Gunnedah Basin sediments, both of which are present in this area of the catchment. This was found to be similar to the water chemistry in the Cox's Creek catchment which has a similar underlying geology (NSW DNR, 2005). Both catchments recorded a mixed cation chemistry and very low sulphate.

Samples taken from different depths within the alluvial aquifers in the Maules Creek catchment (Andersen and Acworth, 2007) found that water within the alluvial systems evolved from calcium-bicarbonate or sodium-chloride composition in the shallow alluvium to a more sodium-bicarbonate dominated chemistry in the deeper parts of the alluvial aquifer.

Waters within the Lower Namoi alluvium were analysed by McLean (2003). There is a large spread in water chemistry from the analysis, indicating that the Lower Namoi alluvium is also a very complex system (Figure 7.25). There is a strong spatial correlation to water quality, with water samples from the east and west of the catchment plotting in distinct locations and water from the centre plotting between the two. Representative samples from the GAB are also shown on Figure 7.25. These are similar to alluvial samples from the centre, west, and south of the Lower Namoi alluvium. This may indicate a connection between the two systems, or could also be representative of water that has moved through similar geology over a similar time period. These samples appear to exhibit less vertical distinction within the alluvium.

Eastern Star Gas have analysed samples from alluvial bores within their exploration area (Table 7.16). The mean analyses for these bores show no dominant anions or cations.

Table 7.16 Alluvial bore chemical analysis (Eastern Star Gas)

Parameter	Unit	Number of samples	Min	Max	Mean
pH	---	97	6	8.7	7.54
EC	µS/cm	92	519	22700	1557
TDS	mg/L	101	438	13863	1065
Ca	mg/L	122	7.4	665	60
Na	mg/L	122	42	2840	182
K	mg/L	122	0	40	2.7
Mg	mg/L	122	1.7	1024	52.6
Cl	mg/L	122	20	7581	251
SO ₄	mg/L	122	2	1450	78.9
HCO ₃	mg/L	121	164	988.2	406
CO ₃	mg/L	11	0	52.8	7.8

(Golder Associates, 2010)

Coal seam and deeper Gunnedah Basin water chemistry

Coal seam gas resources are typically found in coal seams with very specific water chemistry. Typical CSG waters are low in calcium, magnesium and sulphate and are dominated by sodium, bicarbonate, and often chloride where there are marine associations (Van Voast, 2003). Water samples taken from CSG wells in the Bowen Basin, immediately to the north of the Gunnedah Basin, show this typical chemical signature although the percentages of chloride present within the production wells varies over short distances both vertically in different coal seams, and laterally due to the presence of a fault which splits the gas field (Kinnon et al., 2010).

In areas where the coal seams do not contain methane the water chemistry is significantly different. There are much higher sulphate concentrations, and high and more variable concentrations of calcium and magnesium. These chemistries are typically found in the recharge areas, with the water evolving towards the discharge zones to a more sodium bicarbonate type through geochemical sulphate reduction, bicarbonate enrichment and calcium and magnesium depletion (Van Voast, 2003).

Eastern Star Gas have published typical values for produced water from their target coal seams in the Gunnedah Basin (Eastern Star Gas, 2009) and these values are summarised in Table 7.17. The water is high in TDS and is of sodium-bicarbonate water type. The water is treated by reverse osmosis which removes a high percentage of the dissolved ions before it is discharged from the site.

Table 7.17 Indicative produced water values (Eastern Star Gas)

Parameter	Unit	As produced	After processing
pH	---	7.5 – 8.0	5.5 – 6.0
TDS	mg/L	8,000 – 10,000	80 – 150
Calcium	mg/L	10	0
Magnesium	mg/L	60	<1
Sodium	mg/L	3,000 – 4,000	20
Potassium	mg/L	50	<1
Bicarbonate	mg/L	5,000 – 8,000	50
Chloride	mg/L	1,000	5
Sulphate	mg/L	Not given	Not given
Fluoride	mg/L	<1	0
Barium	mg/L	1	0
Iron	mg/L	<1	<1
Strontium	mg/L	2	0

(Eastern Star Gas, 2009)

Santos has also published a summary of groundwater encountered during their drilling program (Golder Associates, 2010). These are summarised for both the Hoskissons seam and the wider Gunnedah Basin units in Table 7.18. Although absolute values for the Hoskissons seam are lower than those provided by ESG the water from the coal seam is still dominated by sodium-bicarbonate. The water quality of the Gunnedah Basin units is noticeably different to the coal seams.

Table 7.18 Mean groundwater quality values for the Gunnedah Basin (Santos)

Parameter	Unit	Hoskissons seam	Gunnedah Basin sediments (excluding coal seams)
pH	---	7.97	7.27
EC	µS/cm	5337	2463
TDS	mg/L	3240	1712
Calcium	mg/L	6.78	55.1
Magnesium	mg/L	8.07	84.1
Sodium	mg/L	1337	313
Potassium	mg/L	11	9.51
Bicarbonate	mg/L	3166	698
Chloride	mg/L	297	349
Sulphate	mg/L	2.56	126
Carbonate	mg/L	102	N/A

(Golder Associates, 2010)

The relatively uniform water types found in CSG producing seams can help to narrow down those areas that are suitable for CSG exploration. Within the Gunnedah Basin sediments the coal seams occur at different depths from surface, with the same seam occurring at the centre of the basin and also at outcrop. Where the coal seams are shallow the waters will be dominated by chemistries that are typical of the recharging waters and the water chemistry will not be compatible with methane production. As the seams are followed deeper underground and the water has a chance to evolve there is a higher probability that higher concentrations of methane will occur.

Great Artesian Basin

The Pilliga Sandstone generally has a lower salinity than the confining layers of the GAB. Salinity within the GAB aquifers in the Namoi catchment is low but the water often contains high concentrations of sodium which is incompatible with clay soils. The sodium binds with the clay particles and reduces the infiltration capacity and hydraulic conductivity of the soil, eventually leading to waterlogging and anaerobic conditions. The GAB water is therefore unsuitable for irrigation over the alluvial areas of the catchment. This sodium-bicarbonate dominated GAB water is a similar water type to that found in CSG production wells although there is no potential for methane production unless there are coal seams present.

7.7 Aquifer interaction / connectivity

Within the Namoi catchment there are several distinct hydrogeological areas. The greatest interactions are going to be through the horizontal and vertical connections encountered within the alluvial aquifers, as these have the highest hydraulic conductivities within the catchment. The alluvial areas are heterogeneous deposits and although they are often split into the Narrabri and Gunnedah Formations there is often no distinction in the geological logs to suggest where this boundary should be.

Multi-pipe piezometers show that the degree of vertical connectivity changes throughout the system, and that the depth at which the alluvial systems starts to react to deep abstractions varies over comparatively short distances. Spatial plotting of the shallow groundwater table (Figure 7.23) shows that there are no large barriers to groundwater flow along the system, although Gins Leap Gap is the location of a major constriction between the Upper Namoi alluvial zones 4 and 5 due to aquifer geometry / extent (rather than permeability).

In the western area of the catchment the GAB underlies the alluvial areas. The artesian pressures recorded in the early years suggest that there is a minimal hydraulic connection between the GAB and the alluvium as a strongly connected system would not have been able to build up heads of over 60 magl in the GAB aquifers. Water pressures with the GAB have fallen significantly since the aquifers were first tapped, and the potential for upwards movement of water into the alluvium will have reduced as the pressure gradient has fallen. The current contribution of the GAB aquifers to the water balance of the Lower Namoi model has been calculated as approximately 3.8 m³/d/km² (Herczeg, 2008). The Lower Namoi model is in the process of being reviewed and updated, and this value may change once this update is completed.

Many of the active coal mines have completed site specific numerical models (e.g. RCA Australia, 2005 and Golder Associates, 2010) which have predicted only small changes in water levels outside the mine lease areas. In many cases these changes will be hard to distinguish from natural variations in water levels. Data is being collected for bores adjacent to the mining areas as part of the environmental programs for each mine and also for mines which are currently in the exploration phase. These datasets are being used by SWS to try and assess the degree of interaction between the alluvium and hard rock aquifers.

The degree of connectivity between the alluvium and hard rock aquifers is a key component for determining any impacts on water resources within the alluvium due to coal mining or CSG extraction. However, it is anticipated that the interconnectivity of the various aquifer systems on a regional scale will represent a significant data gap for this study at the present time. The data gap is discussed further in Section 10.

7.8 Groundwater dependent ecosystems

There are a large number of water dependent ecosystems within the Namoi catchment. High priority groundwater dependent ecosystems (GDE's), have to be identified as part of the implementation of Water Sharing Plans within the catchment. High priority GDE's are those which are ecologically significant and which could be most easily impacted by changes in the groundwater environment. Historically there has been little work undertaken to map these sites and determine their tolerance to changes in the groundwater regime. There have recently been a number of studies which have sought to improve this knowledge.

A study complete by Eco Logical (2008) mapped all sites over 1 ha in size, both natural and artificial, using aerial photographs. The sites were then classified according to the Wetlands Monitoring, Evaluation and Reporting classification scheme (NSW DECCW, 2010a) to determine their degree of interaction with both surface water and groundwater. Of the 2,766 sites identified only 321 were classed as being groundwater supported, with the majority of sites identified being supported by surface water. Artificial wetlands include constructed water storages and highly modified natural features, which may include large farm dams. Their ecological significance will depend on the type of vegetation associated with them.

Work to determine the condition and water requirements of these identified groundwater dependent ecosystems (GDE's) is at an early stage. Several high priority GDE's have already been mapped using a flexible framework developed for the catchment by Eco Logical (2008). The framework is based on an assessment of ecological needs of each site and the degree that it could be impacted by nearby activities.

All of the sites identified as high priority sites in the most recent State of the Catchment report (NSW DECCW, 2010b) are displayed on Figure 7.26. This number is expected to rise as investigations at other sites continue. The high priority sites are almost exclusively springs, although there are three sites which are noted as being karst environments. The sites are all located within the hard rock aquifers, and all but three lie at elevations above 400 mAHD.

Table 7.19 summarises the high priority GDE's identified in Water Sharing Plans within the catchment (see Section 9 for more about Water Sharing Plans). The only place where current high priority GDE's lie within a Water Sharing Plan area is the Peel Valley. Conditions have been placed within all Water Sharing Plans to protect high priority GDE's from nearby groundwater abstraction, and any sites identified in the future will also be protected. The conditions include the creation of buffer zones around GDE's, within which any new or replacement bores must not access the aquifer units supporting the GDE.

Table 7.19 High priority groundwater dependent ecosystems identified in Water Sharing Plans

Water Sharing Plan area	Subcatchment	High priority GDE identified
Upper and Lower Namoi Groundwater sources 2003	---	No high priority GDE identified
Peel Valley Regulated, Unregulated, Alluvium and Fractured Rock Water Sources 2010	Upper Peel Tributaries water source	Black Spring
	Lower Peel Tributaries water source	Bundys Spring, Jacks Camp Spring, Moore Creek (K), Sulcor (K)
	Cockburn water source	Black Springs
	Chaffey water source	Crawney Pass (K)
NSW Great Artesian Basin Groundwater Sources 2008	---	No high priority GDE identified in the Namoi catchment area of the WSP

K = High priority karst environment groundwater dependent ecosystem

A second study, completed by SKM (2010), used a combination of remote sensing and GIS layers to map areas of potential GDE's. The study looked at evapotranspiration, rainfall, soil water holding capacity, depth to water table, native vegetation, riparian and wetland GIS layers to create a catchment map of the most likely locations for terrestrial, wetland and riparian GDE's.

In total 286,042 ha of the catchment was classed as potentially supporting a GDE. Of this 96.7% was for terrestrial vegetation, 2% for riparian vegetation, and 1.3% for wetlands. The largest area of high potential for supporting terrestrial GDE's is the Pilliga Forest.

On a local scale work completed on the Maules Creek (Connected Waters, 2011) has identified reaches which are important habitats for stygofauna.

Stygofauna are aquatic groundwater invertebrates that are a relatively new classification of animals. Due to the nature of their habitats their ecology, lifestyle and significance is generally poorly understood (Connected Waters, 2011). Many species appear to have restricted ranges (ALS, 2011) although there has been so little research on a national scale that this is highly uncertain. Stygofauna have been found by ALS in Western Australia, Queensland, and New South Wales, suggesting to them that stygofauna probably occur in nearly all alluvial aquifers. Tomlinson and Boulton (2008) also suggest that stygofauna are most likely present across a variety of subsurface environments within Australia, including unconsolidated, karstic, and fractured rock aquifers.

Tomlinson and Boulton (2008) also report that a widespread stygofaunal community was found in the Peel alluvium during surveys from 2005 to 2007.

Additional work will have to be completed on these stygofauna communities to determine their extent and significance within the groundwater flow systems of the Namoi catchment.

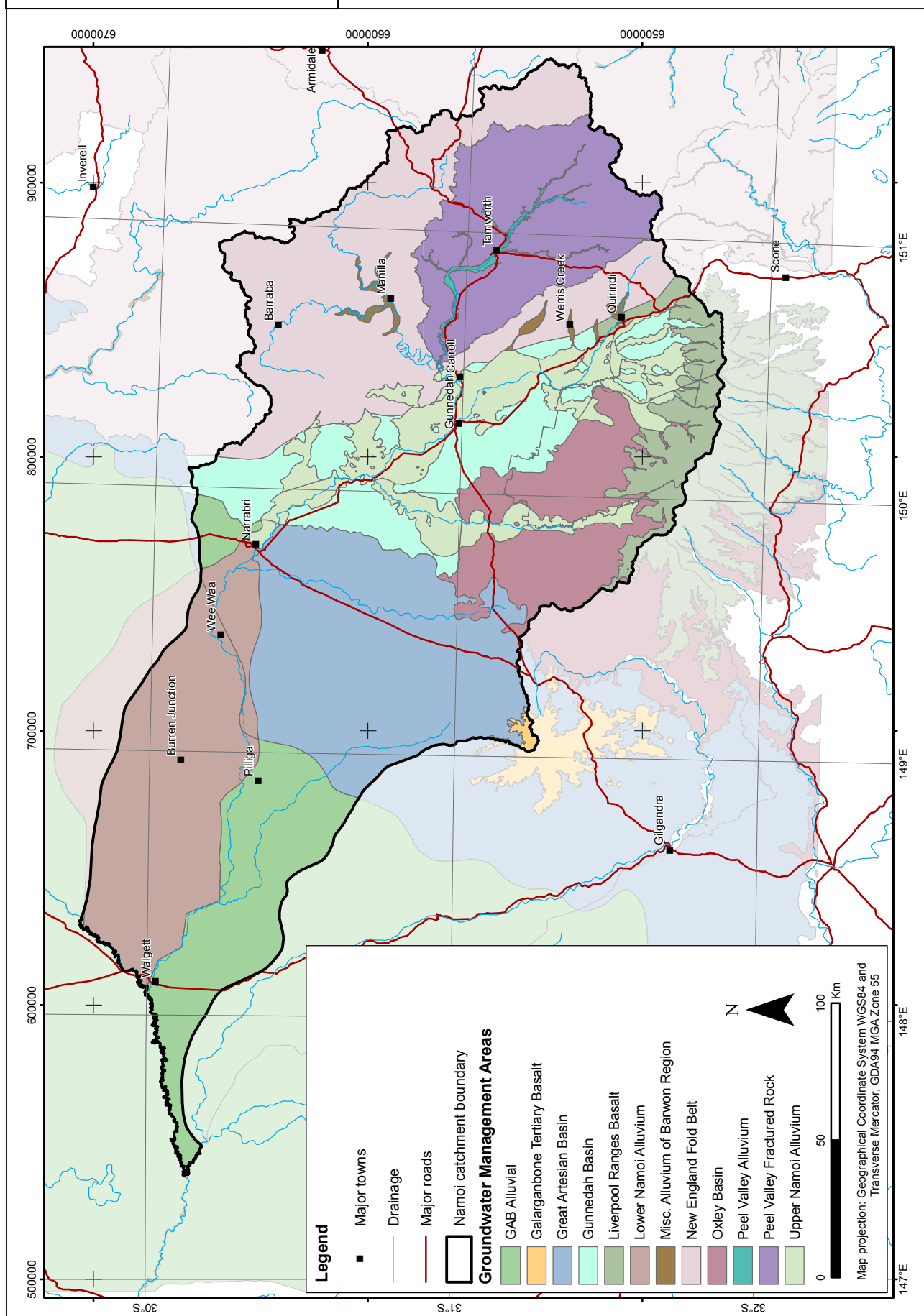
7.9 Summary

The hydrogeology of the catchment can be summarised as follows:

- The catchment has been divided into 12 Groundwater Management Areas, in accordance with the Murray Darling Basin Plan. The Upper Namoi Alluvium GMA has been further divided into 12 management units. The catchment comprises alluvial areas underlain by permeable and/or fractured hard rock units.
- The principal aquifers within the catchment are the Upper Namoi and Lower Namoi alluvium. These areas have historically been heavily utilised for water supplies as yields are high and the water quality is good. Water supplies can also be obtained from hard rock aquifers surrounding the main alluvial areas, and also the smaller areas of alluvium in the east of the catchment although yields are lower and often more brackish.
- The alluvial units are complex multi layered aquifer systems. Historical over abstraction of the deeper alluvial units in several areas has led to falling water levels.
- Several numerical models have been built to look at groundwater flow within the alluvial aquifers. The hydraulic properties of the alluvial units are therefore relatively well constrained. Models for the Upper Namoi region assumed that there is no hydraulic connection between the alluvium and underlying hard rock aquifer. The Lower Namoi model includes an inflow from the underlying GAB.
- There is very little catchment specific information available relating to the hydraulic properties of the hard rock aquifers. The majority of work completed for the Gunnedah Basin units has been undertaken by the coal mining and CSG companies. There have been no comprehensive studies to the east of the Hunter-Mooki Fault.
- There are a significant number of time variant groundwater level monitoring bores in the alluvial aquifers and the Peel Valley but few in the remainder of the catchment.
- Groundwater level contours are similar to topography on a regional scale, with flow moving downslope to the alluvial areas before discharging through the river network.
- The government water quality dataset is limited although there are a number of private studies that have investigated water chemistry of the alluvium and shallow hard rock aquifers. There is little information on the hydrochemistry of the deeper formations and coal seams.

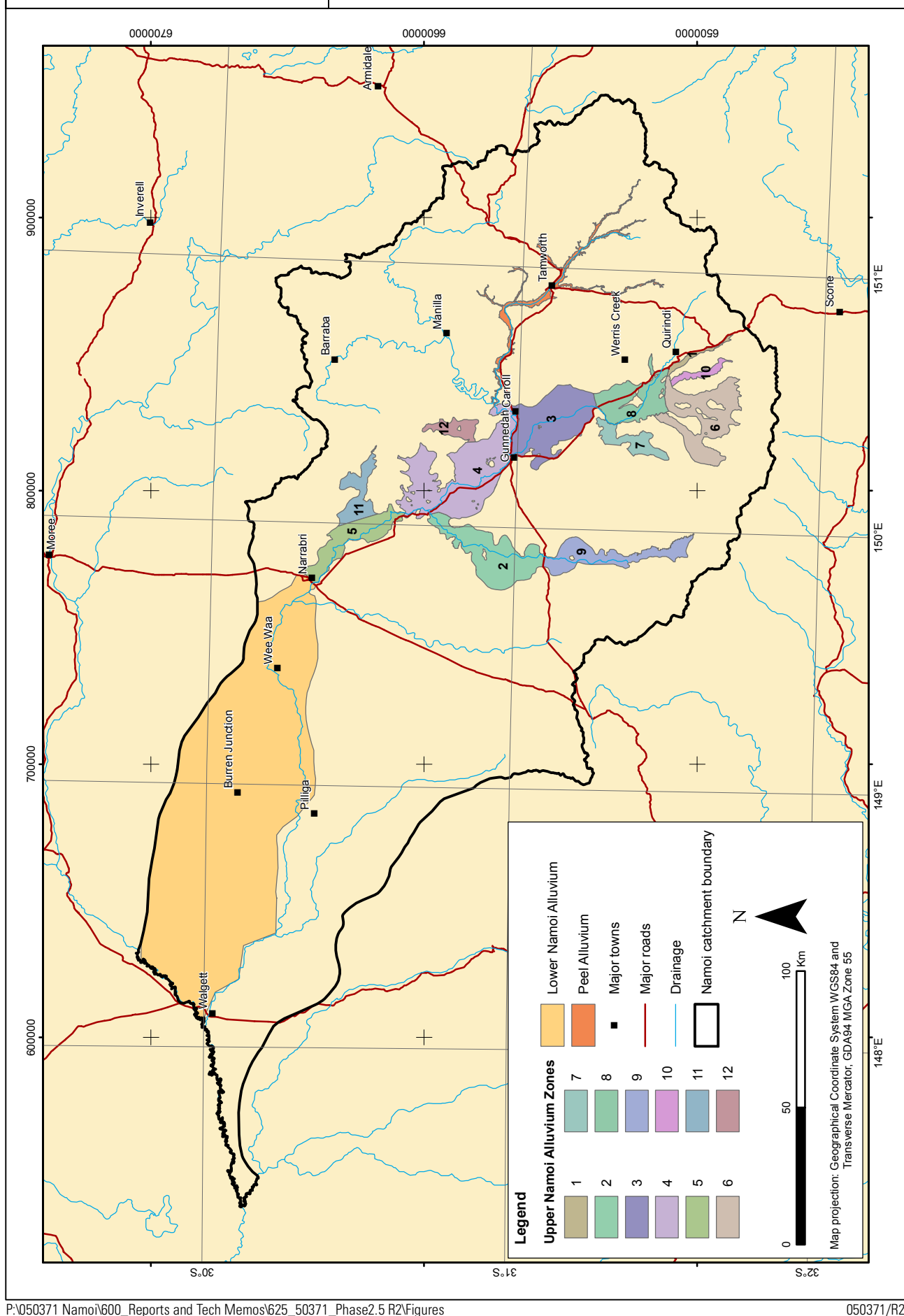
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Figure 7.1 Namoi catchment groundwater management areas



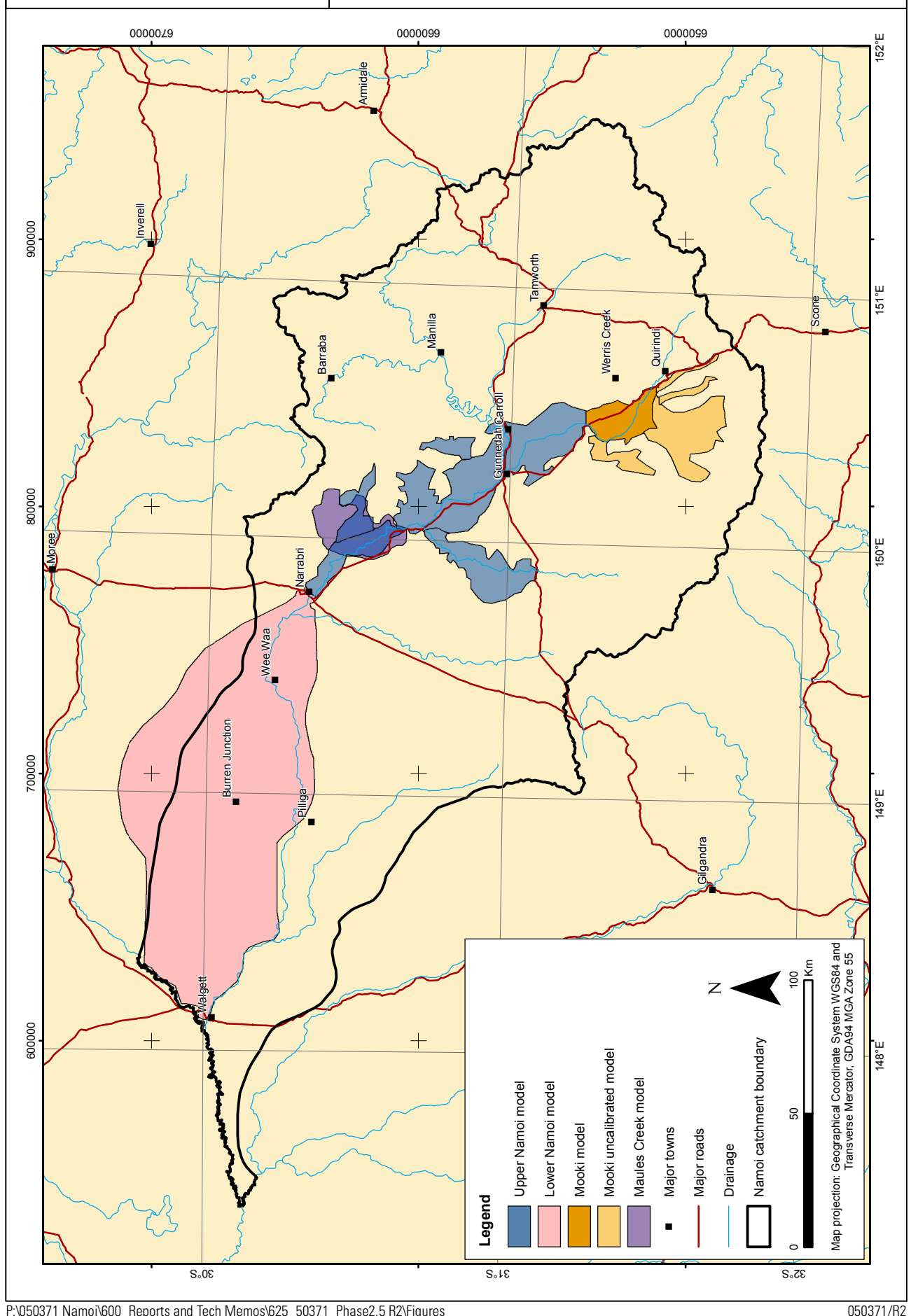
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Figure 7.2 Significant alluvial units



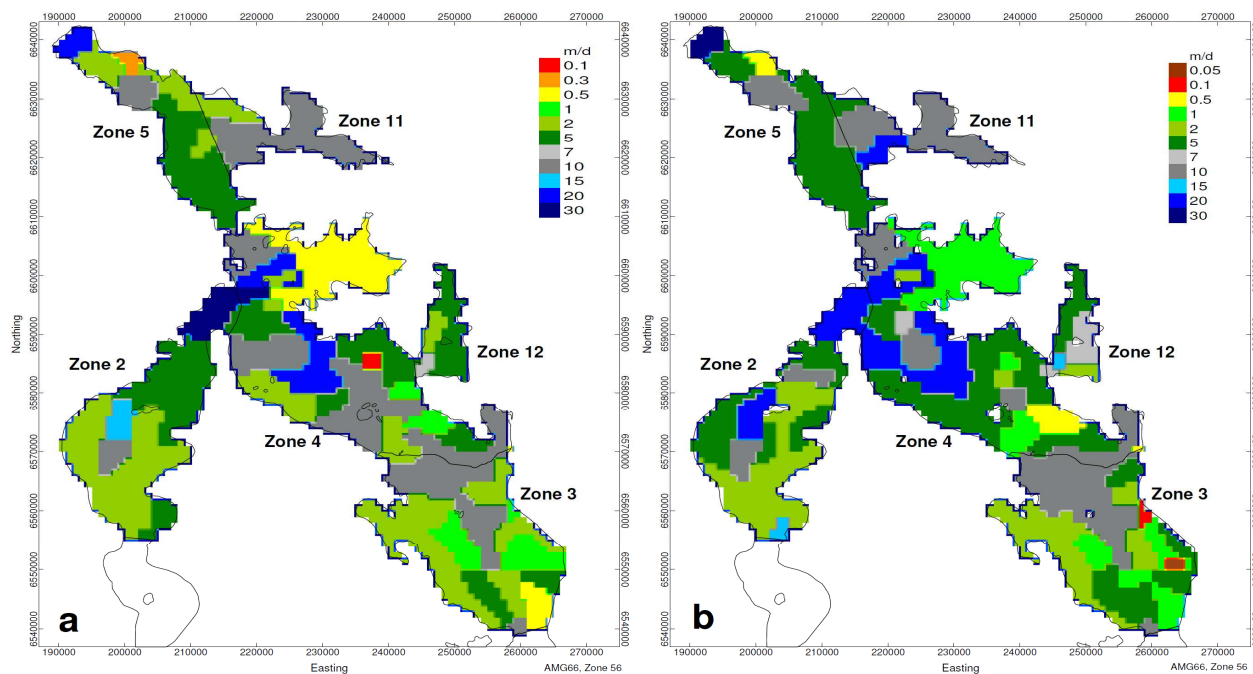
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Figure 7.3 Existing numerical model areas

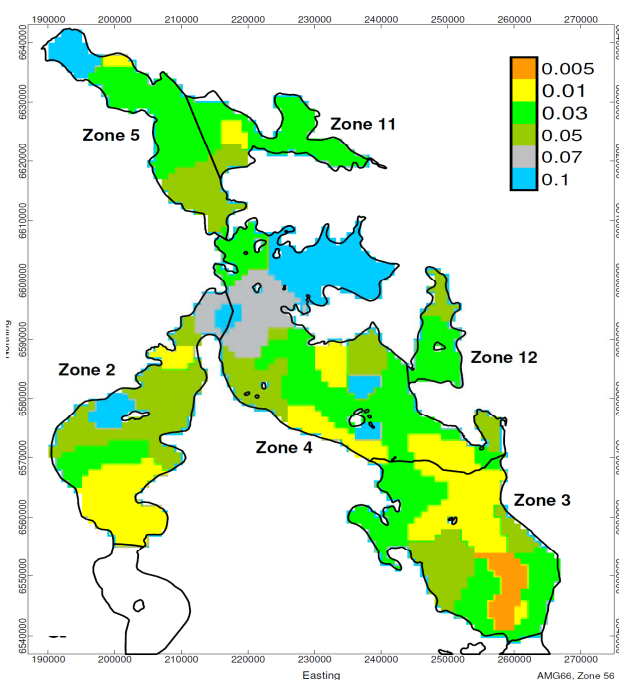


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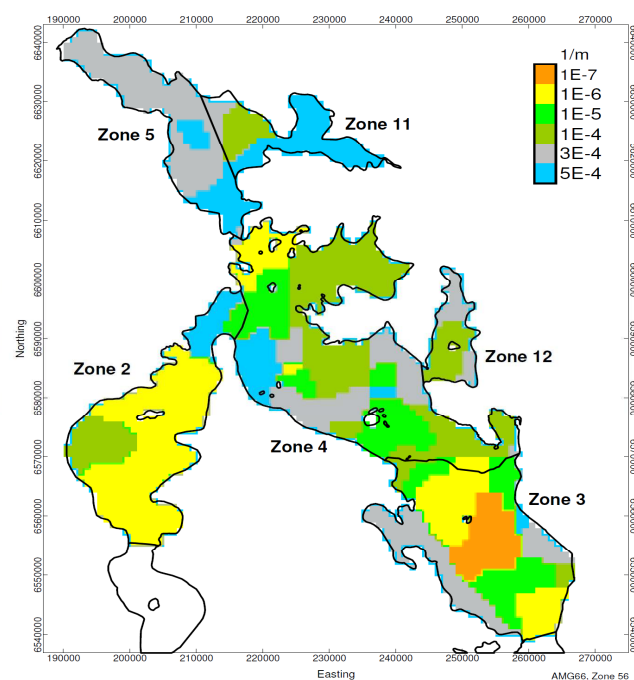
Hydraulic conductivity zoning, Layers 1 (a) and 2 (b)



Specific yield (Layer 1)



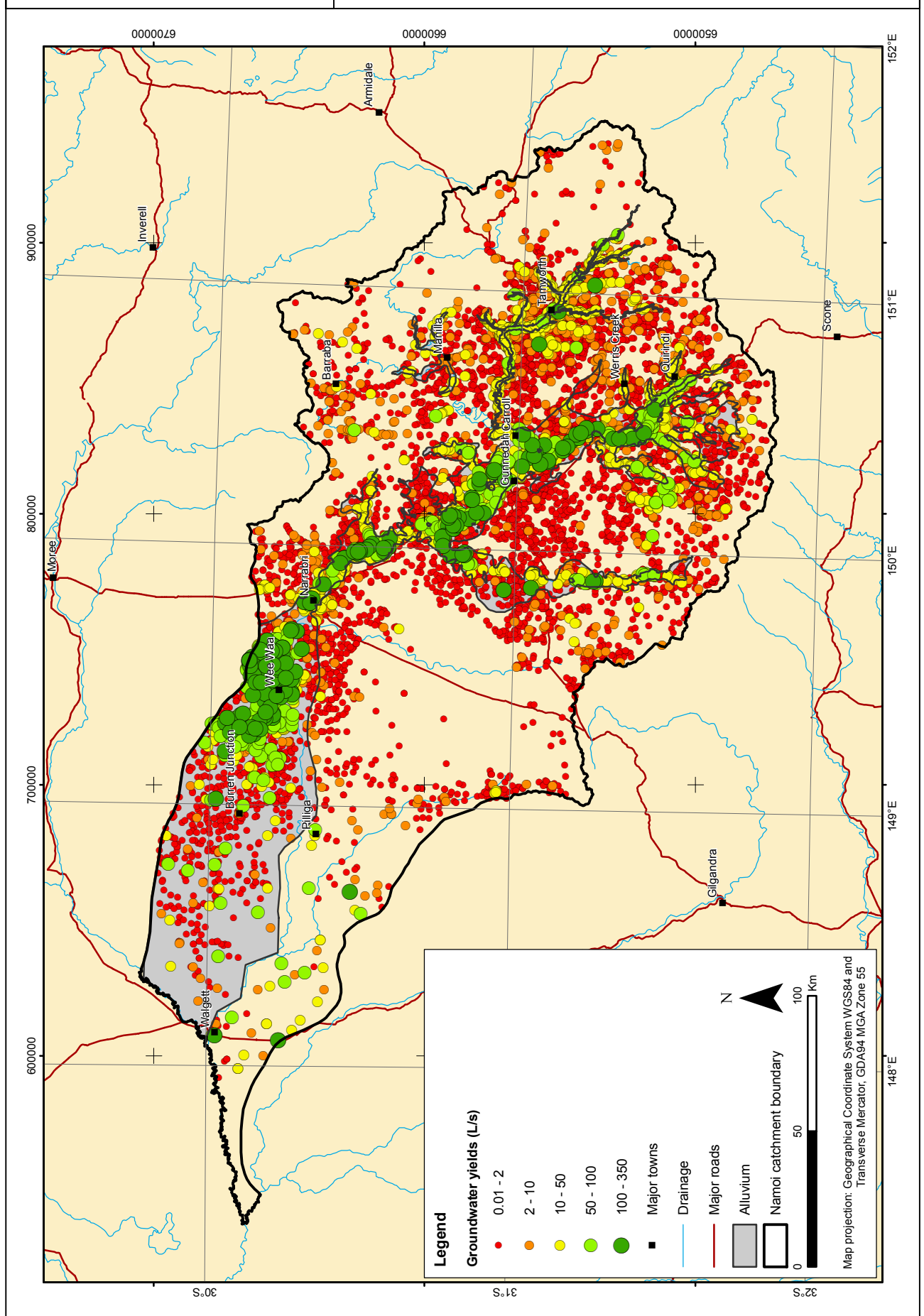
Specific storage (Layer 2)



Reprinted from McNeilage (2006)

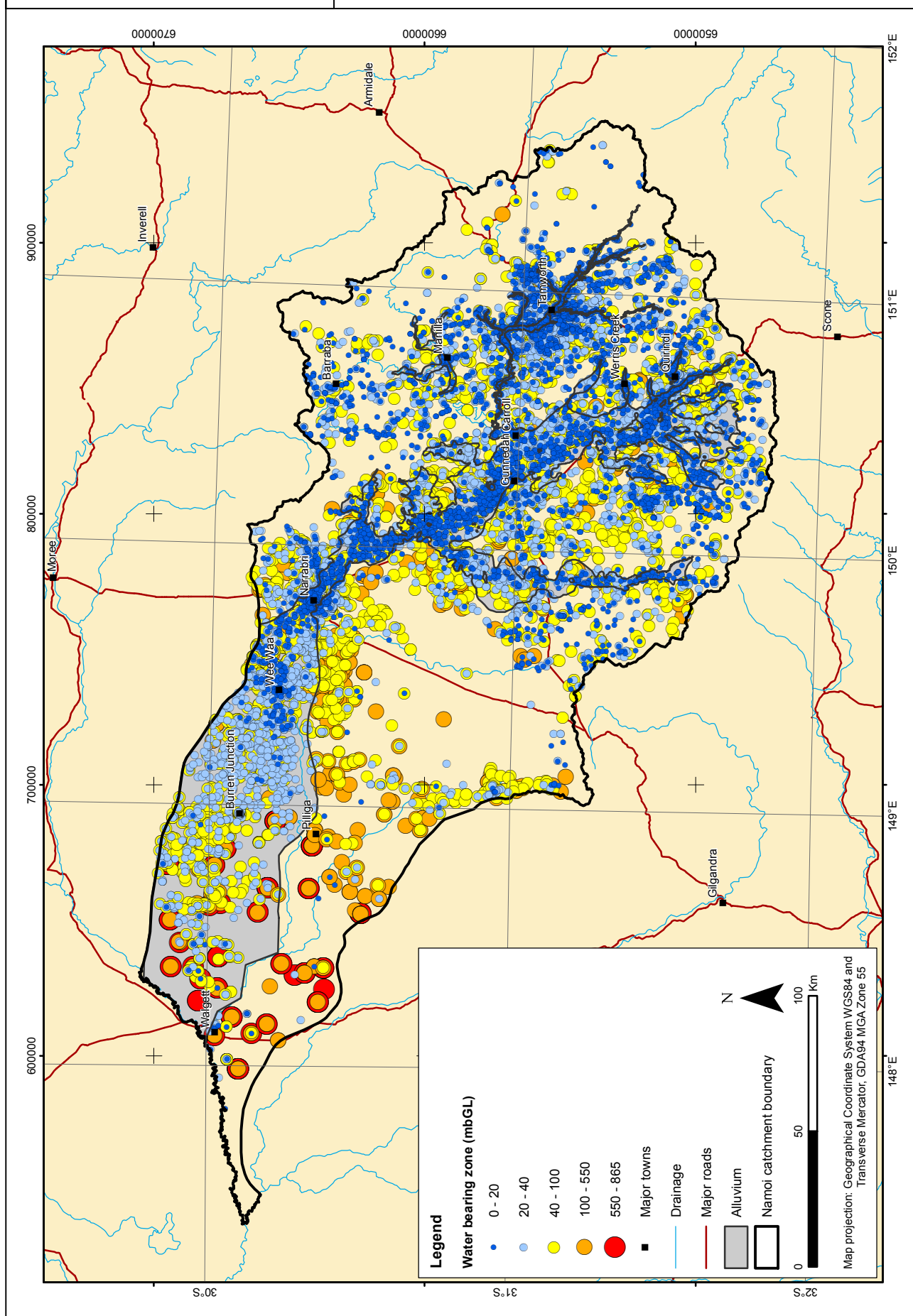
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Figure 7.5 Borehole yields provided in the Pinneena database



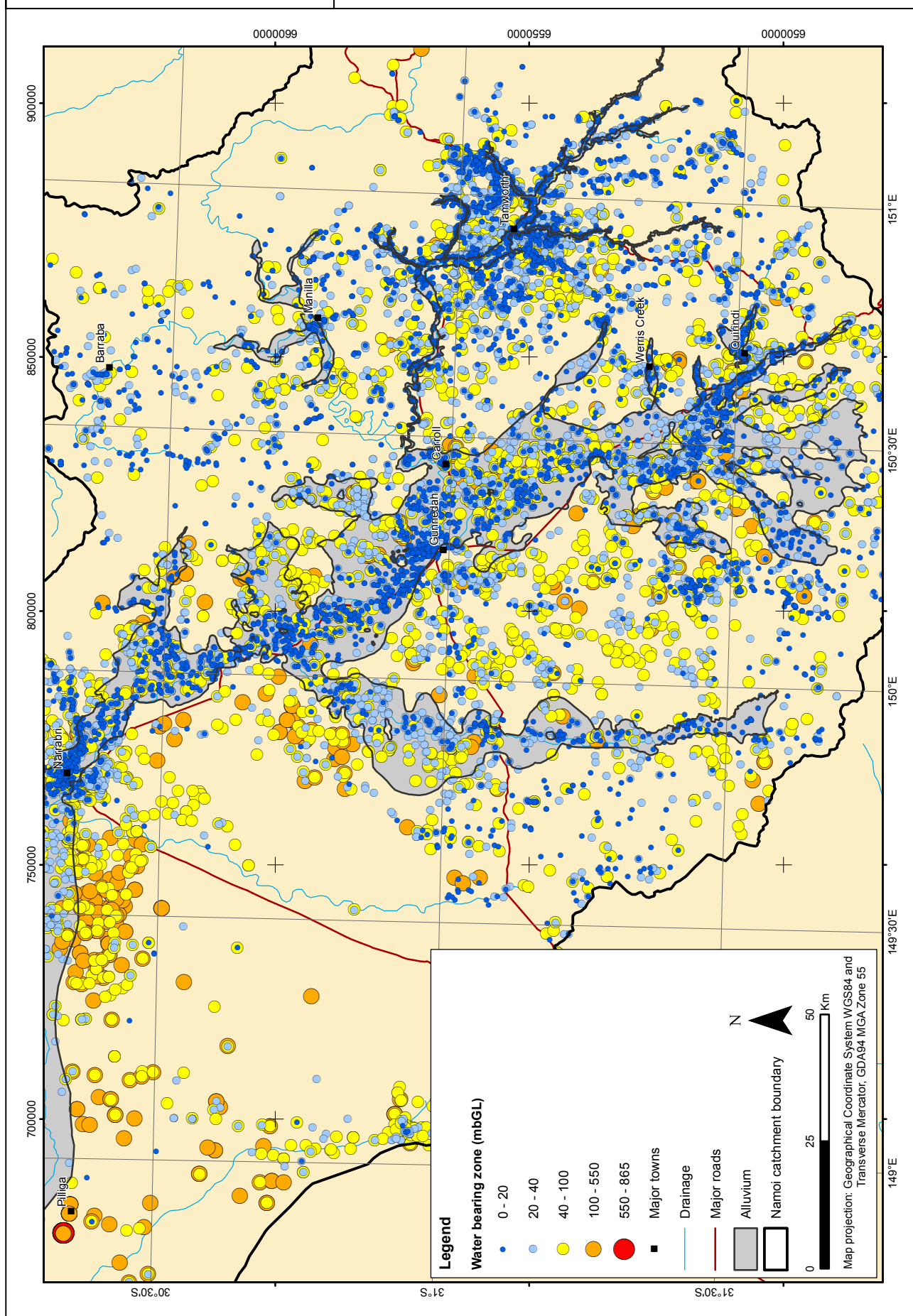
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Figure 7.6 Depth to water bearing zones from the Pinneena database



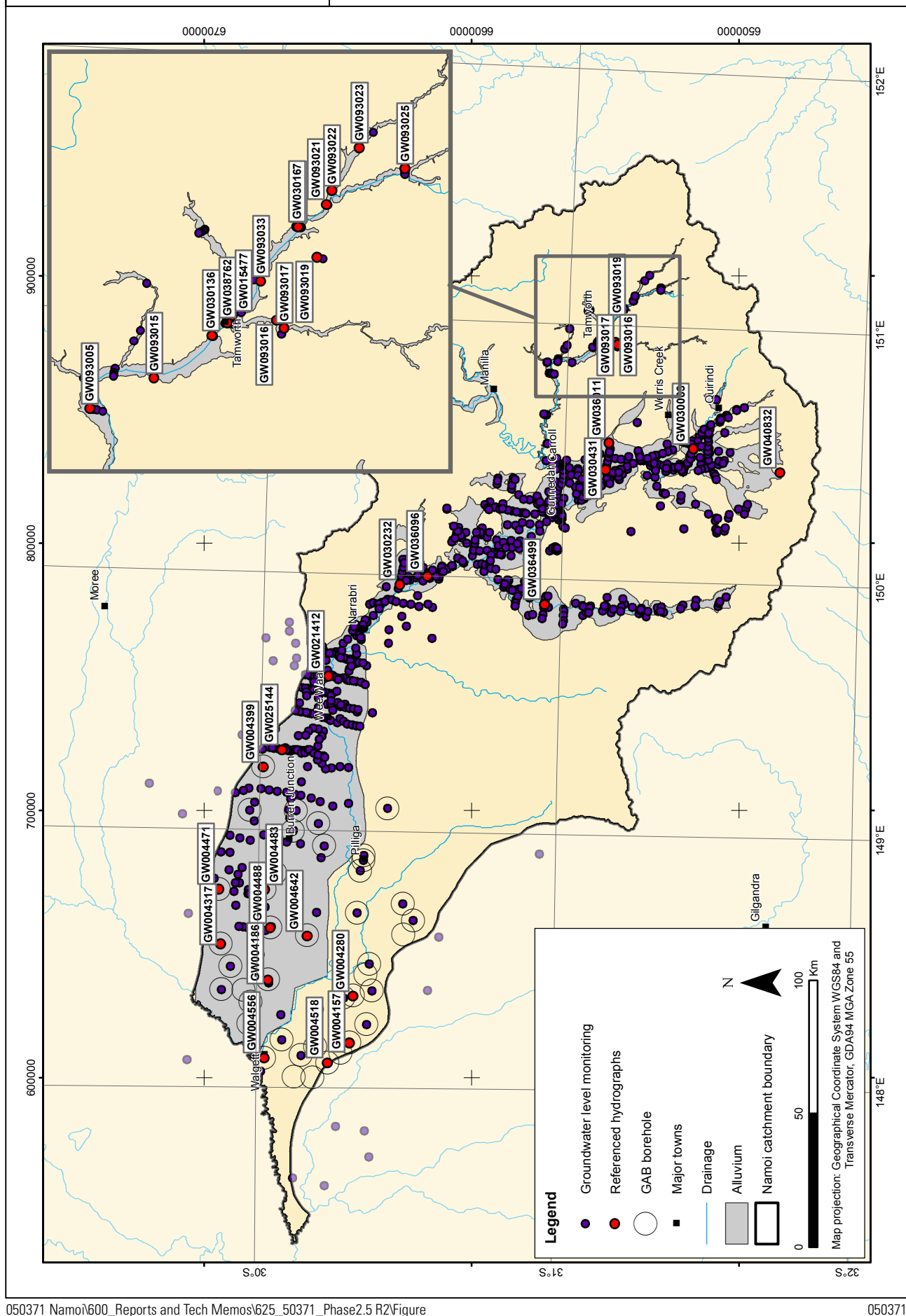
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Figure 7.7 Depth to water bearing zones from the Pinneena database - upper catchment



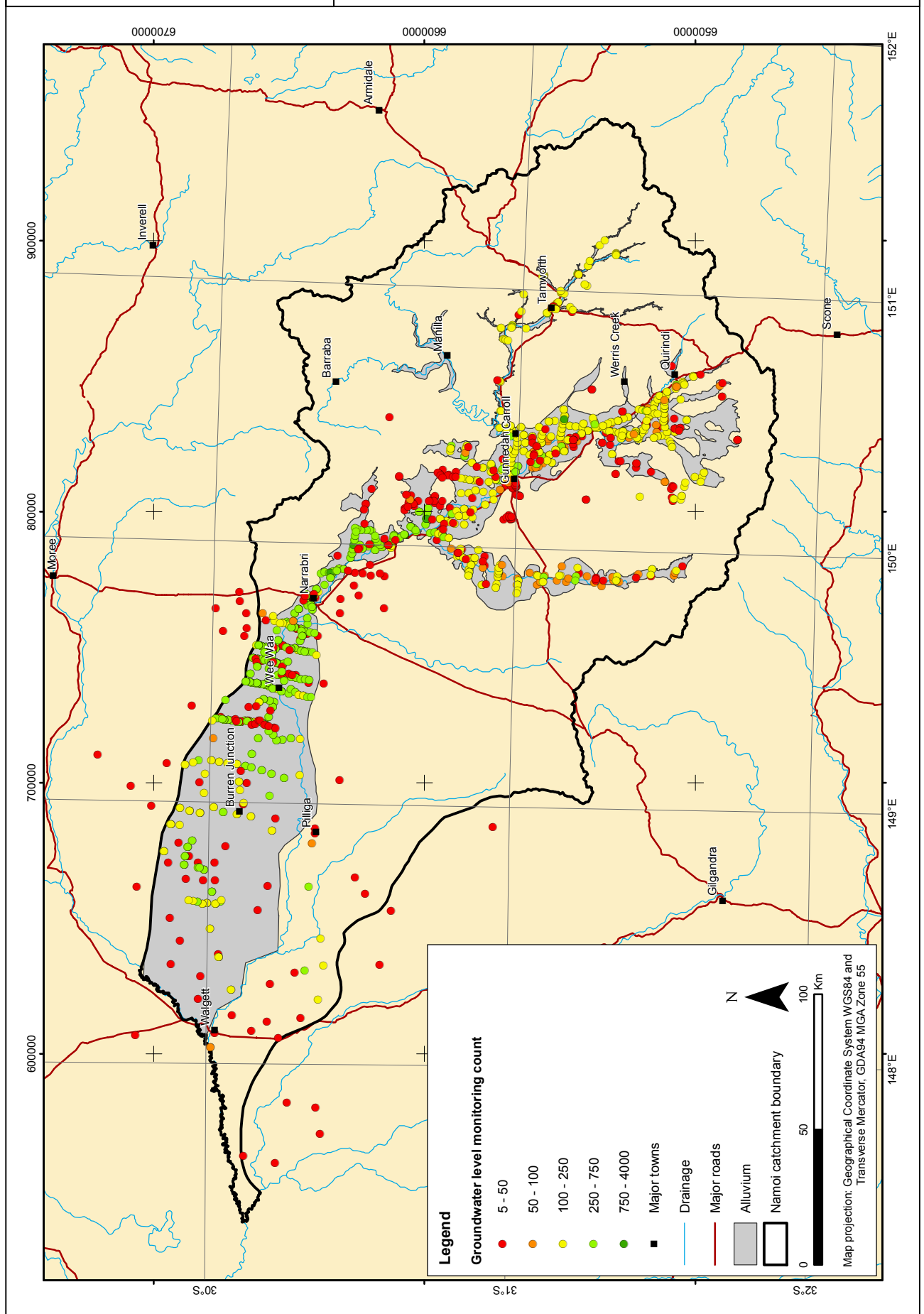
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Figure 7.8 Locations of time variant monitoring bores



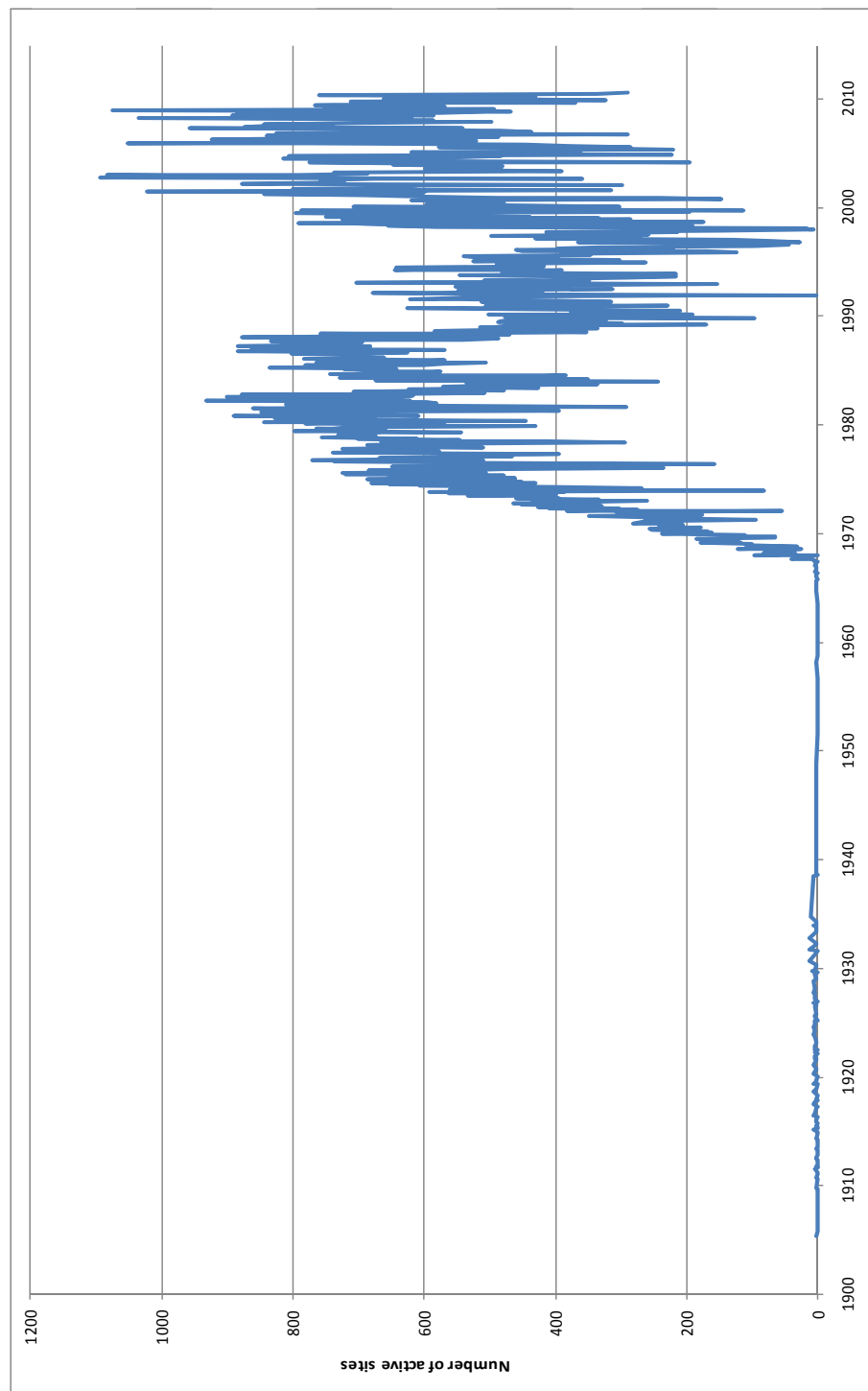
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Figure 7.9 Number of readings for each time variant groundwater monitoring site



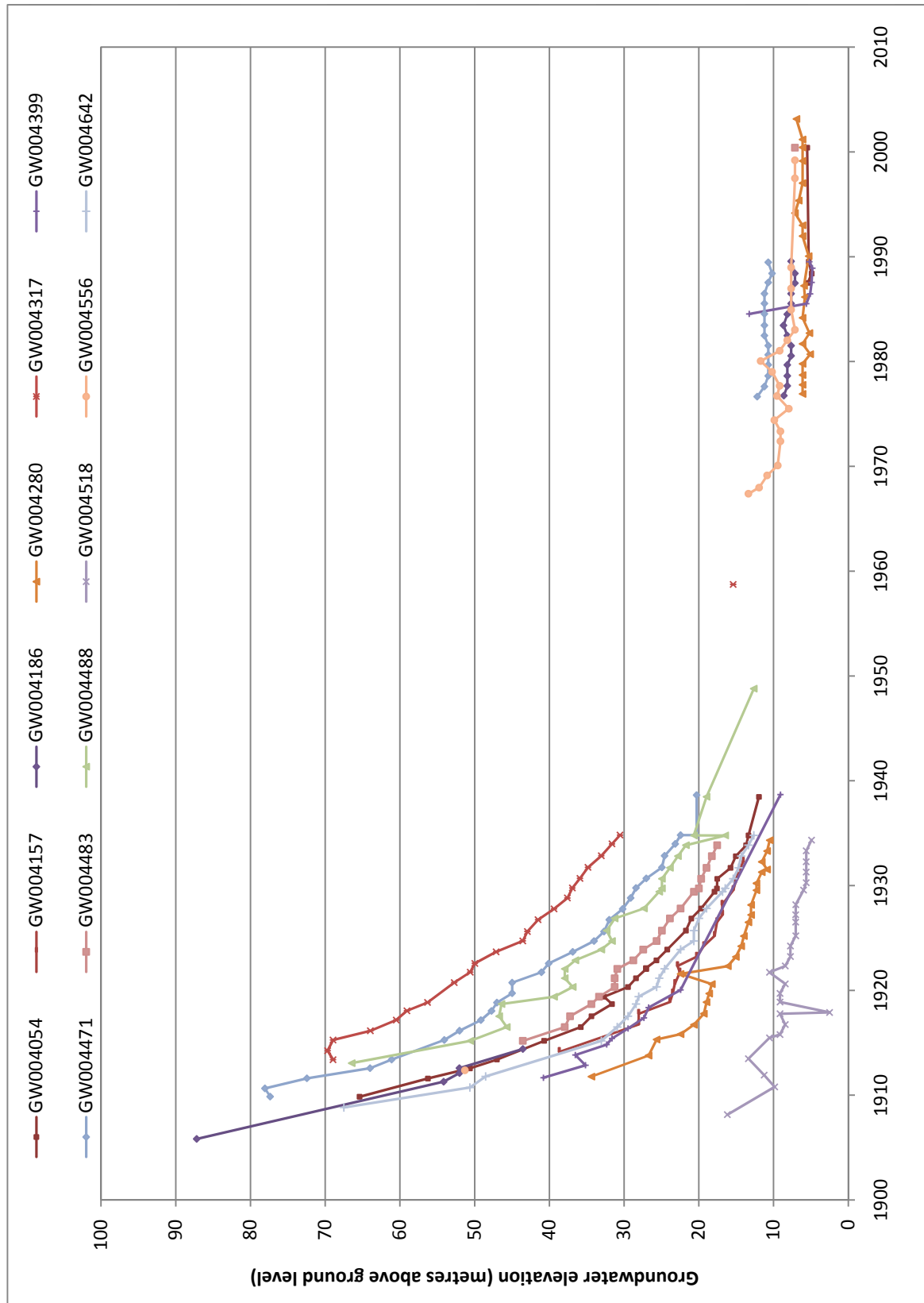
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Figure 7.10 Active groundwater monitoring sites in each month



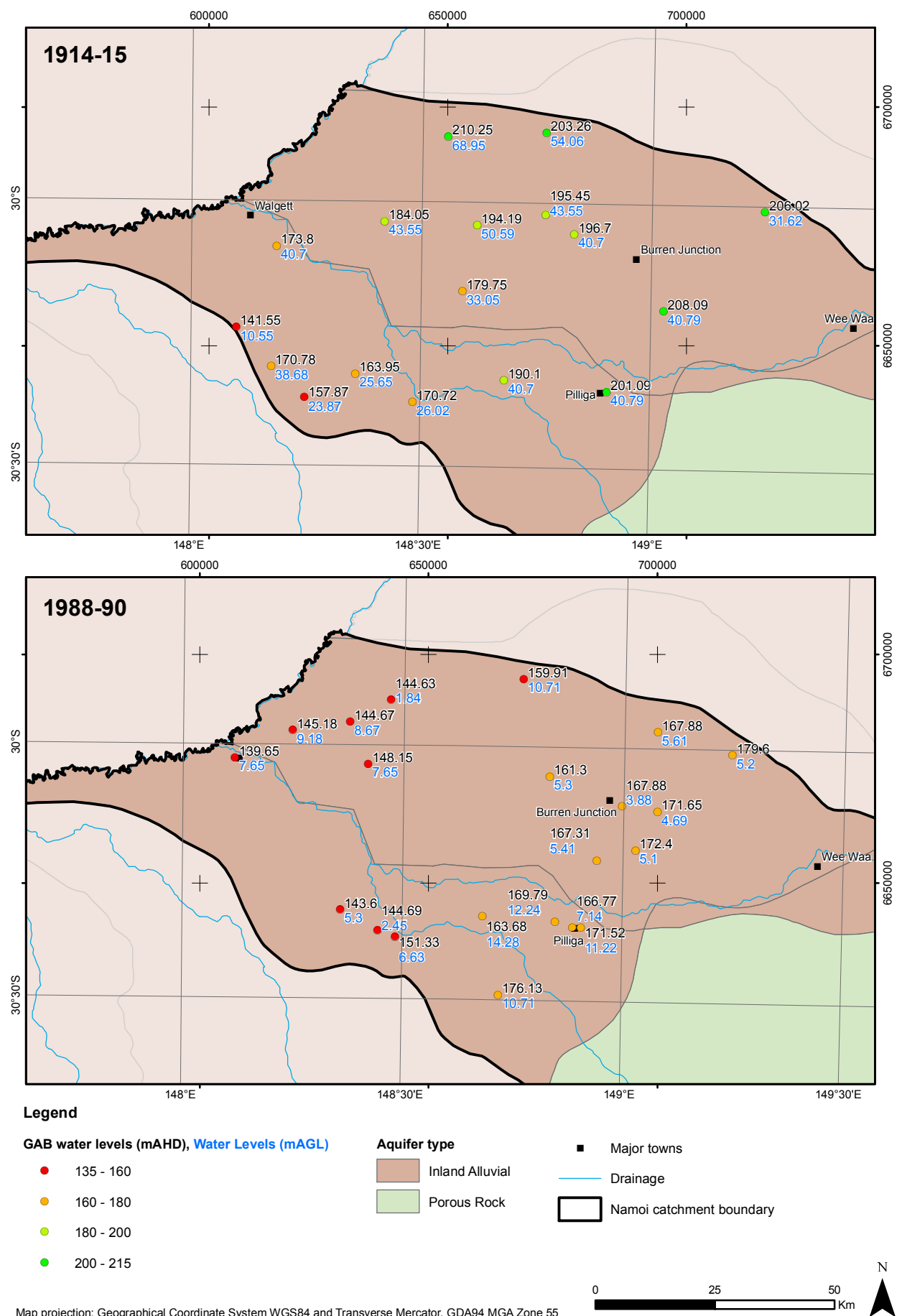
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Figure 7.11 Artesian groundwater heads in selected Great Artesian Basin bores

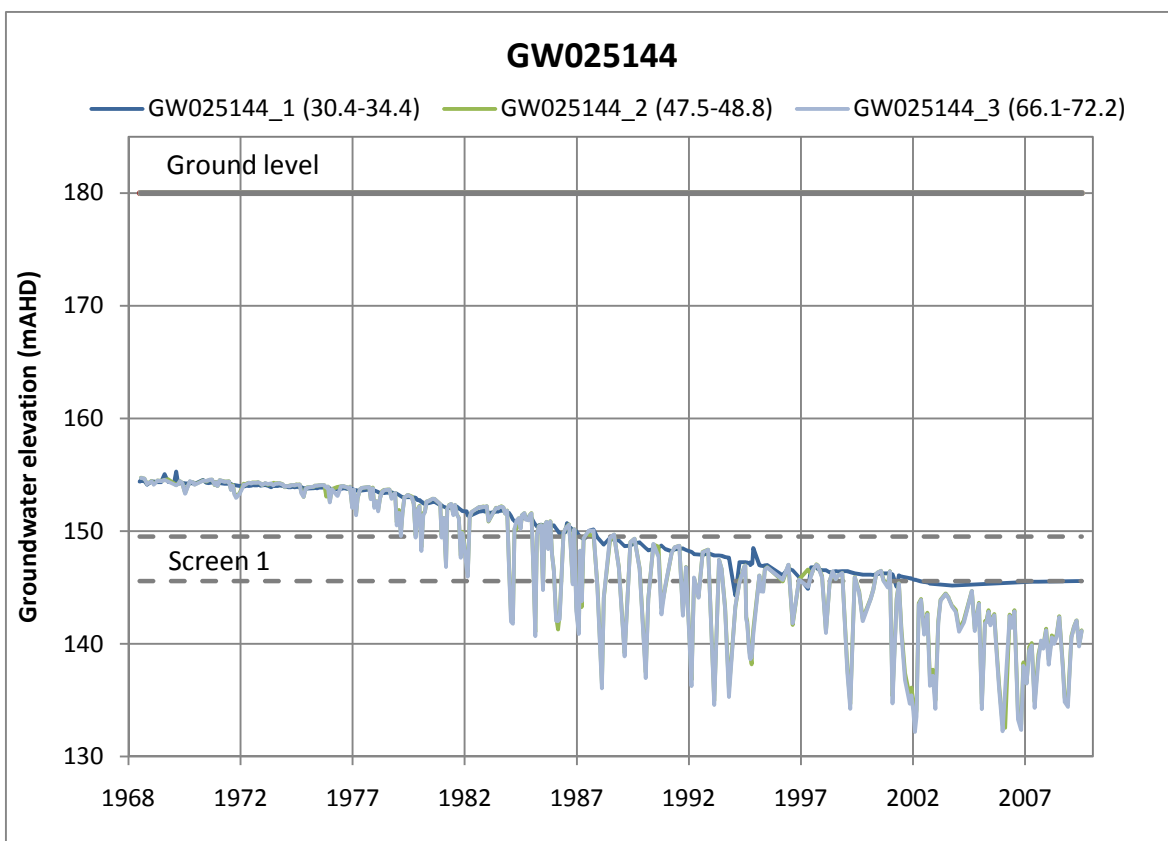
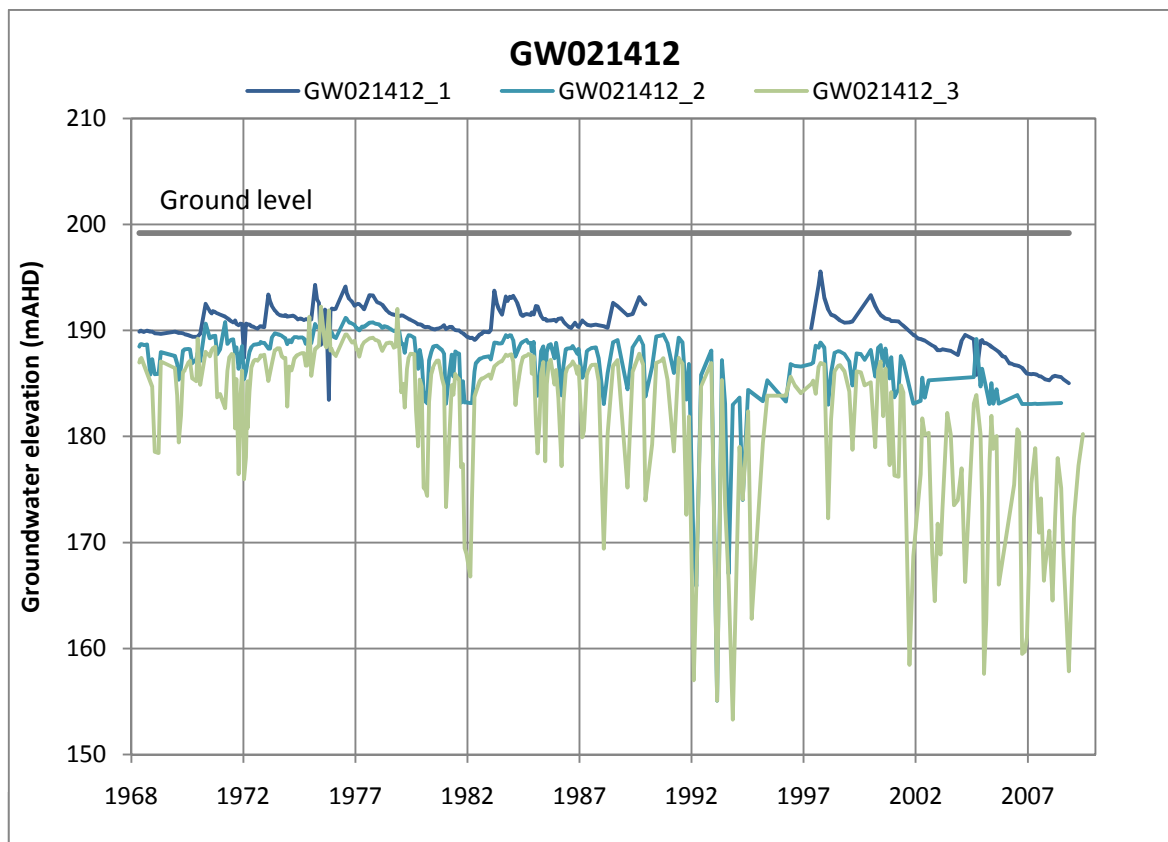


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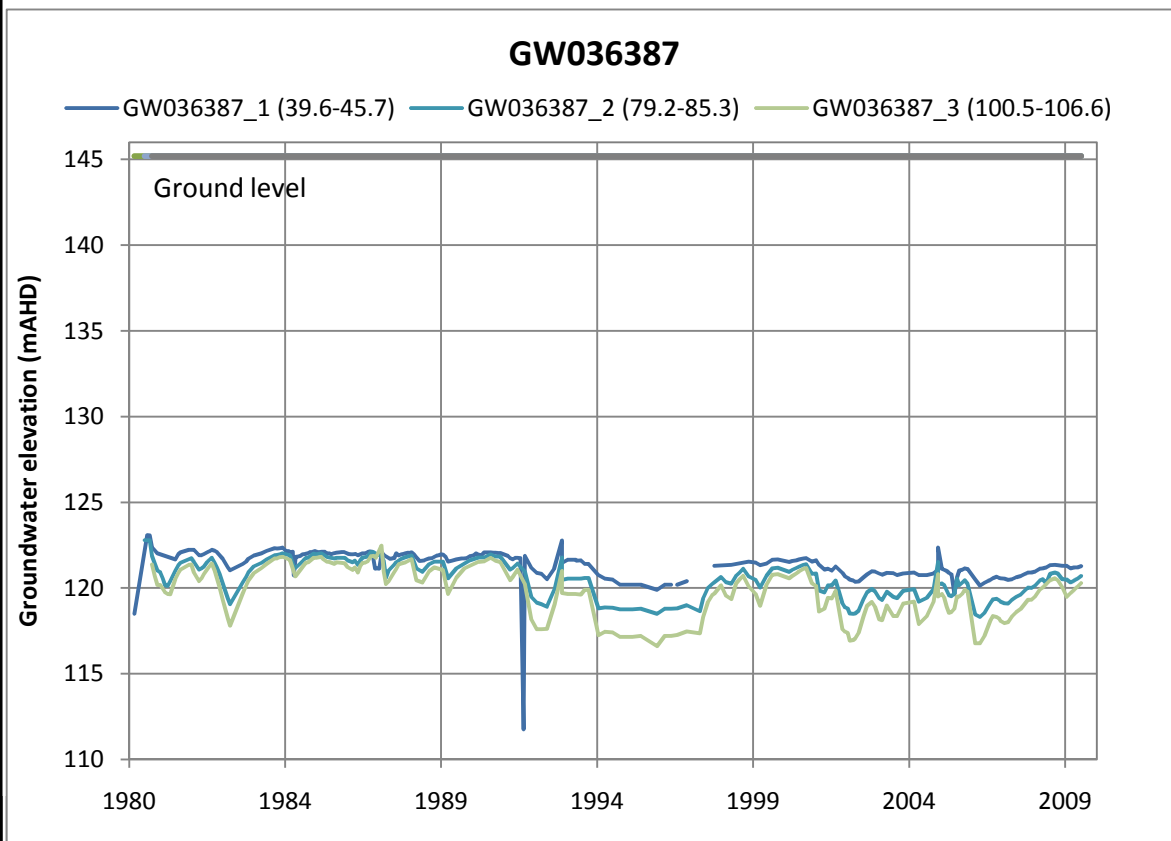
Figure 7.12 Great Artesian Basin water levels in 1914-15 and 1988-90



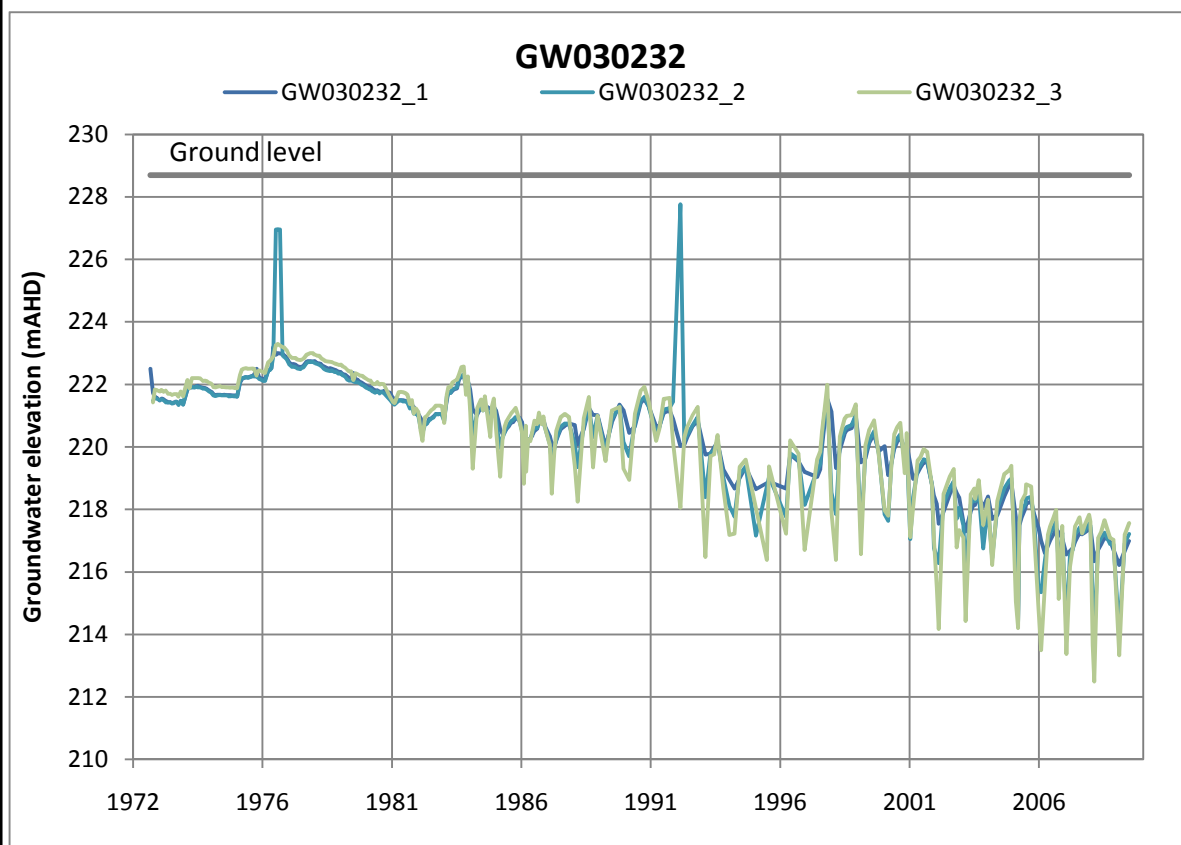
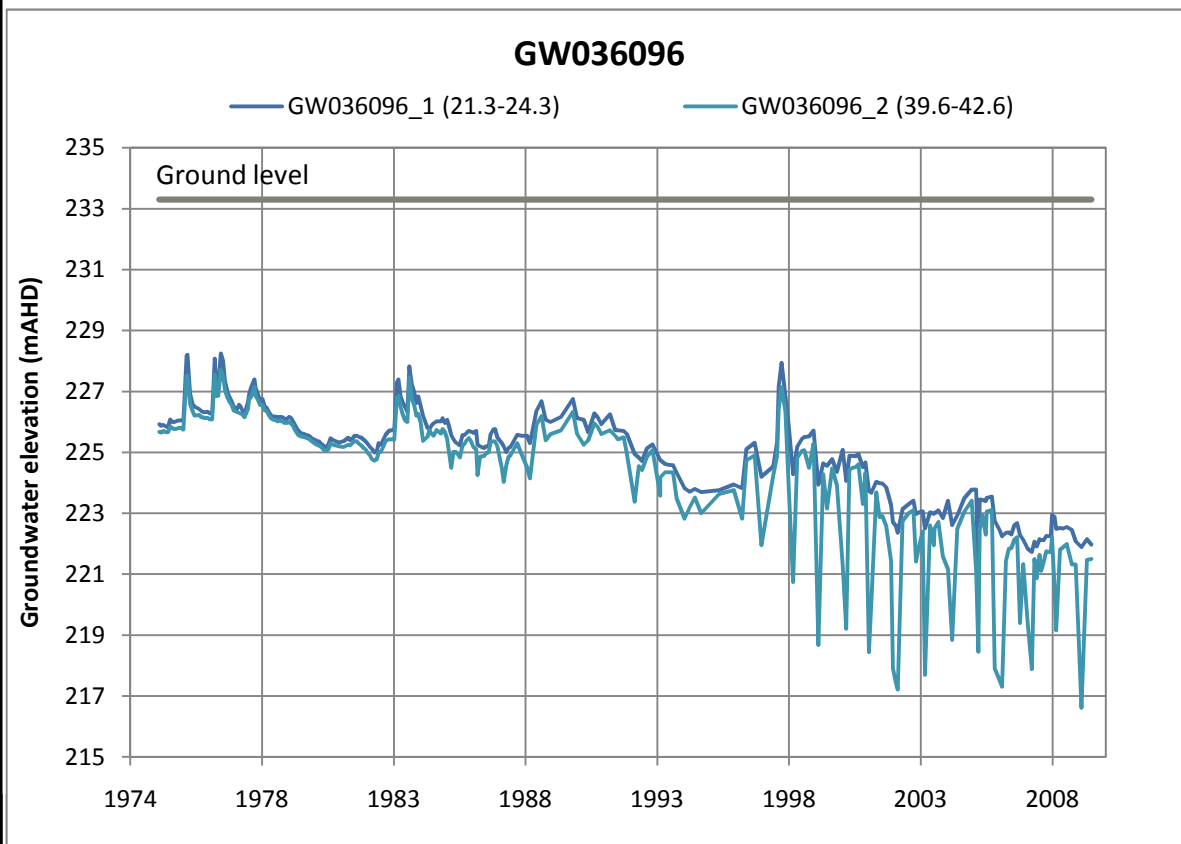
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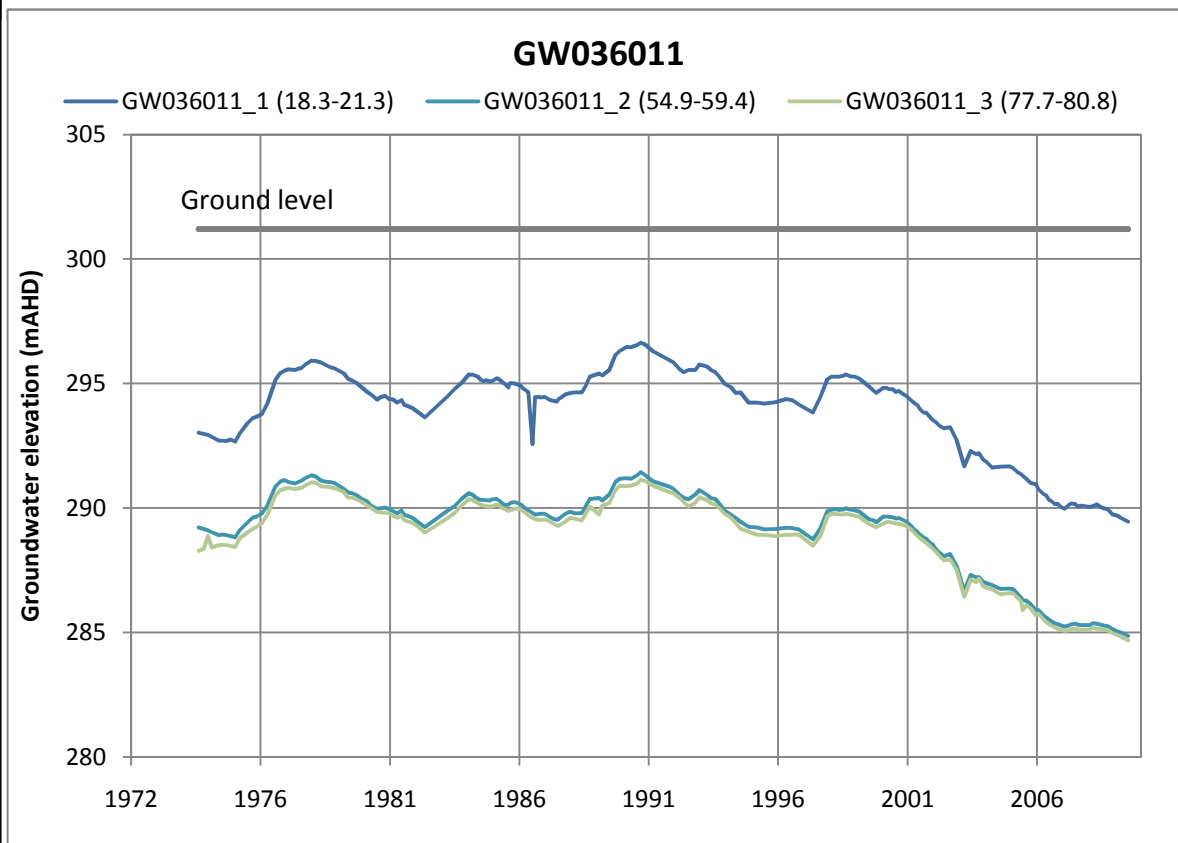
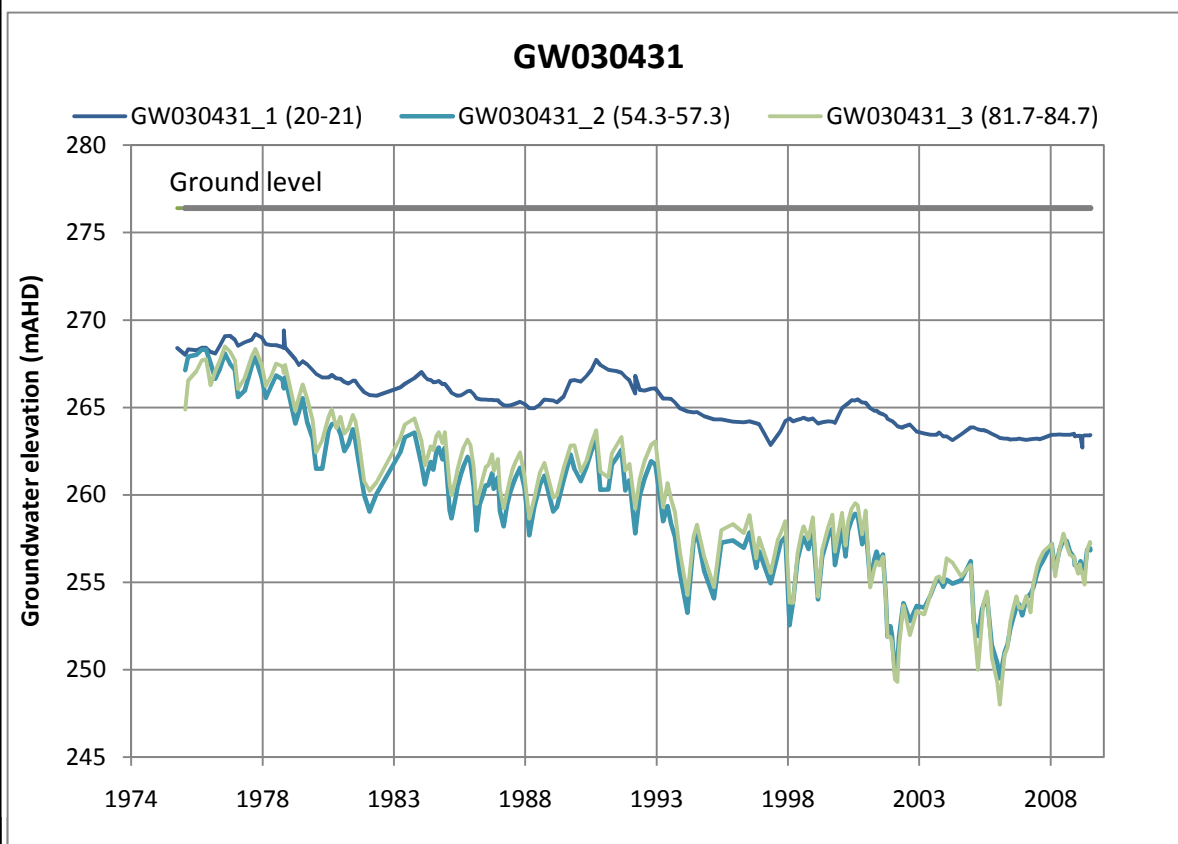
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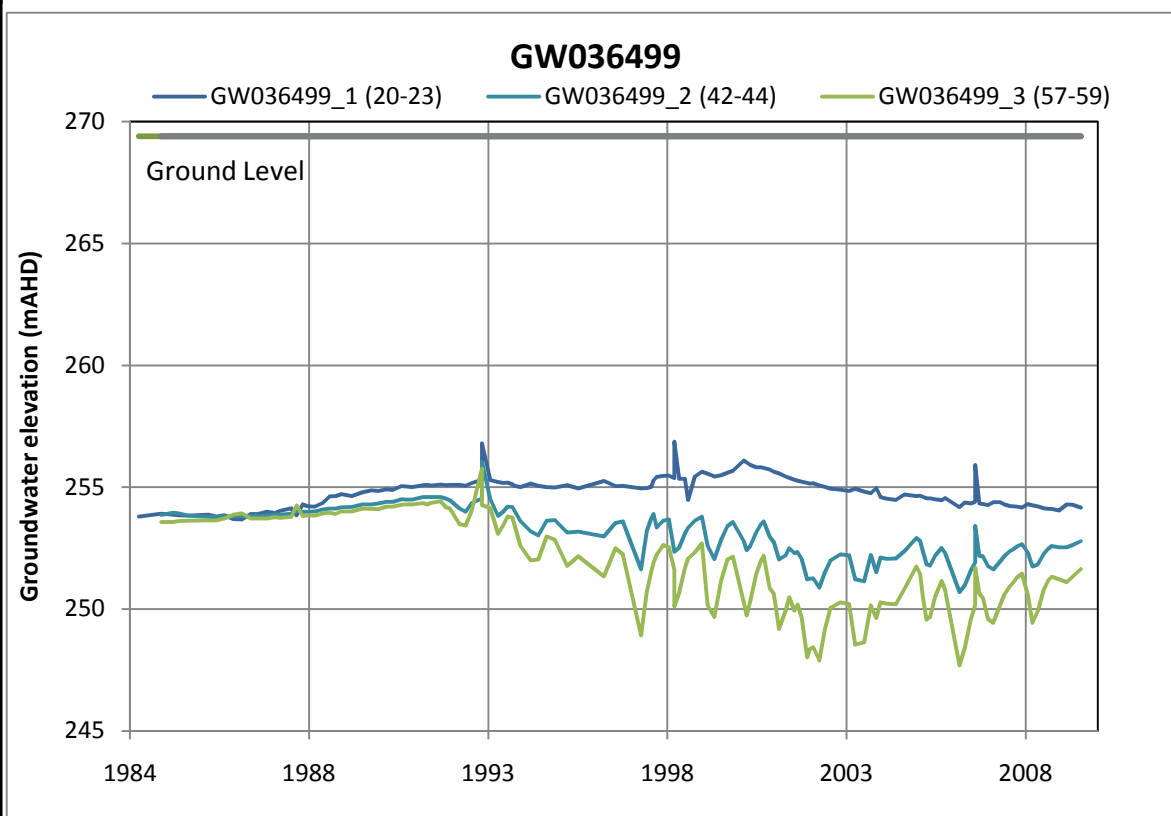
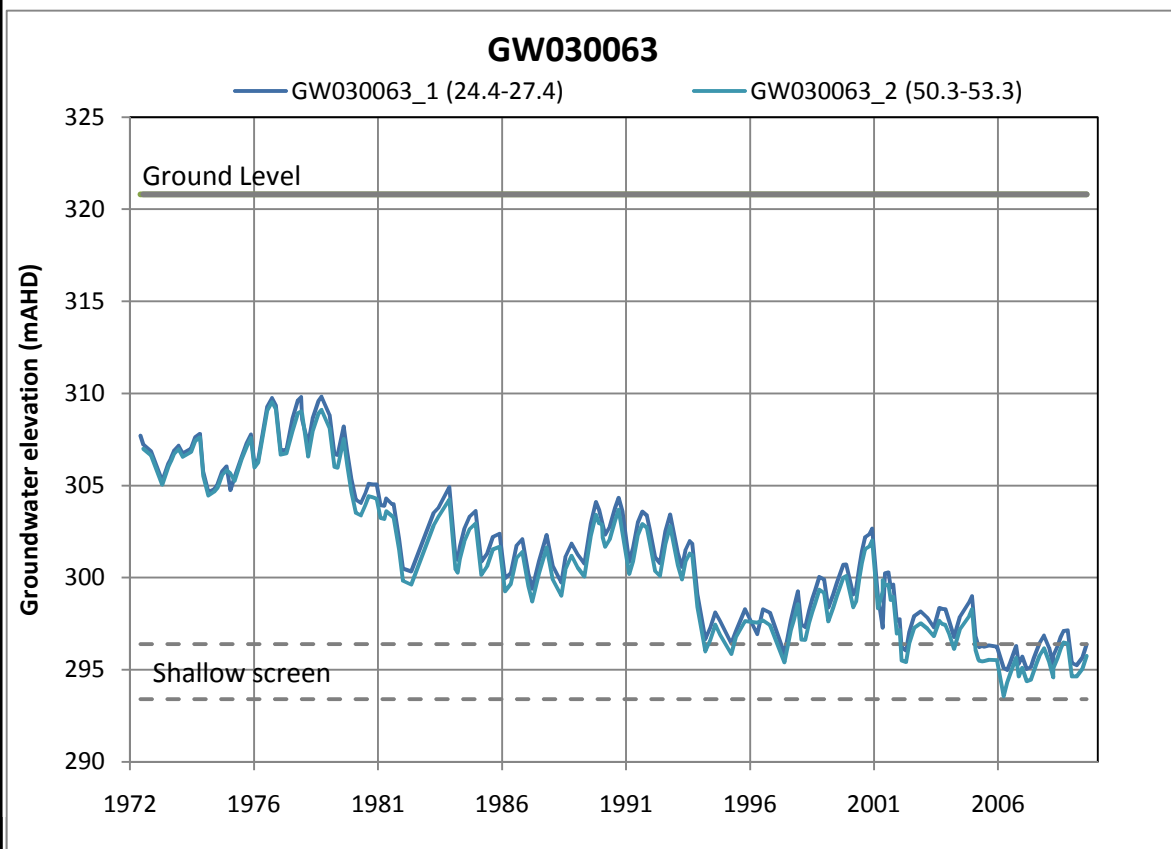
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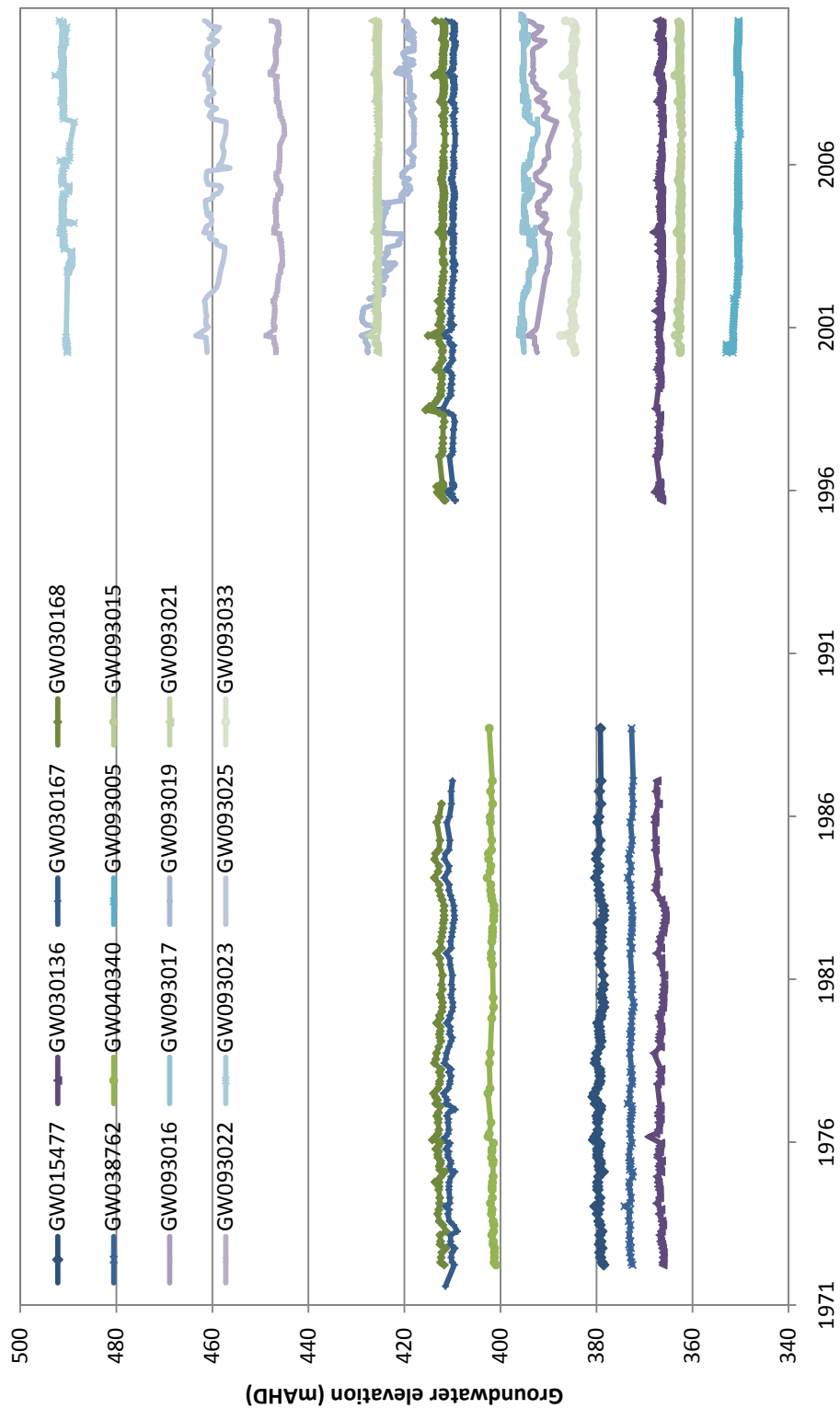


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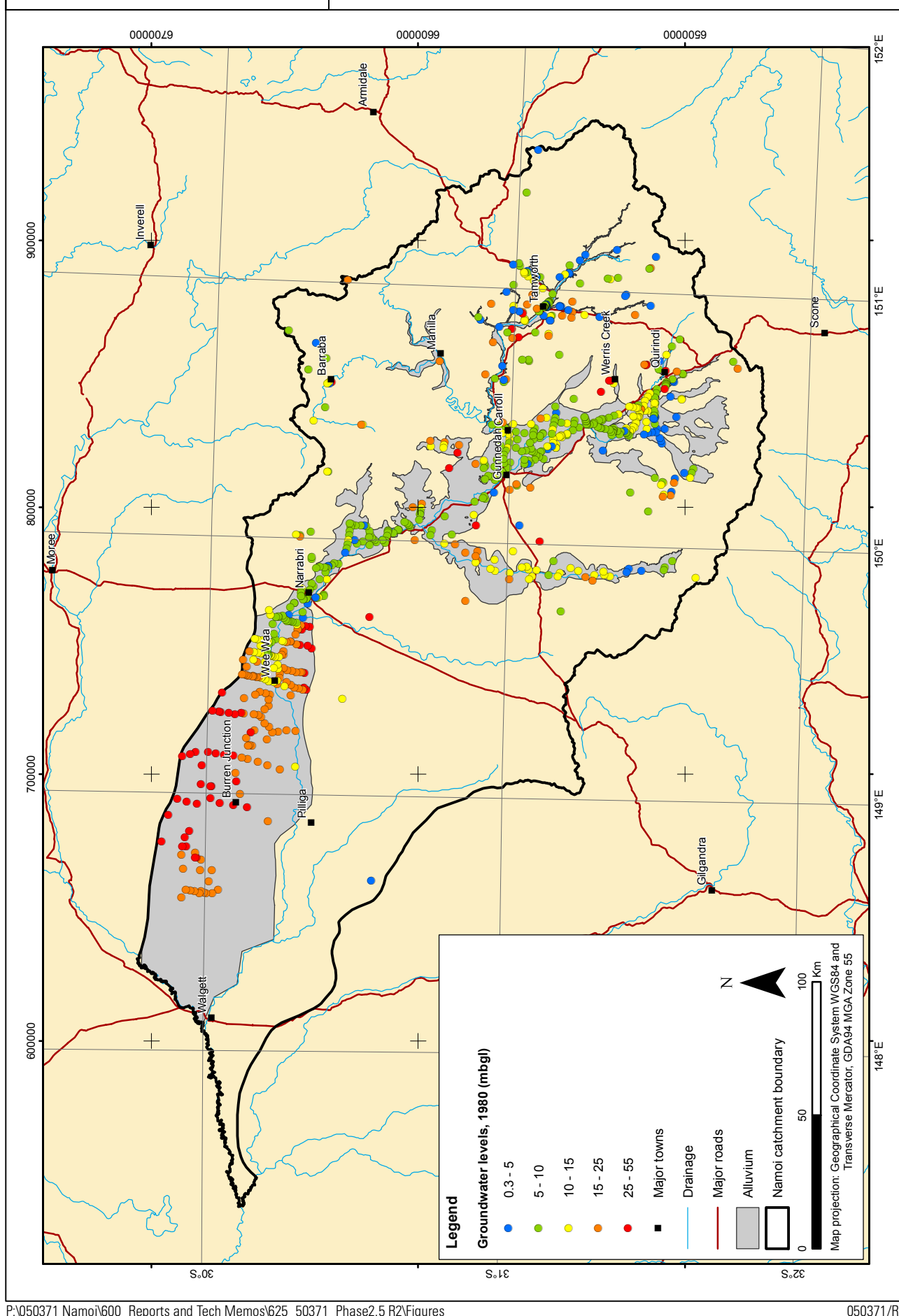
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Figure 7.18 Example hydrographs - Peel valley



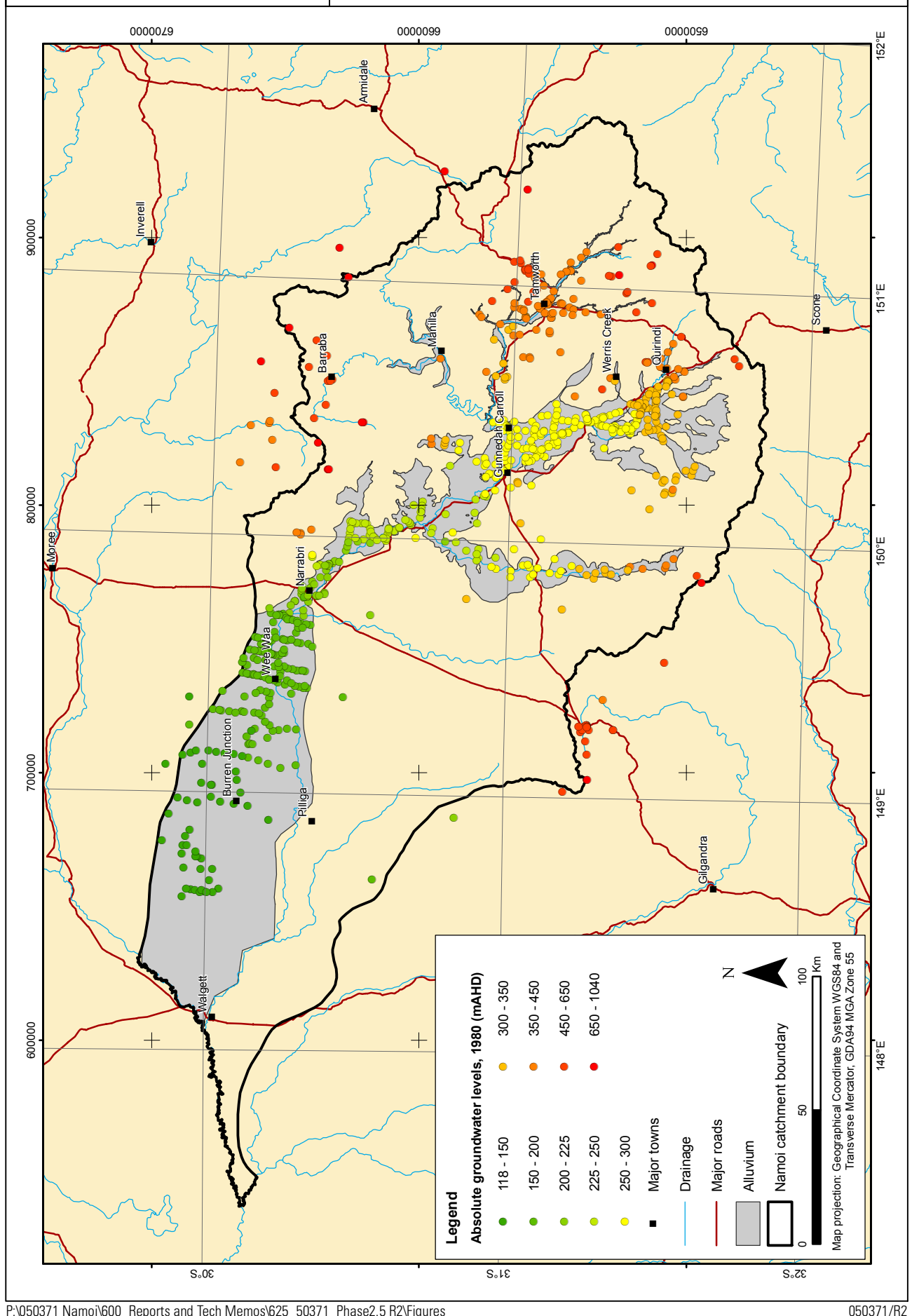
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Figure 7.19 Depth to shallow groundwater in 1980



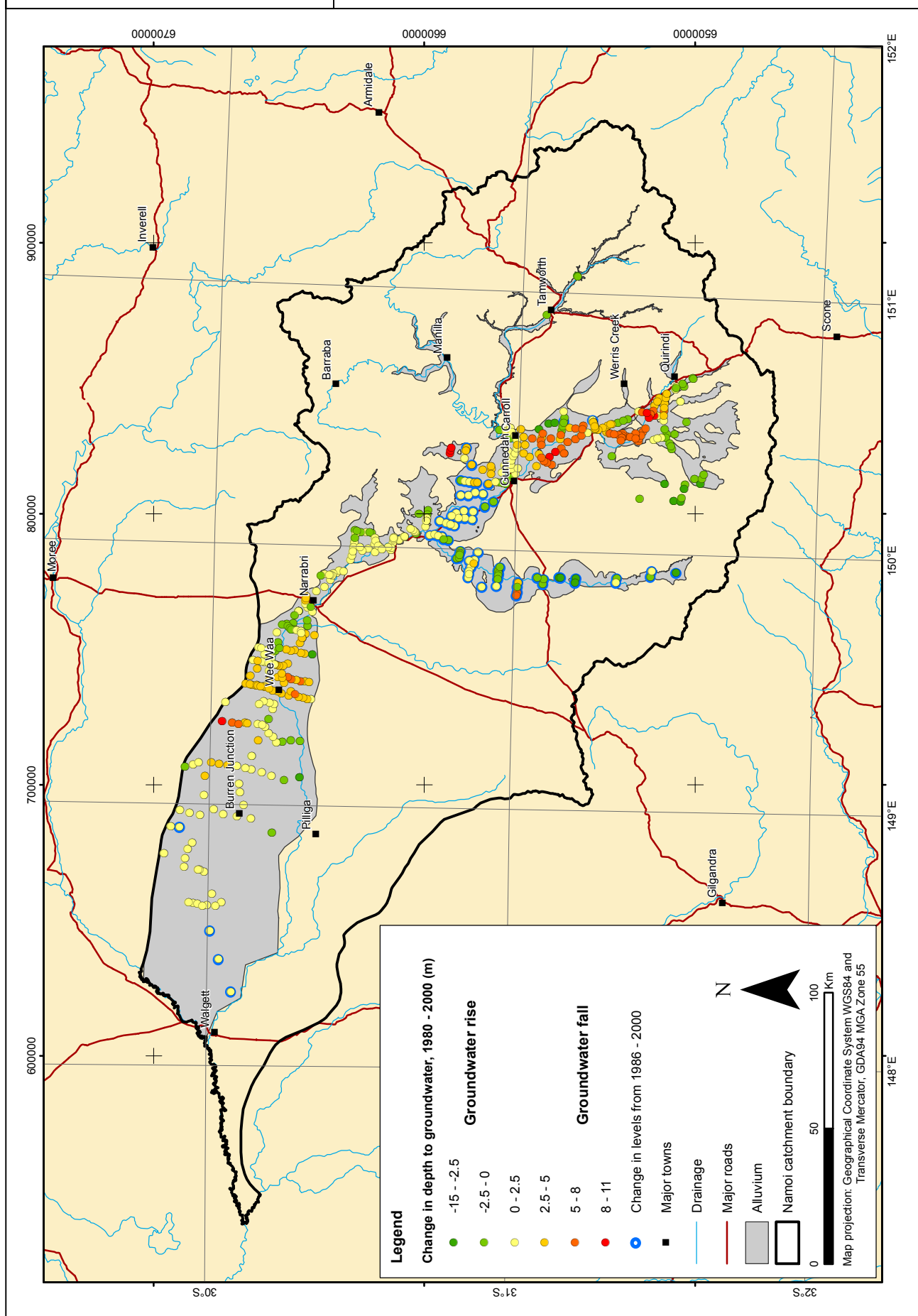
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Figure 7.20 Absolute groundwater levels in 1980



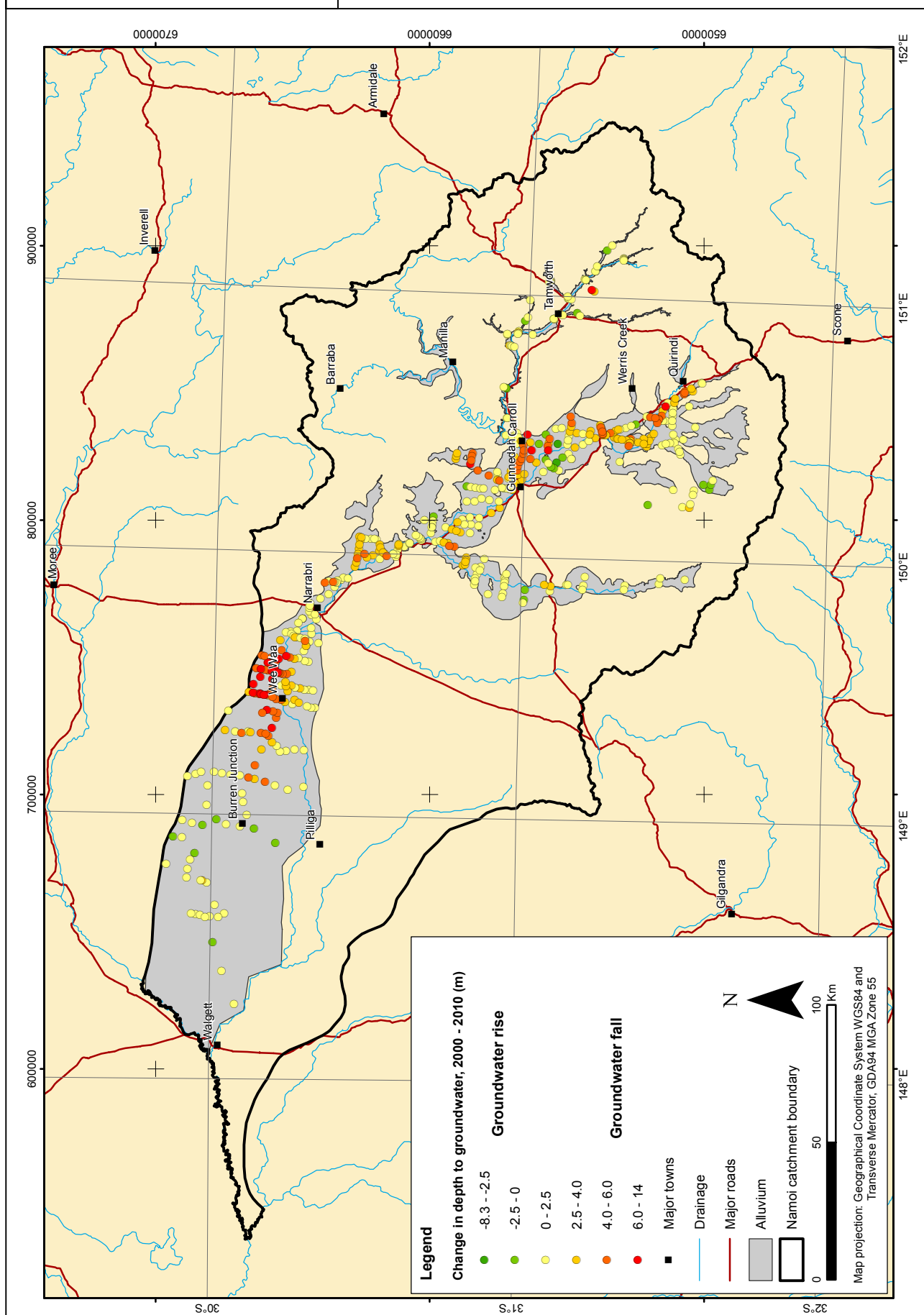
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Figure 7.21 Change in depth to shallow groundwater from 1980 to 2000



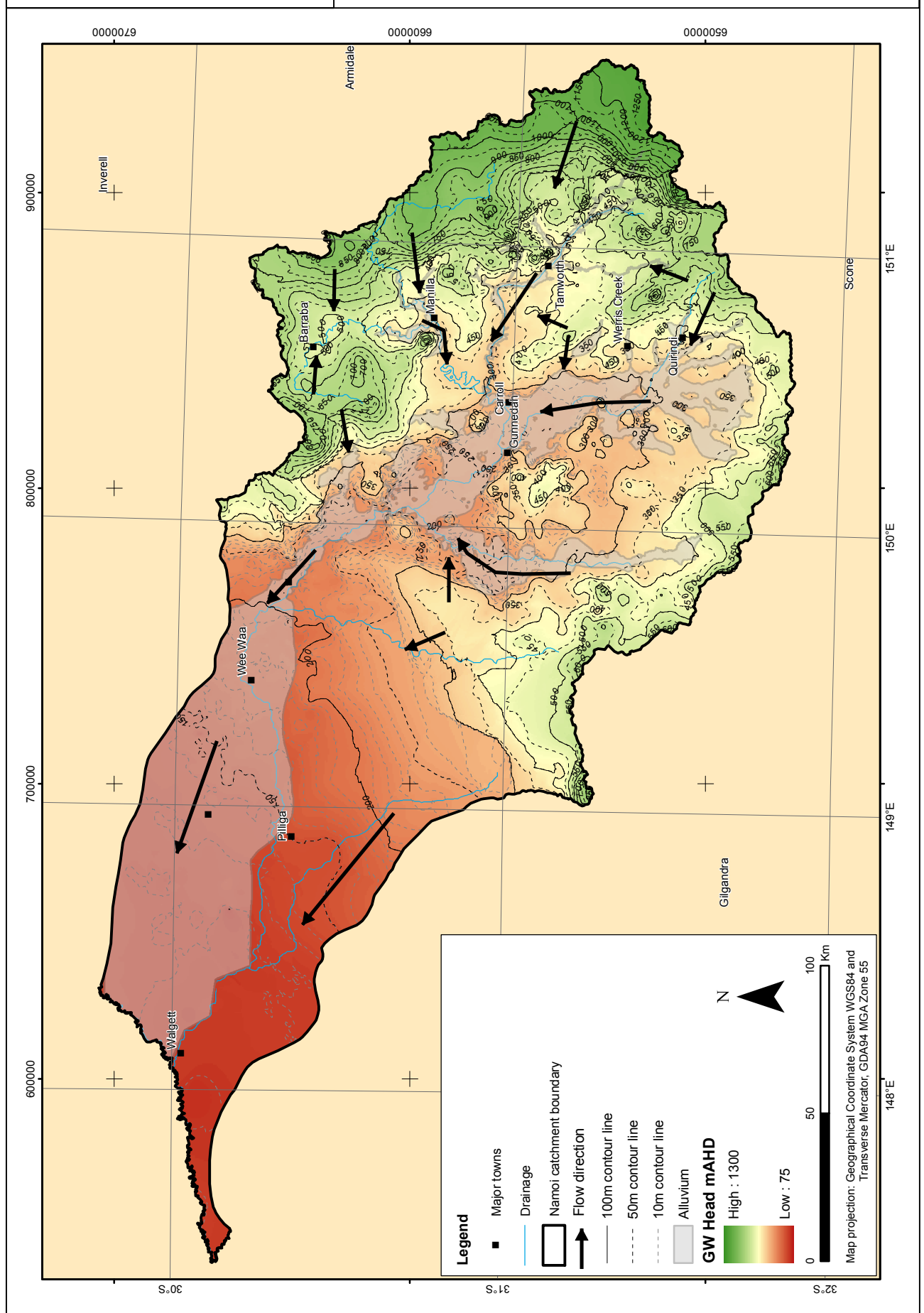
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Figure 7.22 Change in depth to shallow groundwater from 2000 to 2010



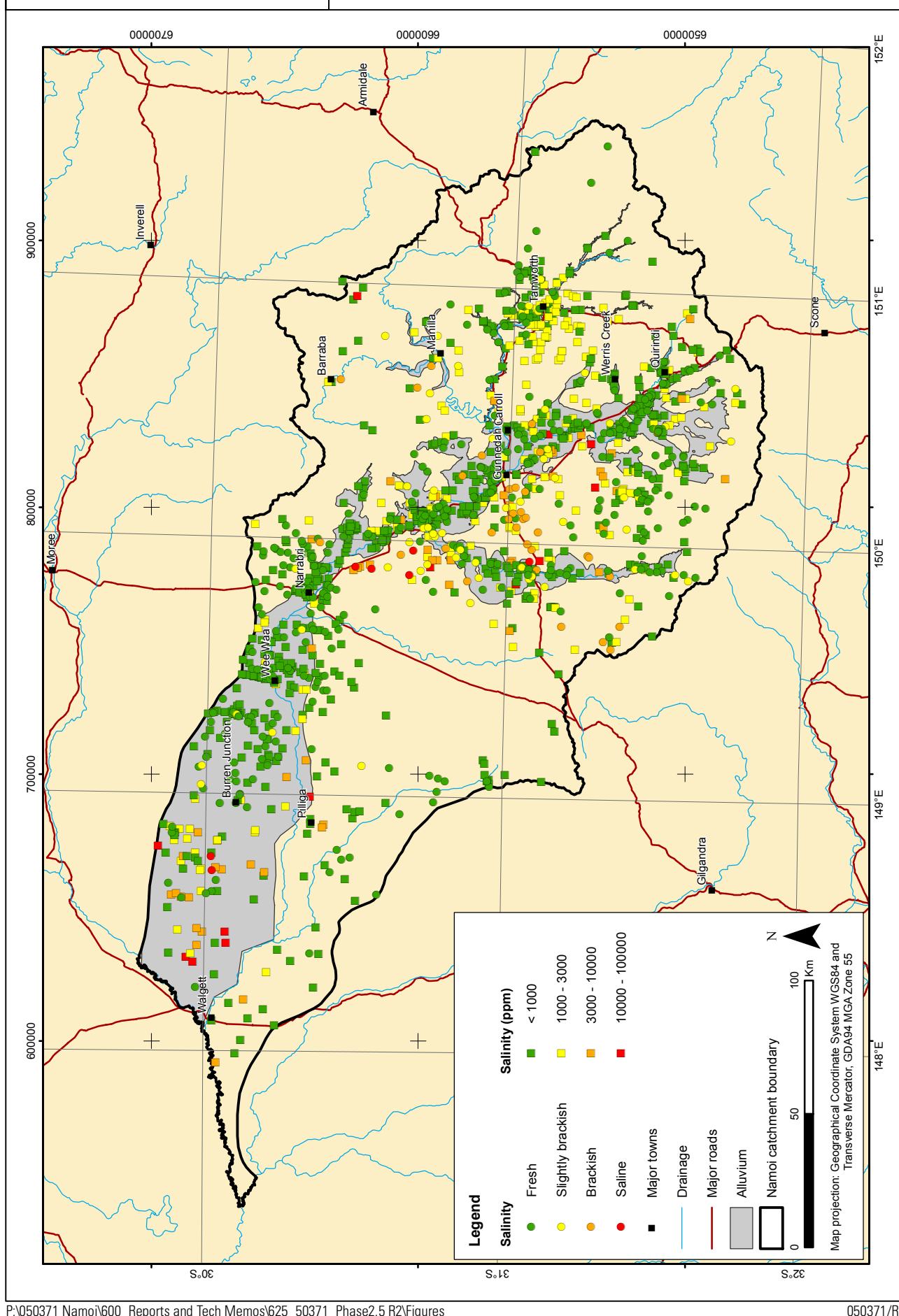
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Figure 7.23 Catchment wide water level contour map



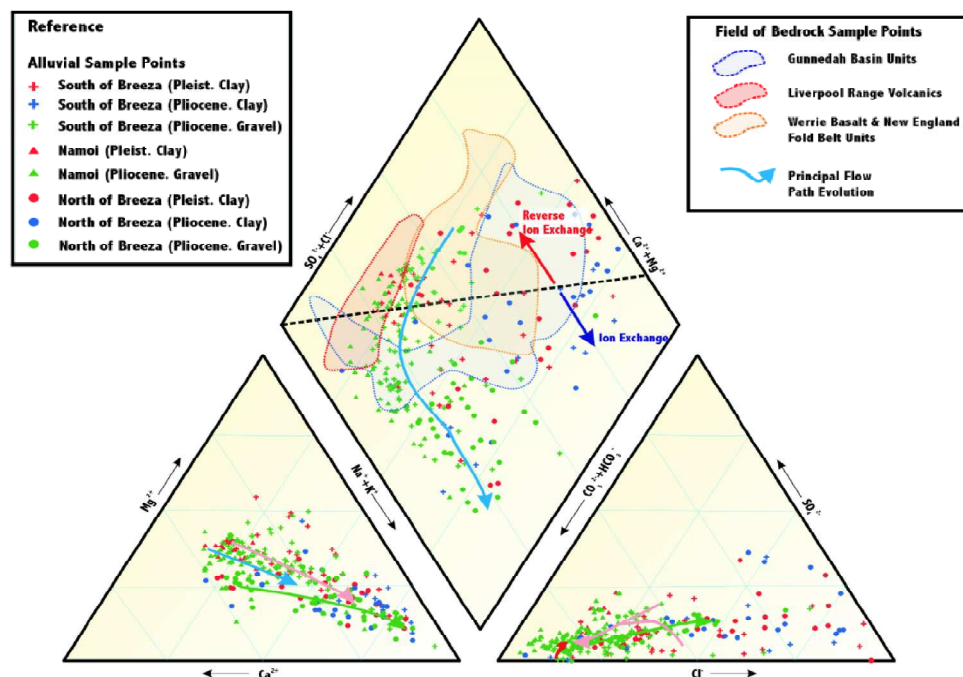
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Figure 7.24 Salinity records from the Pinneena database

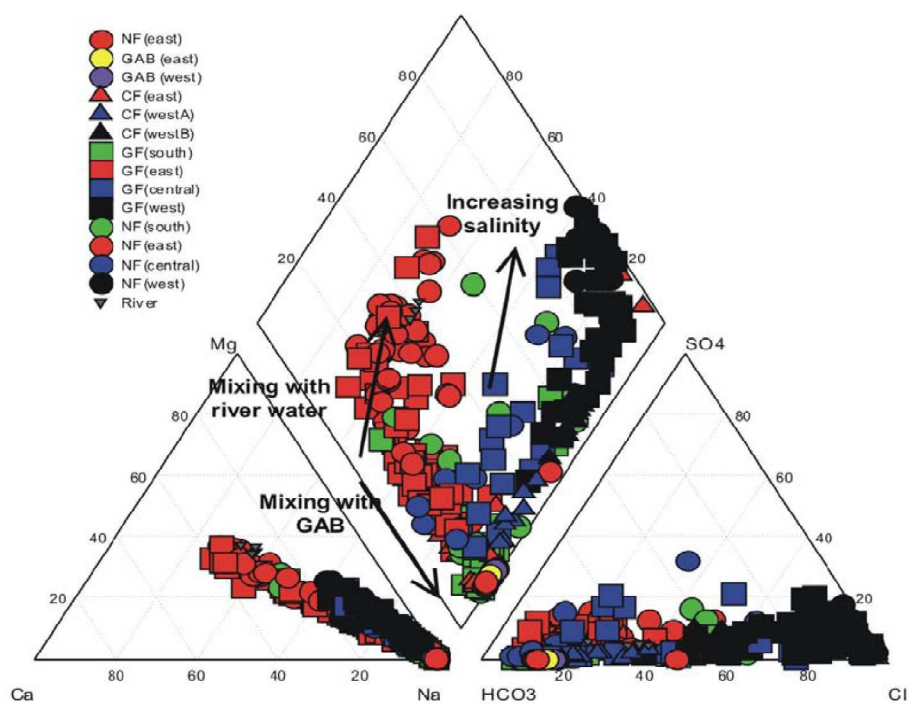


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Mooki (Upper Namoi alluvium) and bedrock water chemistry (Lavitt, 1999)



Lower Namoi alluvium and GAB water chemistry (McLean, 2003)



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