Australian Government

BIOREGIONAL ASSESSMENTS

PROVIDING SCIENTIFIC WATER RESOURCE INFORMATION ASSOCIATED WITH COAL SEAM GAS AND LARGE COAL MINES

Observations analysis, statistical analysis and interpolation for the Namoi subregion

Product 2.1-2.2 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment

2018

A scientific collaboration between the Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia

The Bioregional Assessment Programme

The Bioregional Assessment Programme is a transparent and accessible programme of baseline assessments that increase the available science for decision making associated with coal seam gas and large coal mines. A bioregional assessment is a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential impacts of coal seam gas and large coal mining development on water resources. This Programme draws on the best available scientific information and knowledge from many sources, including government, industry and regional communities, to produce bioregional assessments that are independent, scientifically robust, and relevant and meaningful at a regional scale.

The Programme is funded by the Australian Government Department of the Environment and Energy. The Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia are collaborating to undertake bioregional assessments. For more information, visit http://www.bioregionalassessments.gov.au.

Department of the Environment and Energy

The Australian Government Department of the Environment and Energy is strengthening the regulation of coal seam gas and large coal mining development by ensuring that future decisions are informed by substantially improved science and independent expert advice about the potential water-related impacts of those developments. For more information, visit https://www.environment.gov.au/water/coal-and-coal-seam-gas/office-of-water-science.

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ISBN-PDF 978-1-925315-61-5

Citation

Aryal SK, Northey J, Slatter E, Ivkovic K, Crosbie R, Janardhanan S, Peña-Arancibia J and Bell J (2018) Observations analysis, statistical analysis and interpolation for the Namoi subregion. Product 2.1-2.2 for the Namoi subregion from the Northern Inland Catchments Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia.
http://data.bioregionalassessments.gov.au/product/NIC/NAM/2.1-2.2.

Authorship is listed in relative order of contribution.

Cover photograph

Gulligal Lagoon, which is located about halfway between Gunnedah and Boggabri on the western side of the Namoi River, NSW, 2005

Credit: Neal Foster

Australian Government

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Bureau of Meteorology

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CSIRO

v20180627

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Acknowledgements

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- Technical Assurance Reference Group: Chaired by Peter Baker (Principal Science Advisor, Department of the Environment and Energy), this group comprises officials from the NSW, Queensland, South Australian and Victorian governments.

Currency of scientific results

The modelling results contained in this product were completed in November 2016 using the best available data, models and approaches available at that time. The product content was completed in February 2018.

All products in the model-data analysis, impact and risk analysis, and outcome synthesis (see Figure 1) were published as a suite when completed.

Introduction

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC) was established to provide advice to the federal Minister for the Environment on potential water-related impacts of coal seam gas (CSG) and large coal mining developments (IESC, 2015).

Bioregional assessments (BAs) are one of the key mechanisms to assist the IESC in developing this advice so that it is based on best available science and independent expert knowledge. Importantly, technical products from BAs are also expected to be made available to the public, providing the opportunity for all other interested parties, including government regulators, industry, community and the general public, to draw from a single set of accessible information. A BA is a scientific analysis, providing a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential impacts of CSG and coal mining development on water resources.

The IESC has been involved in the development of *Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (the BA methodology; Barrett et al., 2013) and has endorsed it. The BA methodology specifies how BAs should be undertaken. Broadly, a BA comprises five components of activity, as illustrated in Figure 1. Each BA is different, due in part to regional differences, but also in response to the availability of data, information and fit-for-purpose models. Where differences occur, these are recorded, judgments exercised on what can be achieved, and an explicit record is made of the confidence in the scientific advice produced from the BA.

The Bioregional Assessment Programme

The Bioregional Assessment Programme is a collaboration between the Department of the Environment and Energy, the Bureau of Meteorology, CSIRO and Geoscience Australia. Other technical expertise, such as from state governments or universities, is also drawn on as required. For example, natural resource management groups and catchment management authorities identify assets that the community values by providing the list of water-dependent assets, a key input.

The Technical Programme, part of the Bioregional Assessment Programme, has undertaken BAs for the following bioregions and subregions (see http://www.bioregionalassessments.gov.au/assessments for a map and further information):

- the Galilee, Cooper, Pedirka and Arckaringa subregions, within the Lake Eyre Basin bioregion
- the Maranoa-Balonne-Condamine, Gwydir, Namoi and Central West subregions, within the Northern Inland Catchments bioregion
- the Clarence-Moreton bioregion
- the Hunter and Gloucester subregions, within the Northern Sydney Basin bioregion

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

Technical products (described in a later section) will progressively be delivered throughout the Programme.

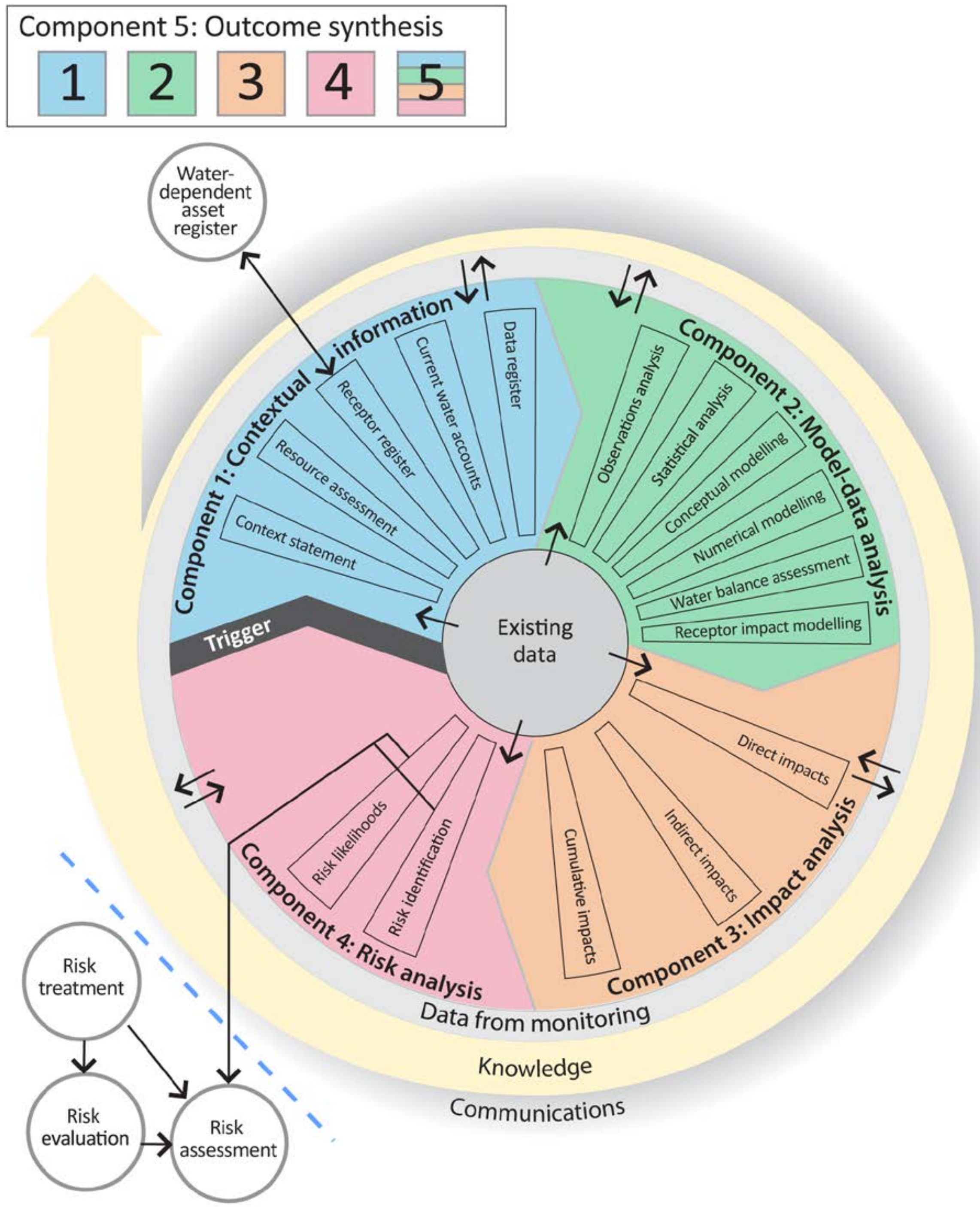

Figure 1 Schematic diagram of the bioregional assessment methodology

The methodology comprises five components, each delivering information into the bioregional assessment and building on prior components, thereby contributing to the accumulation of scientific knowledge. The small grey circles indicate activities external to the bioregional assessment. Risk identification and risk likelihoods are conducted within a bioregional assessment (as part of Component 4) and may contribute activities undertaken externally, such as risk evaluation, risk assessment and risk treatment.
Source: Figure 1 in Barrett et al. (2013), © Commonwealth of Australia

Methodologies

The overall scientific and intellectual basis of the BAs is provided in the BA methodology (Barrett et al., 2013). Additional guidance is required, however, about how to apply the BA methodology to a range of subregions and bioregions. To this end, the teams undertaking the BAs have developed and documented detailed scientific submethodologies (Table 1), in the first instance, to support the consistency of their work across the BAs and, secondly, to open the approach to scrutiny, criticism and improvement through review and publication. In some instances, methodologies applied in a particular BA may differ from what is documented in the submethodologies.

The relationship of the submethodologies to BA components and technical products is illustrated in Figure 2. While much scientific attention is given to assembling and transforming information, particularly through the development of the numerical, conceptual and receptor impact models, integration of the overall assessment is critical to achieving the aim of the BAs. To this end, each submethodology explains how it is related to other submethodologies and what inputs and outputs are required. They also define the technical products and provide guidance on the content to be included. When this full suite of submethodologies is implemented, a BA will result in a substantial body of collated and integrated information for a subregion or bioregion, including new information about the potential impacts of coal resource development on water and water-dependent assets.

Table 1 Methodologies

Each submethodology is available online at http://data.bioregionalassessments.gov.au/submethodology/XXX, where 'XXX' is replaced by the code in the first column. For example, the BA methodology is available at http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology and submethodology M02 is available at http://data.bioregionalassessments.gov.au/submethodology/M02. Submethodologies might be added in the future.

Code	Proposed title	Summary of content
bioregional-assessment-methodology	*Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources*	A high-level description of the scientific and intellectual basis for a consistent approach to all bioregional assessments
M02	*Compiling water-dependent assets*	Describes the approach for determining water-dependent assets
M03	*Assigning receptors to water-dependent assets*	Describes the approach for determining receptors associated with water-dependent assets
M04	*Developing a coal resource development pathway*	Specifies the information that needs to be collected and reported about known coal and coal seam gas resources as well as current and potential resource developments
M05	*Developing the conceptual model of causal pathways*	Describes the development of the conceptual model of causal pathways, which summarises how the 'system' operates and articulates the potential links between coal resource development and changes to surface water or groundwater
M06	*Surface water modelling*	Describes the approach taken for surface water modelling
M07	*Groundwater modelling*	Describes the approach taken for groundwater modelling
M08	*Receptor impact modelling*	Describes how to develop receptor impact models for assessing potential impact to assets due to hydrological changes that might arise from coal resource development
M09	*Propagating uncertainty through models*	Describes the approach to sensitivity analysis and quantification of uncertainty in the modelled hydrological changes that might occur in response to coal resource development
M10	*Impacts and risks*	Describes the logical basis for analysing impact and risk
M11	*Systematic analysis of water-related hazards associated with coal resource development*	Describes the process to identify potential water-related hazards from coal resource development

Technical products

The outputs of the BAs include a suite of technical products presenting information about the ecology, hydrology, hydrogeology and geology of a bioregion and the potential impacts of CSG and coal mining developments on water resources, both above and below ground. Importantly, these technical products are available to the public, providing the opportunity for all interested parties, including community, industry and government regulators, to draw from a single set of accessible information when considering CSG and large coal mining developments in a particular area.

The information included in the technical products is specified in the BA methodology. Figure 2 shows the relationship of the technical products to BA components and submethodologies. Table 2 lists the content provided in the technical products, with cross-references to the part of the BA methodology that specifies it. The red outlines in both Figure 2 and Table 2 indicate the information included in this technical product.

Technical products are delivered as reports (PDFs). Additional material is also provided, as specified by the BA methodology:

- unencumbered data syntheses and databases
- unencumbered tools, model code, procedures, routines and algorithms
- unencumbered forcing, boundary condition, parameter and initial condition datasets
- lineage of datasets (the origin of datasets and how they are changed as the BA progresses)
- gaps in data and modelling capability.

In this context, unencumbered material is material that can be published according to conditions in the licences or any applicable legislation. All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.

Technical products, and the additional material, are available online at http://www.bioregionalassessments.gov.au.

The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.

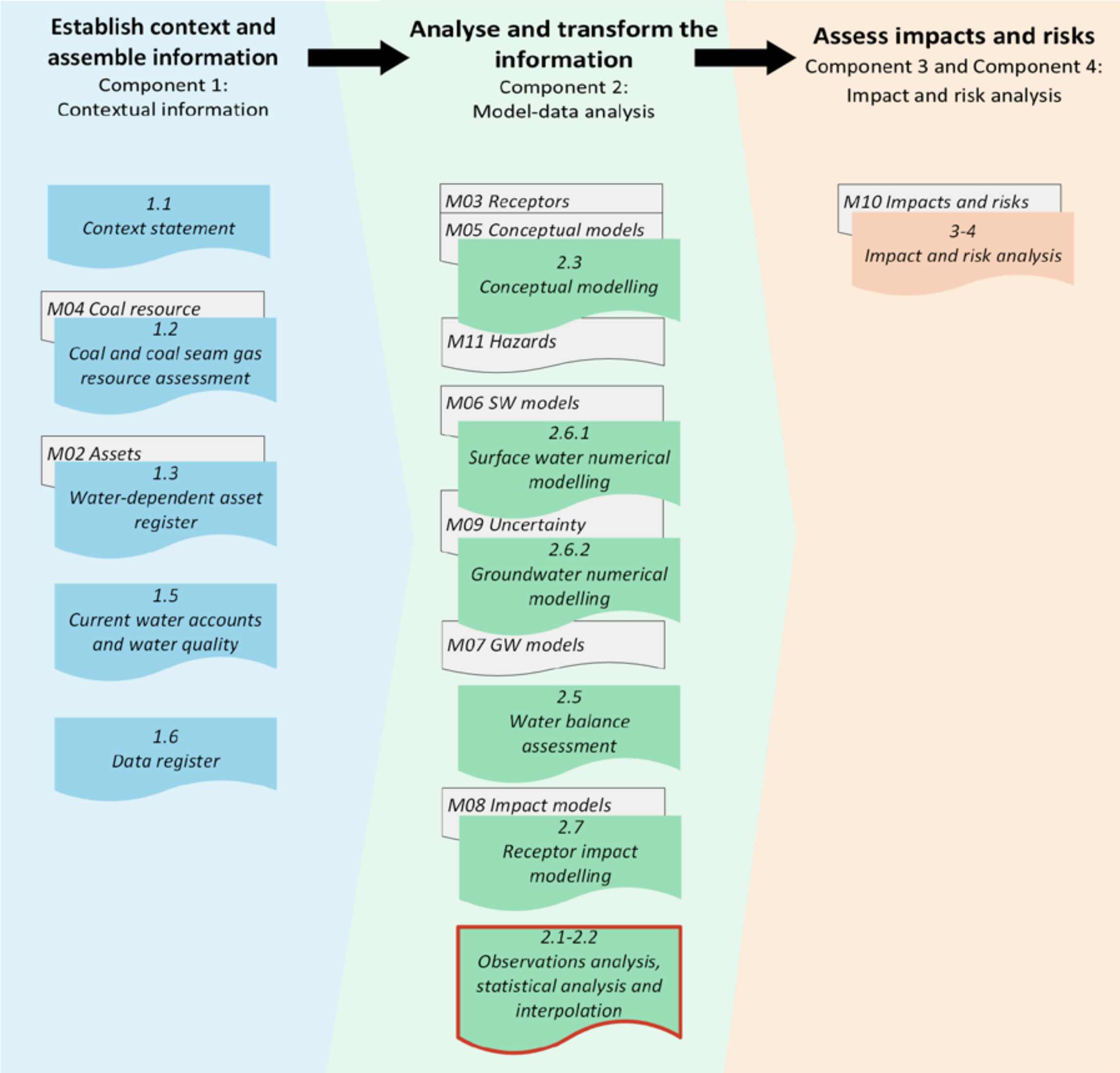

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

In each component (Figure 1) of a bioregional assessment, a number of technical products (coloured boxes, see also Table 2) are potentially created, depending on the availability of data and models. The light grey boxes indicate submethodologies (Table 1) that specify the approach used for each technical product. The red outline indicates this technical product. The BA methodology (Barrett et al., 2013) specifies the overall approach.

Table 2 Technical products delivered for the Namoi subregion

For each subregion in the Northern Inland Catchments Bioregional Assessment, technical products are delivered online at http://www.bioregionalassessments.gov.au, as indicated in the 'Type' column[a]. Other products – such as datasets, metadata, data visualisation and factsheets – are provided online. There is no product 1.4. Originally this product was going to describe the receptor register and application of landscape classes as per Section 3.5 of the BA methodology, but this information is now included in product 2.3 (conceptual modelling) and used in product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling). There is no product 2.4. Originally this product was going to include two- and three-dimensional representations as per Section 4.2 of the BA methodology, but these are instead included in products such as product 2.3 (conceptual modelling), product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling).

Component	Product code	Title	Section in the BA methodology[b]	Type[a]
Component 1: Contextual information for the Namoi subregion	1.1	Context statement	2.5.1.1, 3.2	PDF, HTML
	1.2	Coal and coal seam gas resource assessment	2.5.1.2, 3.3	PDF, HTML
	1.3	Description of the water-dependent asset register	2.5.1.3, 3.4	PDF, HTML, register
	1.5	Current water accounts and water quality	2.5.1.5	PDF, HTML
	1.6	Data register	2.5.1.6	Register
Component 2: Model-data analysis for the Namoi subregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2	PDF, HTML
	2.3	Conceptual modelling	2.5.2.3, 4.3	PDF, HTML
	2.5	Water balance assessment	2.5.2.4	PDF, HTML
	2.6.1	Surface water numerical modelling	4.4	PDF, HTML
	2.6.2	Groundwater numerical modelling	4.4	PDF, HTML
	2.7	Receptor impact modelling	2.5.2.6, 4.5	PDF, HTML
Component 3 and Component 4: Impact and risk analysis for the Namoi subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Namoi subregion	5	Outcome synthesis	2.5.5	PDF, HTML

[a]The types of products are as follows:

- 'PDF' indicates a PDF document that is developed by the Northern Inland Catchments Bioregional Assessment using the structure, standards and format specified by the Programme.
- 'HTML' indicates the same content as in the PDF document, but delivered as webpages.
- 'Register' indicates controlled lists that are delivered using a variety of formats as appropriate.

[b]*Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (Barrett et al., 2013)

About this technical product

The following notes are relevant only for this technical product.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence. The copyright owners of the following figures, however, did not grant permission to do so: Figure 6. It should be assumed that third parties are not entitled to use this material without permission from the copyright owner.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151.0° East for the Northern Inland Catchments bioregion and two standard parallels of –18.0° and –36.0°.
- Visit http://www.bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived Datasets, the created date is used.

References

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 27 June 2018, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 27 June 2018, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

2.1 Observations analysis for the Namoi subregion

This product includes the observations analysis, statistical analysis and interpolation of datasets used in the bioregional assessment. Only those datasets required for product 2.6.1 (surface water numerical modelling), product 2.6.2 (groundwater numerical modelling) and product 2.3 (conceptual modelling) are covered.

The data are categorised according to the following disciplines:

- geography
- geology
- hydrogeology and groundwater quality
- surface water hydrology and water quality
- surface water – groundwater interactions.

The observations analysis includes an assessment of data errors and uncertainties; the spatial and temporal resolution of observations; and algorithms used in the development of derived datasets. It requires development – and reporting – of summary statistics that describe the datasets' nature, variation and uncertainty.

The statistical analysis and interpolation aims to develop a quantitative understanding of the Namoi subregion by analysing the observed data and – where required – interpolating into locations where data are sparse.

This product also provides advice on data gaps. More information on data gaps will be reported in later products.

This product concludes with a detailed description of water management for coal resource developments. Only that information required for numerical modelling (in product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling)) is included.

2.1.1 Geography

Summary

This section provides a brief description of characteristics and errors associated with the geographical datasets used for the hydrological and other modelling in the Namoi subregion related to the (i) digital elevation model, (ii) surface watercourses, (iii) vegetation height and (iv) land use datasets.

Descriptions of input climate data are also provided for (i) precipitation (P), (ii) maximum and minimum air temperature (Tmax and Tmin) and (iii) net solar radiation (Rn). To characterise errors of the data, the long-term (1980 to 2009) monthly values were calculated along with mean of the root mean square error (RMSE) values. Results showed relative errors of 56%, 1.8% and 7.5% in P, Tmax and Tmin, respectively.

The basic geographic data for the Namoi subregion were reported in companion product 1.1 (Welsh et al., 2014). Details of the source data and methods are provided in Section 2.1.1.1 about observed data. Spatial analyses specific to the Namoi subregion undertaken for some of the meteorological datasets to characterise the errors are presented in Section 2.1.2.2. All these datasets were used directly or indirectly as input to the surface water and groundwater models.

2.1.1.1 Observed data

2.1.1.1.1 Physical geography

Digital elevation model

Information from a digital elevation model (DEM) is needed in the groundwater and surface water models to assess surface topography for representing hydraulic gradients, defining flow directions and contributing areas. The DEM was obtained from the GEODATA 9 second DEM (DEM-9S) (~250 m resolution grid cell) together with the 9 second flow direction grid (D8-9S) covering the whole of Australia (Geoscience Australia, Dataset 1).

Elevation errors in the DEM-9S are closely related to terrain complexity. The errors range from no more than 10 m in low relief areas (about half of Australia), up to around 60 m in highland areas with steep and complex terrain. In such areas there is significant variation in elevation across each 9 second grid cell. Maximum absolute errors are naturally larger than standard errors. These range from around 20 to 40 m in the lower relief half of the continent, up to around 200 to 300 m in complex highland areas (Geoscience Australia, 2008).

The percent slopes were derived from the 1 second smoothed DEM (DEM-S) derived from the Shuttle Radar Topography Mission (STRM) data, then generalised to 3 seconds by taking the mean over 3 x 3 cells. The RMSE of the derived slope varies from place to place due to the nature of source data and the adaptive smoothing. The RMSE is estimated to be between 2% and 5% (J Gallant, 2016, pers. comm.).

Surface watercourses

Surface watercourses were defined using the GeoData Topo 250K Series 3 Topographic Data, which is a vector representation of the major features appearing on 1:250,000 scale NATMAP topographic maps published by Geoscience Australia (2006). Using the hydrology theme from this dataset, major and minor watercourses are identified and both used to describe the surface hydrology of the Namoi subregion. Surface water basins or catchments are defined using the Australian Hydrological Geospatial Fabric (Geofabric), a specialised geographic information system published by the Bureau of Meteorology (2012).

Vegetation

The Australian Water Resources Assessment landscape model (AWRA-L), a rainfall-runoff model, and groundwater model use information derived from vegetation height to differentiate between deep-rooted and shallow-rooted vegetation. The difference in rooting depth is used in the process of scaling potential evapotranspiration (PET) to actual evapotranspiration (AET), by defining the depth to which water can be extracted from the soil via plant roots. Vegetation height was measured using a satellite based light detection and ranging system (LiDAR) between 20 May 2005 and 23 June 2005 using the Geoscience Laser Altimeter System (GLAS) aboard Ice, Cloud and Land Elevation Satellite (ICESat). Simard et al. (2011) were able to globally model overstorey vegetation height at 1 km spatial resolution with a vertical RMSE of 4.4 m and coefficient of determination (r^2) of 0.7 when compared against 59 flux-tower field observations globally.

Fraction of tree cover and leaf area index (LAI) information is also used in the AWRA-L model (Viney et al., 2014). It is based on the Advanced Very High Resolution Radiometer (AVHRR) satellite derived fractions of persistent and recurrent photosynthetically active absorbed radiation (fPAR) (Donohue et al., 2008). Here the persistent vegetation is interpreted to be tree cover (deep-rooted) and recurrent vegetation is interpreted to be grass cover (shallow-rooted). The maximum achievable LAI is derived from a time series of LAI from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite. These data form an inherent component of AWRA-L and they are not sourced in the bioregional assessment (BA).

Land use

The Australian Water Resources Assessment river model (AWRA-R) needs details of irrigated areas and crop types along each section of the river in order to distribute non-spatial irrigation diversion data appropriately in the model. Land use data were clipped using reach boundaries to derive irrigated areas and crop types. Namoi subregion land use data were obtained from the Catchment Scale Land Use Management (CLUM) raster surface compiled on November 2012 (Australian Bureau of Agricultural and Resource Economics and Sciences, Dataset 3).

The most current catchment scale land use dataset for Australia uses the nationally agreed land use mapping principles and procedures of the Australian Land Use and Management Program (ALUMP) Classification version 7. The land use datasets have been compiled from vector datasets, part of the state and territory mapping programmes and the Australian Collaborative Land Use and Management Program (ACLUMP). CLUM data, compiled in March 2014, incorporates data from 1997 to 2012 with a mapping scale from 1:25,000 to 1:250,000 to produce a seamless 50 m raster dataset for Australia. The differences in resolution of the primary input datasets (~25 to ~250 m) means that in some areas the boundary between existing land use types may be inaccurate. However, this may have limited contribution to model errors given that modelling is being done at least at a 1 km resolution.

2.1.1.1.2 Climate

The following variables are required for hydrological modelling of the Namoi subregion: (i) precipitation (P), (ii) maximum and minimum air temperature (Tmax and Tmin) and (iii) net radiation (Rn). National coverage is available at a 0.05 degree (or ~5 km) grid cell resolution and a daily time step. They come from various sources and have different start dates. These input grids are used in the calculation of PET and catchment runoff. A brief description of these climate variables follows.

Precipitation

Daily and monthly precipitation grids generated by the Bureau of Meteorology (Jones et al., 2009) from 1900 onwards are available. These grids are developed using a geostatistics technique, which takes account of ground elevation, to interpolate daily and monthly station P totals between isolated stations (Bureau of Meteorology, Dataset 4). The estimates were cross-validated using seven years of data from 2001 for the whole of Australia (Jones et al., 2009). Between 2001 and 2007, the Australia-wide mean daily P was 1.8 mm/day with a RMSE of 3.1 mm/day (Jones et al., 2009, Table 3b). This represents a relative error of 172% (calculated as RMSE/mean), although absolute differences may be small. For the same period, the Australia-wide mean monthly P was 54.3 mm/month with a RMSE of 21.2 mm/month (Jones et al., 2009, Table 3a). This represents a relative error of 39% (calculated as RMSE/mean). These errors may be large and may reflect the data problem on a continental basis, however errors for the Namoi subregion are much smaller (see Section 2.1.1.2).

Temperature

Daily Tmax and Tmin grids generated by the Bureau of Meteorology are available from 1900 onwards (Jones et al., 2009). These grids are developed using optimal geostatistics techniques, taking elevation into account (the environmental lapse rate), to interpolate daily extreme air temperatures measured at isolated stations (Bureau of Meteorology, Dataset 4). The mean daily Tmax and mean daily Tmin for Australia between 2001 and 2007 were 24.9 and 12.8 °C with RMSE statistics of 1.2 and 1.7 °C, respectively (Jones et al., 2009, Table 2b). These represent relative errors of 5 and 13%, respectively (calculated as RMSE/mean). The mean monthly Tmax and mean monthly Tmin for all Australia between 2001 and 2007 were 24.9 and 12.7 °C with RMSE statistics of 0.7 and 1.0 °C, respectively (Jones et al., 2009, Table 2a). These represent relative errors of 3 and 8%, respectively.

Solar radiation

Daily solar net radiation (Rn) values are available from 1900 onwards as part of the Bureau of Meteorology gridded climate surfaces for Australia (Bureau of Meteorology, Dataset 4). The dataset comprises two distinct periods: post-1982, daily solar radiation values are based on observations from ground-based and satellite instruments; prior to 1982, the daily values are based on the long-term climatologies from the post-1982 period. This means, for example, that the solar radiation on 1 January is the same for every year from 1900 to 1981 and reflects the average solar radiation on 1 January in the years since 1981. Uncertainties in the solar radiation data arise from the effect of cloud cover (~5%) and water vapour in the atmosphere (~2%). Comparisons with ground-based measurements (made with pyranometers) indicate that satellite methods tend to slightly over estimate the radiant exposure in wet, cloudy conditions and to under estimate in dry conditions (Bureau of Meteorology, 2016).

2.1.1.2 Statistical analysis and interpolation

All geographic data specific to the Namoi subregion were obtained from state or national datasets. Results of the analysis that characterises the errors of the subregion-specific input climate data for the water balance modelling are outlined in this section.

In addition to generating daily and monthly grids of meteorological variables (P, Tmax and Tmin), the Bureau of Meteorology (Jones et al., 2009) also generate daily and monthly RMSE grids of the same variables. These daily and monthly RMSE grids are a combined measure of the observational error and geostatistical error. The latter is a function of the interpolation method, density of observation stations and degree of spatial correlation of the process(es).

To characterise errors of the input climate data, the long-term (from January 1980 to December 2009) monthly mean values for P, Tmax and Tmin were calculated. Also calculated were the long-term monthly RMSE values for the same variables for the same time period. Relative error, expressed as a percentage, was calculated by dividing the monthly RMSE grid by the monthly mean grids (i.e. RMSE grid/mean grid for each meteorological variable).

The spatially-averaged long-term monthly mean P for the Namoi subregion is 60 mm/month, and the associated RMSE mean for the subregion is 29 mm/month (see Figure 3a and Figure 3b, respectively). This results in a relative error of 56% in the input P grids (Figure 3c). The high relative error is due, in part, to P being a highly spatially variable process. Relative error tends to be lower around the larger inland towns, reflecting the denser network of rainfall gauges, and higher in the less populous areas. The mean RMSE value based on the whole catchment may not represent error in input P in the model. This is because the input P in the model is determined for specific modelled catchments whose P value is heavily influenced by the P measured in local rainfall stations.

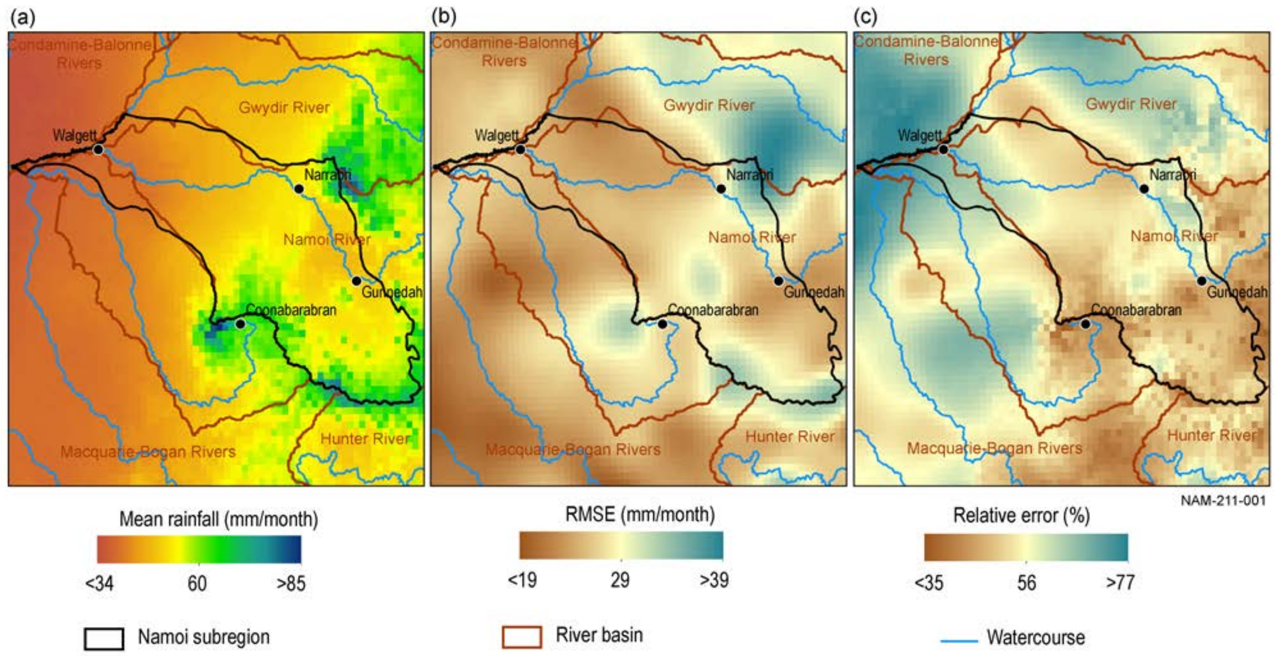

Figure 3 Spatial variation of precipitation from 1980 to 2009 (a) monthly mean precipitation, (b) monthly root mean square error (RMSE) precipitation and (c) monthly mean precipitation relative error for the Namoi subregion

Data: Bioregional Assessment Programme (Dataset 2)

For air temperatures, a meteorological variable that has higher spatial autocorrelation than P, the regional distribution is governed by topography and distance from the ocean. The Tmax spatially-averaged long-term monthly mean is 23 °C for the Namoi subregion (Figure 4a). The associated RMSE is approximately 0.39 °C (Figure 4b), which leads to a relative error of 1.8% for Tmax (Figure 4c). For Tmin there are similar spatial patterns, with the spatially-averaged long-term monthly mean being 10 °C (Figure 5a) and the associated RMSE being approximately 0.64 °C (Figure 5b), leading to a relative error of 7.5% (Figure 5c).

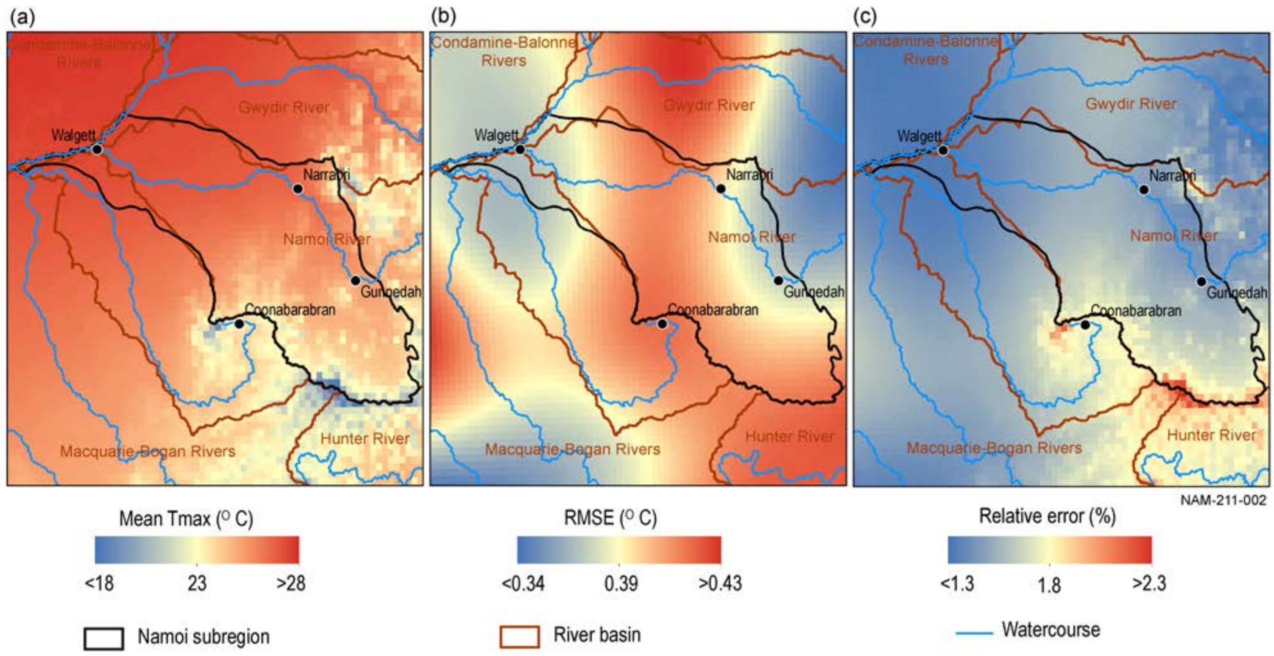

Figure 4 Spatial variation of maximum air temperature (Tmax) from 1980 to 2009 (a) monthly mean Tmax, (b) monthly root mean square error (RMSE) Tmax and (c) monthly mean Tmax relative error for the Namoi subregion

Data: Bioregional Assessment Programme (Dataset 2)

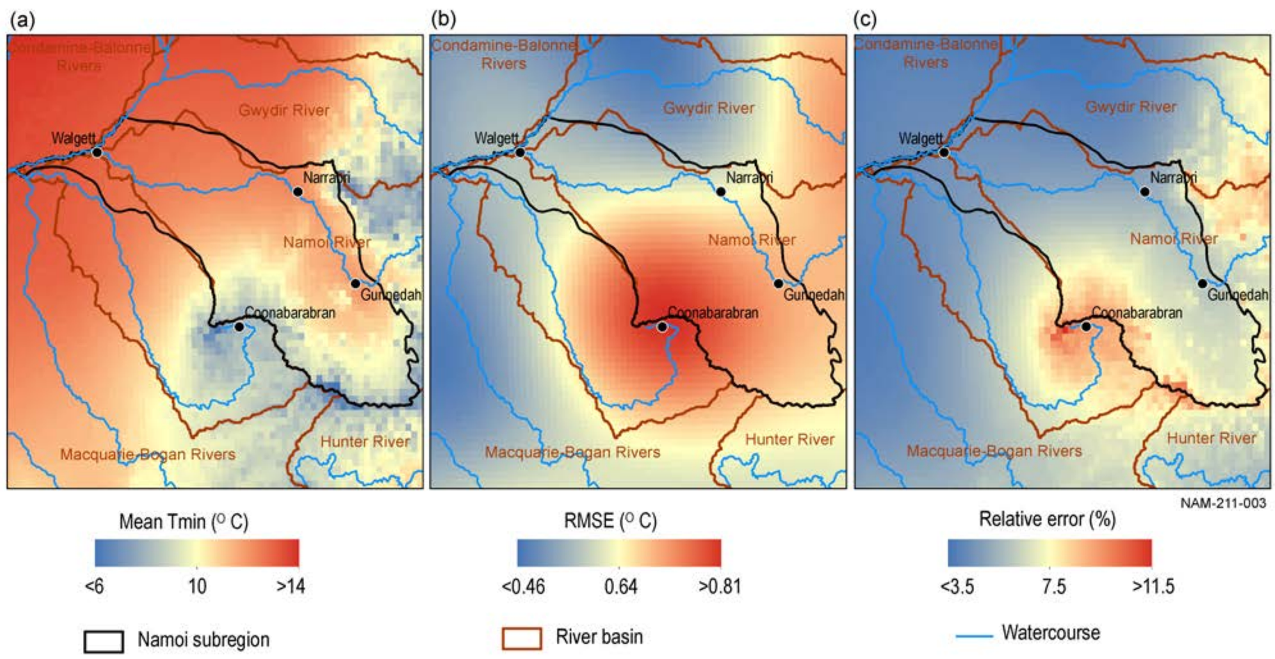

Figure 5 Spatial variation of minimum air temperature (Tmin) from 1980 to 2008 (a) monthly mean Tmin, (b) monthly root mean square error (RMSE) Tmin and (c) monthly mean Tmin relative error for the Namoi subregion

Data: Bioregional Assessment Programme (Dataset 2)

2.1.1.3 Gaps

2.1.1.3.1 Density of meteorological observations

The density of stations for meteorological observations impacts the accuracy of smoothed surfaces depicting the spatial variation of a climate variable (e.g. P, Tmax). On a continental scale, overall errors (e.g. RMSE) can be large due to the low density of gauging stations in remote areas. Locally however, errors may be low due to higher station density within a region which captures the spatial variability better. Note that the error is also dependent on how much a given climate variable varies spatially.

The characterisation of input data errors suggests that having a denser network of Bureau of Meteorology stations recording climate data has the potential for reducing the uncertainty in input climate variables, which can lead to improved water-related modelling in the Namoi subregion.

Finding an optimum density of gauging stations is a non-trivial exercise. Therefore it is impractical to suggest if the present density of climate data are sufficient for modelling purposes. It is also possible that any systematic errors in model parameterisation may be compensated through calibration. Furthermore, as the BA Programme reports on the relative difference of hydrological response variables between the baseline and coal resource development pathway (CRDP), any error introduced by the lack of optimum station density would cancel out.

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Datasets

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2.1.2 Geology

Summary

An existing three-dimensional geological model was adapted to define regional-scale geology for modelling impacts of coal resource development on water-dependent assets in the Namoi subregion. The model was adapted from CDM Smith's geological model that was developed for Santos' Gunnedah Coal Seam Gas Project. The CDM Smith model was modified in areas where more updated geological knowledge was available, namely in the Surat Basin and the alluvium. The geological model also forms the basis of the conceptual modelling of causal pathways and for the hydrogeological modelling.

The geological model is an interpretation of the subsurface geology and structure of the Gunnedah and Surat basins. The tops and bottoms of each stratigraphic layer in the Gunnedah Basin were extracted from the CDM Smith model, and in the Surat Basin from the Water Resource Assessment of the Great Artesian Basin (GABWRA) and the Hydrogeological Atlas of the Great Artesian Basin (GAB Atlas). The thicknesses for each modelled layer were calculated from these surfaces.

The geological model is just one of many possible representations of the system based on information available. However, the geological model is considered to provide a fit-for-purpose tool at a regional scale to aid in understanding how coal resource development may affect water resources and water-dependent assets, and for the conceptual modelling of causal pathways. The model can be updated and refined in the future with the input of additional or new datasets.

2.1.2.1 Observed data

2.1.2.1.1 Overview

The Namoi subregion is underlain by portions of the Gunnedah Basin, the Surat Basin and the smaller Werrie Basin (Figure 6). These geological basins are overlain by alluvial cover of variable thickness and extent. For bioregional assessment (BA) purposes, a three-dimensional geological model of the Namoi subregion was needed to define regional-scale geology for modelling impacts of coal resource development on groundwater. This section describes the geological model that was developed for the Namoi BA. The geological model also forms the basis for the hydrogeological modelling, discussed in more detail in companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018). A generalised stratigraphic column of the geology underlying the Namoi subregion is shown in Figure 7 and additional information about the geology of the Namoi subregion is summarised in companion product 1.1 (Welsh et al., 2014). The surface geology of the Namoi subregion is shown in Figure 8. The key strata of interest are the two major aquifer systems (the Namoi alluvium and the Pilliga Sandstone) and the coal-bearing Black Jack Group and Maules Creek Formation.

This section describes the model that was used in the Assessment, how this model was assessed to be fit for purpose and how the model was modified during the Assessment using other data.

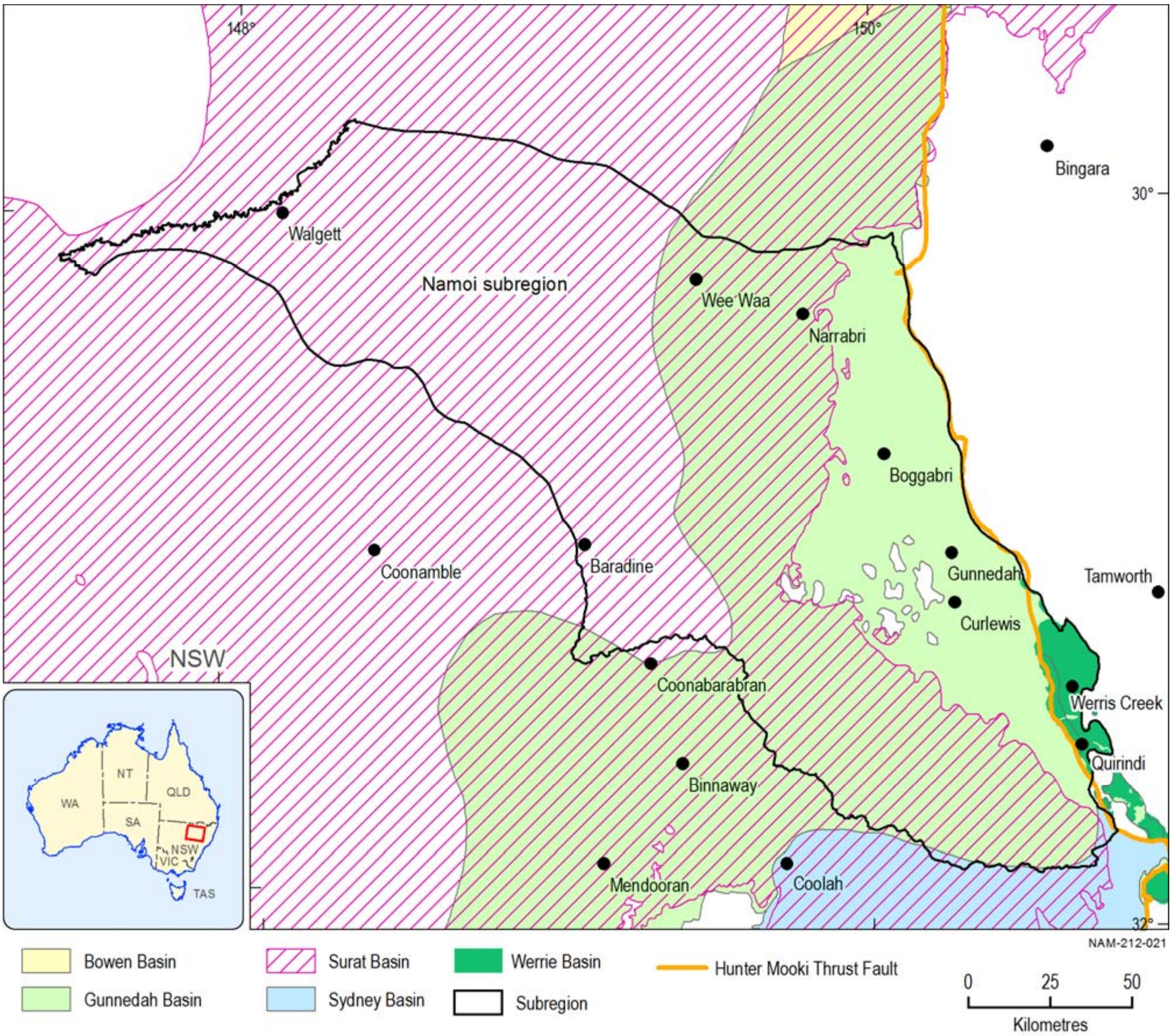

Figure 6 Geological basins in the Namoi subregion

Data: Geoscience Australia (Dataset 1, Dataset 2), FROGTECH (Dataset 3)
Note: The stratigraphic units of the Gunnedah, Bowen, Sydney and Werrie basins are Permo-Triassic and the overlying stratigraphic units of the younger Surat Basin are Jurassic.

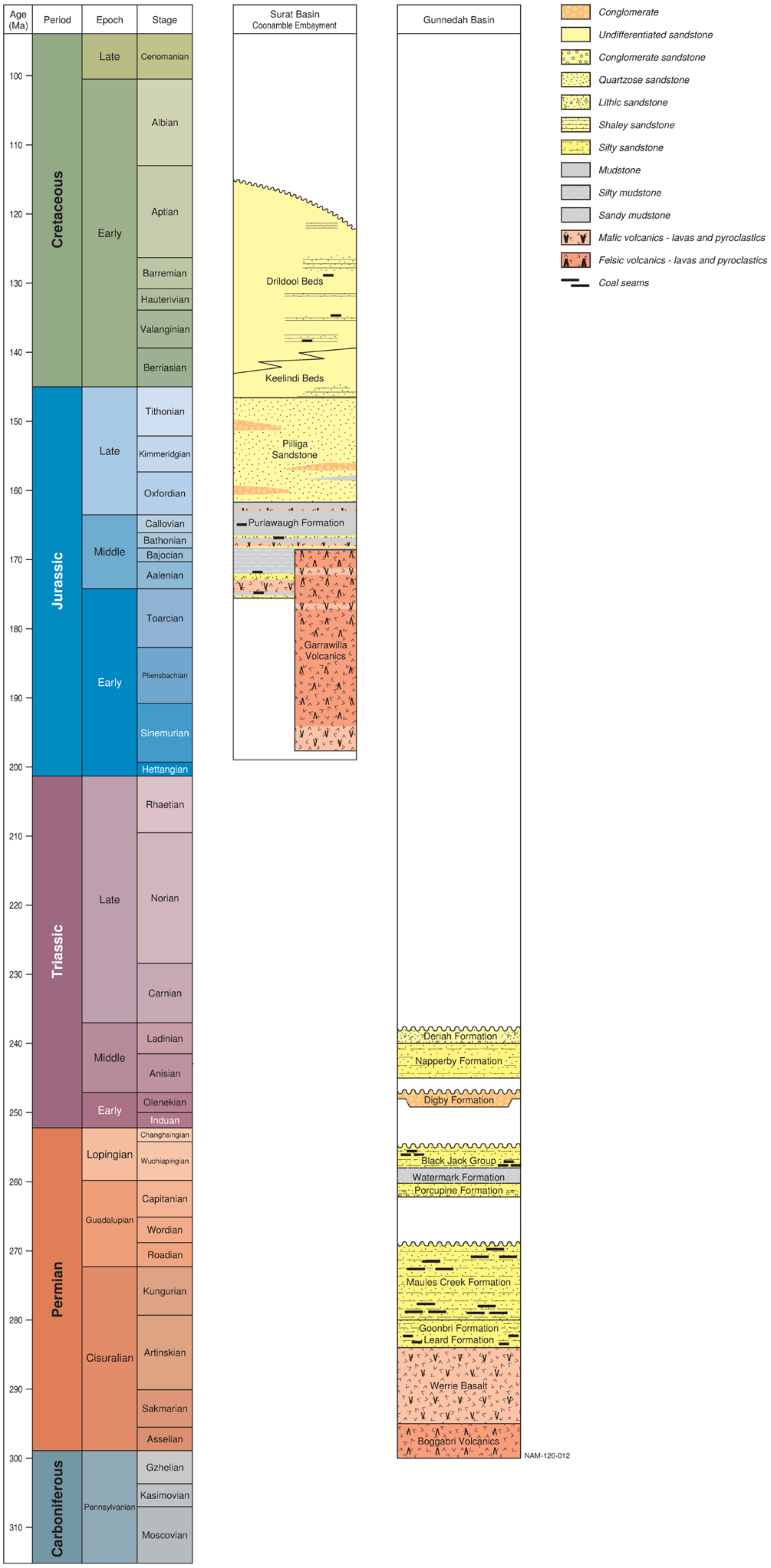

Figure 7 Representation of Permian to Cretaceous stratigraphy of the Namoi subregion

The younger sediments overlying the Surat and Gunnedah basins are not shown.
Data: derived from data presented in McKellar (1998), Totterdell et al. (2009), Cook and Draper (2013), and the Australian Stratigraphic Units Database (Geoscience Australia and Australian Stratigraphy Commission, 2017)
This figure has been optimised for printing on A3 paper (297 mm x 420 mm)

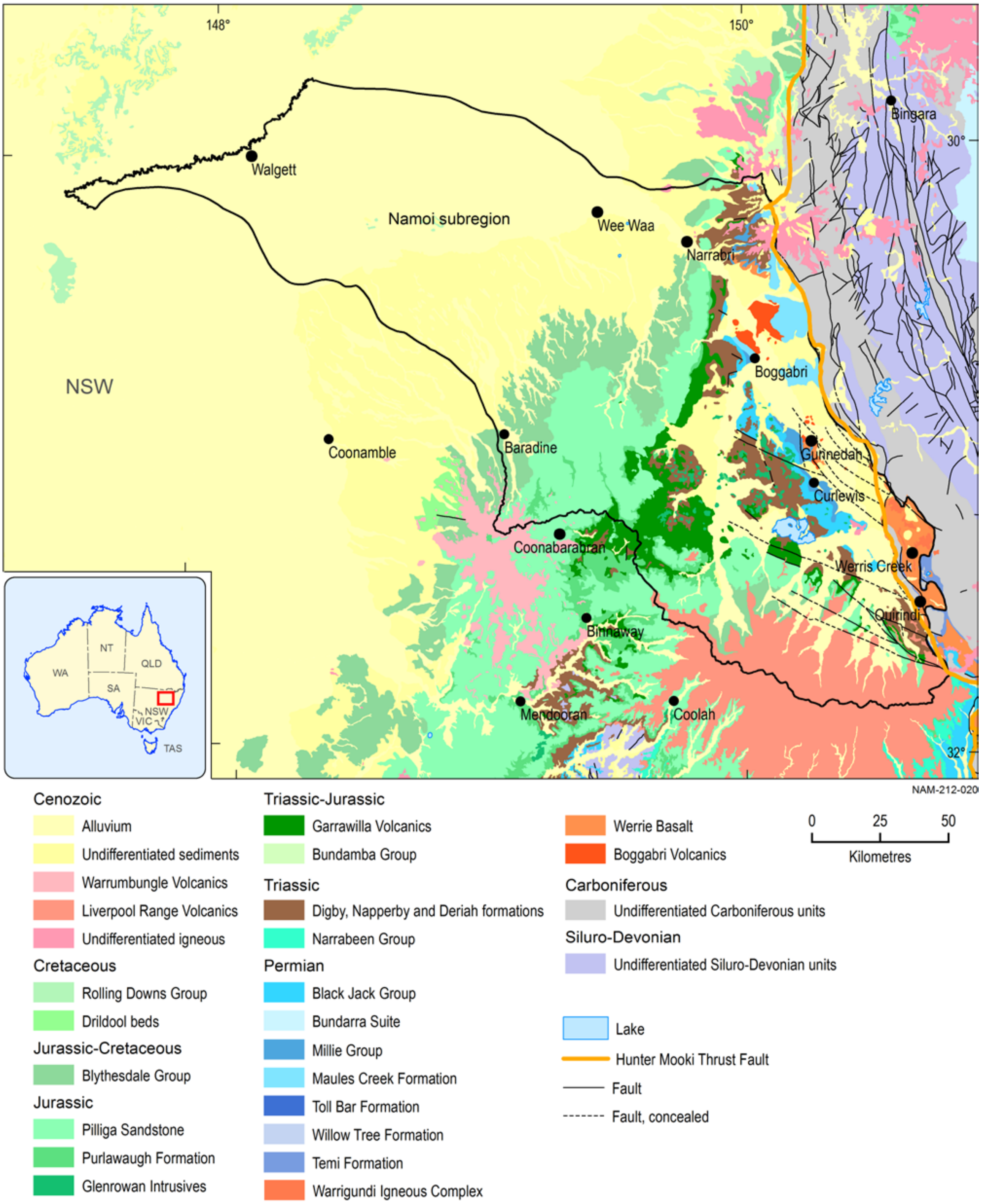

Figure 8 Surface geology of the Namoi subregion

Data: Geoscience Australia (Dataset 2), FROGTECH (Dataset 3)

There are a number of pre-existing geological models in the Namoi subregion that were considered for use in this Assessment. Historically, the majority of geological models are local-scale models for mining operations that are not publicly available. Many of the mine-scale geological models are developed primarily for resource estimation and mine planning, for example the Maules Creek Mine (Hansen Bailey, 2011), and are therefore not suitable as the basis for a regional geological model.

There are two geological models that are regional in extent and include Gunnedah Basin strata in the Namoi subregion: the geological model developed by Schlumberger for the Namoi Catchment Water Study using Petrel software (Schlumberger Water Services, 2012), and the model developed by CDM Smith for the proposed Santos' Gunnedah Coal Seam Gas Project (NTEC, 2013) using Leapfrog Hydro™. The geological model developed by Schlumberger Water Services (2012) was not available to the Assessment team. The geological model developed by CDM Smith (referred to as the CDM Smith model) was available, so the model was assessed for its suitability for the Namoi BA. Following some modifications which are discussed below, the CDM Smith model was considered to be fit for purpose, where the primary purpose is to delineate stratigraphic layers for the stochastic regional groundwater modelling of the impacts of additional coal resource development (discussed further in companion product 2.6.2 (Janardhanan et al., 2018)). Other factors that resulted in the model being considered fit for purpose were that it is regional in extent, includes the geological layers that have important water-dependent assets and the coal measures, is based on recent data and was available for use by the Assessment team. The model forms the basis for the stratigraphic layers for the numerical groundwater model, and is used as a basis for conceptual modelling of causal pathways, to aid the understanding of where and how coal resource development may affect water resources and water-dependent assets.

Modifications were made by the Assessment team to the CDM Smith model to incorporate recent improvements in knowledge, where available, and to simplify the number of layers given the regional extent of the model. The geological model isolates the layers of interest for the Assessment, namely the Permian coal seams and the layers with water-dependent assets (the alluvium and the Pilliga Sandstone). Most of the other layers have been lumped into interburden layers. The main modification made was to incorporate the model developed from the Water Resource Assessment for the Great Artesian Basin (GABWRA) (Smerdon et al., 2012) and the Hydrogeological Atlas of the Great Artesian Basin (GAB Atlas) (Ransley et al., 2015). The GAB Atlas is a compilation of up-to-date interpretations of the extent and thickness of key regional geological and hydrogeological aspects of the GAB (Ransley et al., 2015). Other modifications could be made to improve the representation of the system in the model if it were to be used for a different purpose, and these are listed in Section 2.1.2.3.

The modified geological model, hereafter termed the Namoi BA geological model, was constructed by first defining the base of the model, and then constructing a series of stratigraphic surfaces and thickness maps for each stratigraphic unit. These have been compiled to form a composite three-dimensional geological model for the Namoi. The domain of the Namoi BA geological model is shown in Figure 9 with the Namoi preliminary assessment extent and the Phanerozoic OZ SEEBASE™ basement structural model of the Gunnedah Basin (FROGTECH, Dataset 3). The Phanerozoic OZ SEEBASE™ is a continent-wide (low resolution) surface interpreted from magnetic, gravity, seismic and borehole data. In the Namoi subregion, OZ SEEBASE™ indicates the basement depth and structure of the Gunnedah Basin.

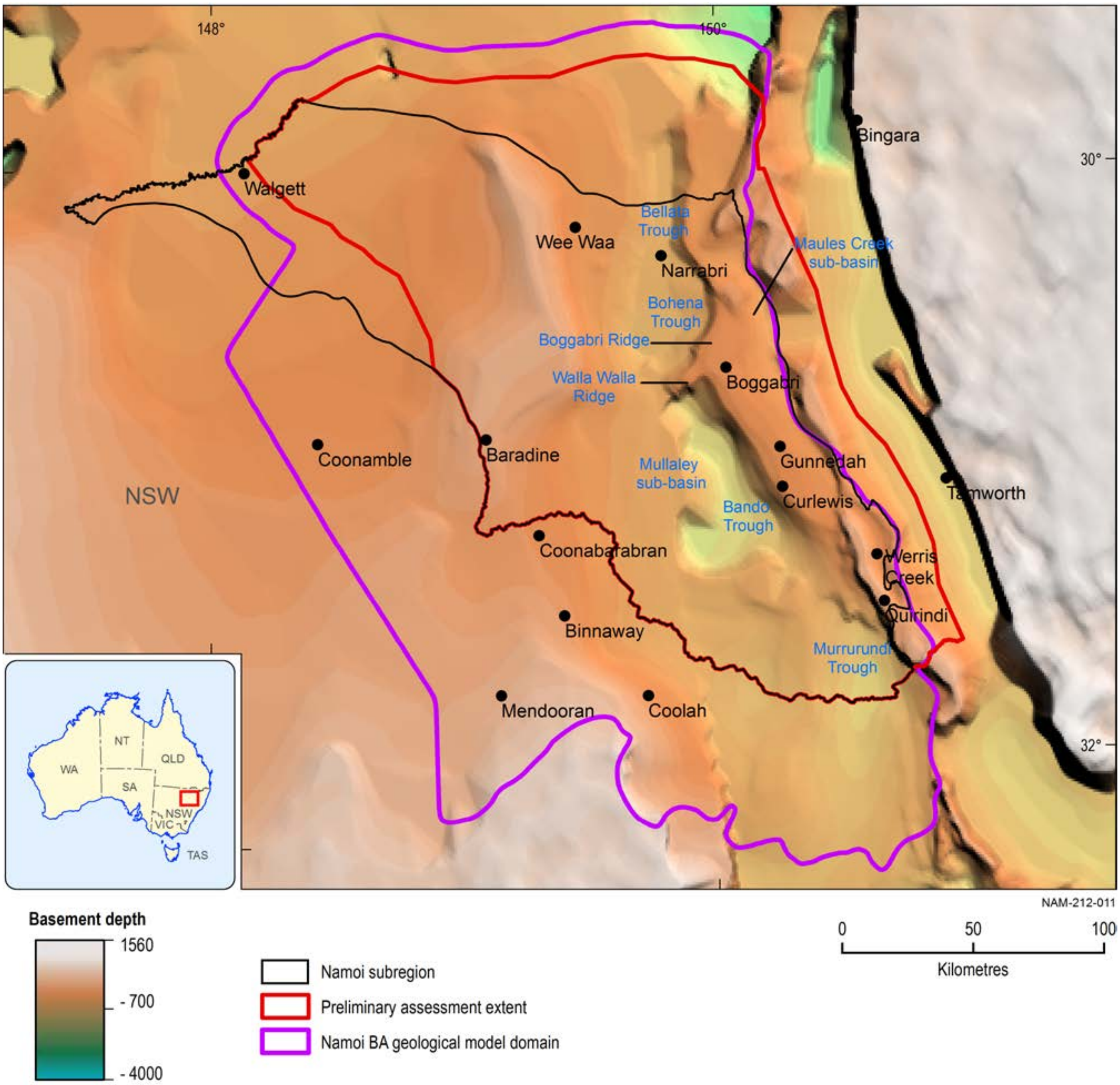

Figure 9 Basement elevation of the Gunnedah Basin with major depositional centres, showing the extent of the Namoi BA geological model and the Namoi preliminary assessment extent

BA = bioregional assessment
Data: FROGTECH (Dataset 3), CDM Smith (Dataset 4)

2.1.2.1.2 The CDM Smith model

The CDM Smith model forms the basis of the Gunnedah Basin strata in the Namoi BA geological model and consists of 13 layers representing the following major stratigraphic units in order of youngest to oldest (Halcrow, 2013):

- Alluvium (includes the Narrabri, Gunnedah and Cubaroo formations)
- Rolling Downs Group and Liverpool Range Volcanics (overlies the Drildool Beds in Figure 7)
- Blythesdale Group (equivalent to the Keelindi and Drildool beds in Figure 7)
- Pilliga Sandstone

- Purlawaugh Formation
- Garrawilla Volcanics
- Deriah and Napperby formations
- Digby Formation
- Black Jack Group above Coal
- Hoskissons Coal (part of the Black Jack Group)
- Black Jack Group below Coal
- Millie Group (the Watermark and Porcupine formations)
- Maules Creek Formation.

There is little documentation available for the geological model, other than that from the Groundwater Impact Assessment for the Gunnedah Coal Seam Gas Project (NTEC, 2013). Each geological layer in the CDM Smith model is represented as a three-dimensional layer that can be continuous or discontinuous within the geological model domain. The thickness of layers and contact between the layers are based on interpolation and extrapolation of the input data and the types of stratigraphic relationships assigned in Leapfrog™. The model is discretised into 500 m x 500 m model cells. The thickness of each layer in each cell represents the mean formation thickness at that location. The model domain extends over approximately 53,200 km^2 from the Hunter-Mooki Thrust Fault System in the east, to the extent of the Gunnedah Basin units in the south and north, which are outside the boundary of the Namoi subregion. The western boundary of the model domain is arbitrary and is parallel to the inferred regional groundwater flow direction in the Surat Basin.

Sources of data for the CDM Smith model include drilling logs from Santos and the NSW Department of Primary Industries Digital Imaging of Geological System (DIGS®) database, stratigraphic surfaces from the Upper and Lower Namoi groundwater models (McNeilage (2006) and Merrick (2001) respectively), the Gunnedah Bowen Study SEEBASE™ (SRK, 2011) and Santos proprietary mapping of Gunnedah Basin formation tops and outcrop geology from geographic information systems (GIS). The ground surface elevation was determined using the Shuttle Radar Topography Mission (SRTM) 500 m digital elevation model (NTEC, 2013, p. 17, Table 2-1).

Well data and drilling logs in the west of the Namoi subregion are sparse, which decreases the reliability of the geological model in this area. However, this area is not a priority for coal or coal seam gas (CSG) development, and there are no developments in the coal resource development pathway (CRDP) to the west of Wee Waa. There are also limited well data in the CDM Smith model in the Maules Creek sub-basin in the east of the subregion. There are seven coal resource developments in this area incorporated in the CRDP so this data gap may increase uncertainty in the Maules Creek sub-basin. More information regarding coal resource development in the Namoi subregion is presented in Section 2.3.4 of companion product 2.3 for the Namoi subregion (Herr et al., 2018).

There are distinct depositional sub-basins within the Gunnedah Basin (e.g. Maules Creek and Mullaley sub-basins, and other troughs), as shown in Figure 9 and discussed in companion product 2.3 for the Namoi subregion (Herr et al., 2018). The depth of these features can be in excess of 1500 m, and this is likely to be associated with faults or folding. The OZSEEBASE™ dataset (FROGTECH, 2014) currently provides the most comprehensive interpretation of structures in the Namoi subregion and shows a complex network of faults, particularly in the eastern part of the subregion where the rocks of the Gunnedah Basin occur at or close to the surface. The most intense faulting occurs in a zone adjacent to the Hunter-Mooki Thrust Fault System. The CDM Smith model does not contain faults and this is a limitation of the model, given faults with vertical displacements of up to 120 m have been identified in the Maules Creek sub-basin (Tadros, 1988). Depending on fault orientation, type and stress direction, faults can act to compartmentalise groundwater flow or provide a conduit for flow, so a more detailed understanding of structures and inclusion in this model would improve geological representation of the system.

Gunnedah Basin model layers have modelling artefacts such as bullseyes which suggest large changes in layer thickness that are unlikely to be realistic. It is not clear why these artefacts have developed in the model, but it may be the result of a model building artefact or the smoothing of thickness contours between data points or between model layers.

2.1.2.1.3 The Great Artesian Basin models

The Great Artesian Basin Water Resource Assessment (Smerdon et al., 2012) is a basin-scale investigation of water resources across the GAB, assessing the status of water resources, identifying the potential impacts of climate change and resource development on those water resources. The Assessment provided an updated interpretation of the geology and hydrogeology of the GAB, resulting in an update of the conceptualisation of how the groundwater system operates.

The GAB Atlas (Ransley et al., 2015) draws on GABWRA and is a compilation of maps documenting some of the key regional geological, hydrogeological and hydrochemical aspects of the GAB and its groundwater systems. It provides insights into the current understanding of the regional geometry and physical characteristics of the basin. The key pieces of new work that are presented in this Atlas are the up-to-date interpretations of the extent and thickness of the major GAB aquifers and aquitards.

Slight discrepancies were found with the boundary of the GAB, and therefore the extent of the Pilliga Sandstone, in the CDM Smith model. Consequently, the Assessment team used model layers derived from GABWRA (Smerdon et al., 2012) and the GAB Atlas (Ransley et al., 2015) for the part of the Namoi underlain by the GAB. The boundary of the GAB, as shown in the GAB Atlas, is coincident with the boundary of the Surat Basin. The information and data contained in the GAB Atlas is more recent than that used for the CDM Smith model, so the isopachs for the Rolling Downs Aquitard (which includes the Blythesdale Group in the CDM Smith model) and Pilliga Sandstone (referred to as the Cadna-owie – Hooray Aquifer) were imported into the geological model (Geoscience Australia, Dataset 5, Dataset 6). The thicknesses of the basal units of the Surat Basin in the Namoi subregion (Purlawaugh Formation and Garrawilla Volcanics) were determined by calculating the difference between the base of the Pilliga Sandstone equivalent and the base of the Surat Basin from GABWRA (Geoscience Australia, Dataset 7, Dataset 8).

2.1.2.2 Statistical analysis and interpolation

This section describes the layers in the Namoi BA geological model that were derived from the CDM Smith model and the modifications that were made to the representation of the Surat Basin strata and alluvium.

Table 3 shows how the layers in the CDM Smith model correspond with the stratigraphy of the Namoi subregion and layers in the Namoi BA geological model.

Table 3 Comparison of geological layers in the CDM Smith model and the Namoi BA geological model

Province	Period or epoch	Division	Formation	Layer in CDM Smith model	Layer in Namoi BA Geological model
Namoi alluvium	Pleistocene	na	Narrabri Formation	1	1 (Alluvium Layer 1)
Namoi alluvium	Pliocene	na	Gunnedah Formation	1	2 (Alluvium Layer 2)
Namoi alluvium	Miocene	na	Cubaroo Formation	1	2 (Alluvium Layer 2)
Surat Basin	Cretaceous	Late	Rolling Downs Group and Liverpool Range Volcanics	2	3 (Interburden 1)
Surat Basin	Cretaceous	Middle	Blythesdale Group	3	3 (Interburden 1)
Surat Basin	Jurassic	Late	Pilliga Sandstone	4	4 (Pilliga Sandstone)
Surat Basin	Jurassic	Middle	Purlawaugh Formation	5	5 (Purlawaugh Formation and Garrawilla Volcanics)
Surat Basin	Jurassic	Early	Garrawilla Volcanics	6	5 (Purlawaugh Formation and Garrawilla Volcanics)
Gunnedah Basin	Triassic	Middle	Napperby and Deriah formations	7	6 (Interburden 2)
Gunnedah Basin	Triassic	Early	Digby Formation	8	6 (Interburden 2)
Gunnedah Basin	Permian	Late	Black Jack Group – Coogal and Nea subgroup	9	6 (Interburden 2)
Gunnedah Basin	Permian	Late	Hoskissons Coal	10	7 (Hoskissons Coal)
Gunnedah Basin	Permian	Late	Black Jack Group – Brothers subgroup	11	8 (Interburden 3)
Gunnedah Basin	Permian	Middle	Watermark Formation	12	8 (Interburden 3)
Gunnedah Basin	Permian	Middle	Porcupine Formation	12	8 (Interburden 3)
Gunnedah Basin	Permian	Early	Upper Maules Creek Formation	13	9 (Maules Creek Formation)
Gunnedah Basin	Permian	Early	Maules Creek coal seams	13	9 (Maules Creek Formation)
Gunnedah Basin	Permian	Early	Lower Maules Creek Formation	13	9 (Maules Creek Formation)
Gunnedah Basin	Permian	Early	Goonbri Formation	na	na
Gunnedah Basin	Permian	Early	Leard Formation	na	na
Gunnedah Basin	Permian	Early	Werrie Basalt and Boggabri Volcanics	na	na

Based on NTEC (2013), BA = bioregional assessment, na = not applicable

The main source of geological information used in the CDM Smith model was 340 petroleum, CSG and coal wells, of which approximately 130 contain publicly available information and can be compared to well completion reports (WCR). A selection of these were accessed to compare the thickness and extent of stratigraphic layers as represented in the CDM Smith model with those in the WCR. Data for the remaining wells was not publicly available. The information on bore intercepts and maximum layer thickness for each layer of the CDM Smith model is shown in Table 4. The maximum thickness for each layer in the Australian Stratigraphic Units Database

(Geoscience Australia and Australian Stratigraphy Commission, 2017) and from other published sources is also included in Table 4. There are some discrepancies between the CDM Smith model intercepts and thickness data in the database and published texts, which can be attributed to a number of reasons including extrapolation of point source (well) data to regional coverage, how stratigraphic data has been interpreted and correlated, the different scales at which data are collected (regional or local), areas with sparse data points and the dataset used (e.g. Santos have some WCR that are not publicly available). The model is just one of many possible representations of the system and is unlikely to be consistent with all the data available in the subregion.

Table 4 Well intercepts and maximum thickness for stratigraphic units in the CDM Smith model

Layer in CDM Smith model	Number of wells intercepting unit	Number of wells intercepting unit within the Namoi subregion	Maximum thickness in the CDM Smith model (m)[a]	Maximum thickness in the Australian Stratigraphic Units Database (m)	Maximum thickness of unit from other sources (m)
Alluvium	na	na	294	NA	170
Rolling Downs Group	3	0	775	1200	200
Blythesdale Group	80	23	560	943	NA
Pilliga Sandstone	124	103	380	300	400
Purlawaugh Formation	140	111	285	100	100
Garrawilla Volcanics	55	41	465	180	NA
Napperby Formation	221	168	425	250	280
Digby Formation	236	203	430	250	180
Black Jack Group above Coal	253	224	650	443.5	400
Hoskissons Coal	261	234	215	18	18
Black Jack Group below Coal	239	213	610	168	285
Millie Group	178	154	480	416	402
Maules Creek Formation	116	113	830	100	800

[a]This is the maximum thickness within the Namoi subregion, not across the full extent of the model domain
The alluvium layer was not determined by bore analysis but the data layers are drawn from the Upper and Lower Namoi groundwater models.
BA = bioregional assessment, na = not applicable, NA = not available
Maximum thickness for Gunnedah Basin units comes from Tadros (1993) and for the Surat Basin from Ransley et al. (2015).
Maximum thickness for the alluvium comes from Barrett (2012).

2.1.2.2.1 Alluvium (Layers 1 and 2)

The alluvium layer in the CDM Smith model is based on the Upper and Lower Namoi groundwater models. These models were developed to determine sustainable diversion limits under the Murray

Darling Basin Plan, and in the case of the Upper Namoi, the zones included in the modelling do not match groundwater source boundaries as recognised in the Upper Namoi water sharing plan. There is a discrepancy between geological mapping of alluvium and the modelled extent of alluvium in the upper reaches of streams in the Upper Namoi in the model.

There are small areas in the Lower Namoi where the thickness of the alluvium layer in the CDM Smith model is greater than 200 m, however other models of the alluvium, including Schlumberger Water Services (2011) and McNeilage (2006), have a maximum alluvium thickness of 170 m. This is confirmed by Kelly et al. (2014) reporting the maximum thickness in the Lower Namoi as 140 m.

Given the importance of the alluvium layer in any modelling of propagation of impacts to water-dependent assets, it was considered that improvements could be made to the extent and thickness of the alluvium as shown in the CDM Smith model. The alluvium layer was therefore removed from the CDM Smith model and the extent of the alluvium was determined using the regolith map (Craig, 2013) and the depth to alluvium was determined using the alluvium layer from the Schlumberger groundwater flow model (Schlumberger Water Services, 2012), which is the same as that used by the NSW Department of Primary Industries for water management in the Upper and Lower Namoi alluvium groundwater sources. The alluvium layer was then further divided into two layers for representation in the Namoi BA hydrogeological model. More detail on the alluvium is provided in Section 2.1.3 of this product and in companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018).

2.1.2.2.2 Interburden 1 (Layer 3)

The data points used to build the Interburden 1 layer (the Blythesdale Group and Rolling Downs Group) in the CDM Smith model are limited to a small number of wells between Wee Waa and Narrabri. Given the availability of more recent data, the Assessment team replaced the Blythesdale Group and Rolling Downs Group layers in the CDM Smith model with the Rolling Downs Aquitard layer from the GAB Atlas (Geoscience Australia, Dataset 5) (Ransley et al., 2015) and referred to it as Interburden 1. The thickness and extent of the Interburden 1 layer in the Namoi BA geological model is shown in Figure 10, indicating it is thickening into the Surat Basin to the north and north-west of the Namoi subregion, where it is up to 353 m thick.

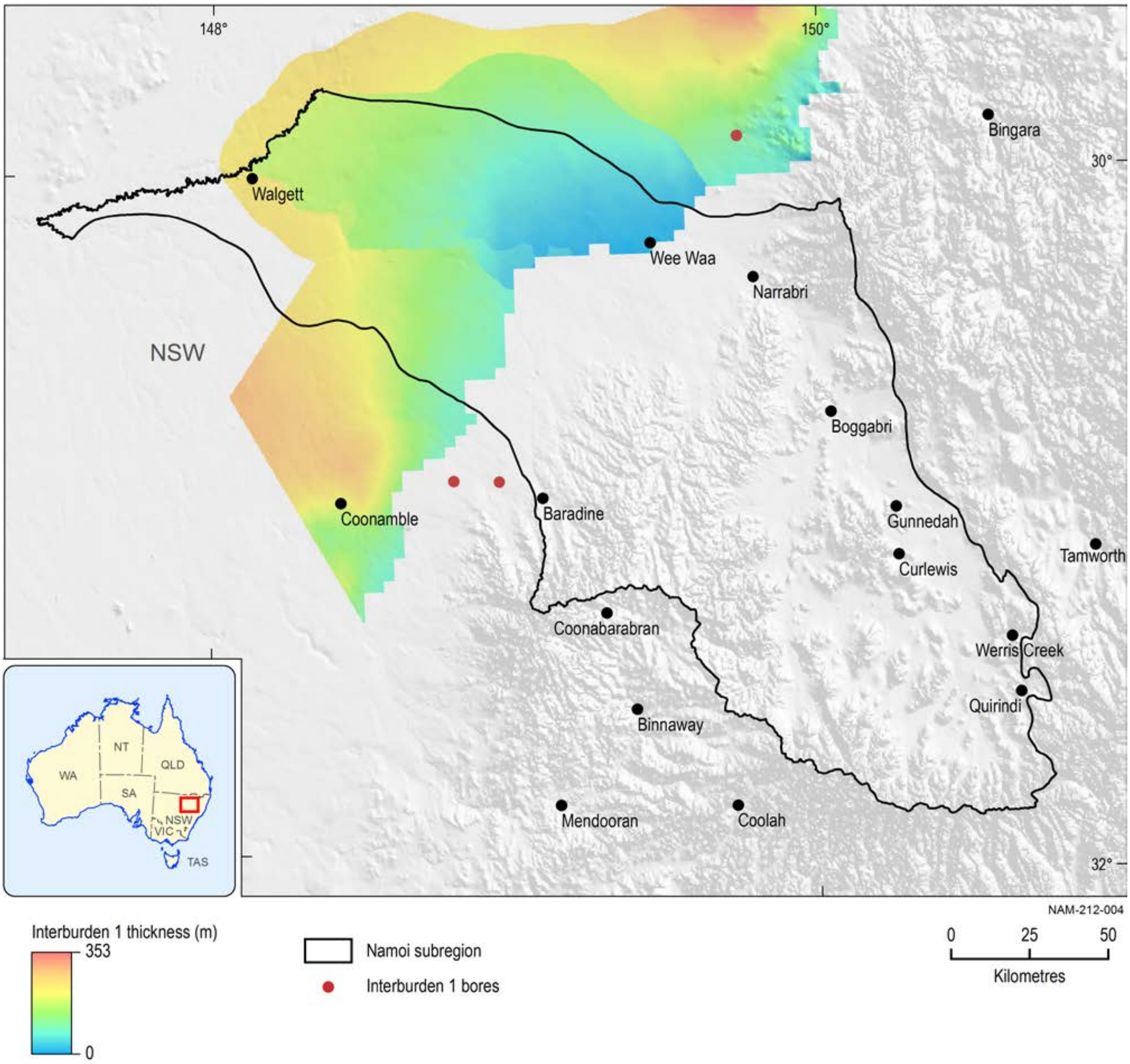

Figure 10 Thickness and extent of the Interburden 1 layer in the Namoi BA geological model

BA = bioregional assessment
Data: Geoscience Australia (Dataset 5)

2.1.2.2.3 Pilliga Sandstone (Layer 4)

The Pilliga Sandstone is widespread in the western part of the Namoi subregion and outcrops extensively along the eastern margin of the Surat Basin. The Pilliga Sandstone thickness in the Namoi subregion varies between 100 and 250 m.

The thickness and location of the outcropping Pilliga Sandstone in the CDM Smith model does not appear to correspond with other sources (e.g. Ransley et al., 2015). Given the availability of more recent data associated with the GAB Atlas (Ransley et al., 2015), the Assessment team replaced the layer for the Pilliga Sandstone in the Surat Basin with the Cadna-owie – Hooray aquifer and equivalents (Geoscience Australia, Dataset 6). The extent and thickness of the Pilliga Sandstone layer is shown in Figure 11, indicating it is up to approximately 800 m to the north and south of the Namoi subregion. The maximum thickness within the Namoi is approximately 400 m.

In the south-east of the subregion the Pilliga Sandstone, and underlying Purlawaugh Formation and Garrawilla Volcanics, identified in surface geology mapping are disconnected from the GAB and this has been referred to as the Oxley Basin or sub-basin (Dulhunty, 1940; O'Neill and Danis, 2013). A groundwater divide demarcates the boundary between the GAB and the adjacent Oxley Basin (Ransley and Smerdon, 2012), indicating the strata identified as GAB units in the south-east of the Namoi subregion are hydrogeologically disconnected from the main GAB strata. This is corroborated by this area being part of the Gunnedah – Oxley Basin Murray Darling Basin Groundwater Source (NSW Office of Water, 2012), not the NSW GAB Groundwater Source. The south-eastern extent of the Pilliga Sandstone in the Oxley Basin was derived from the CDM Smith model (CDM Smith, Dataset 4) and merged with Cadna-owie – Hooray aquifer and equivalents in the Surat Basin (Geoscience Australia, Dataset 6).

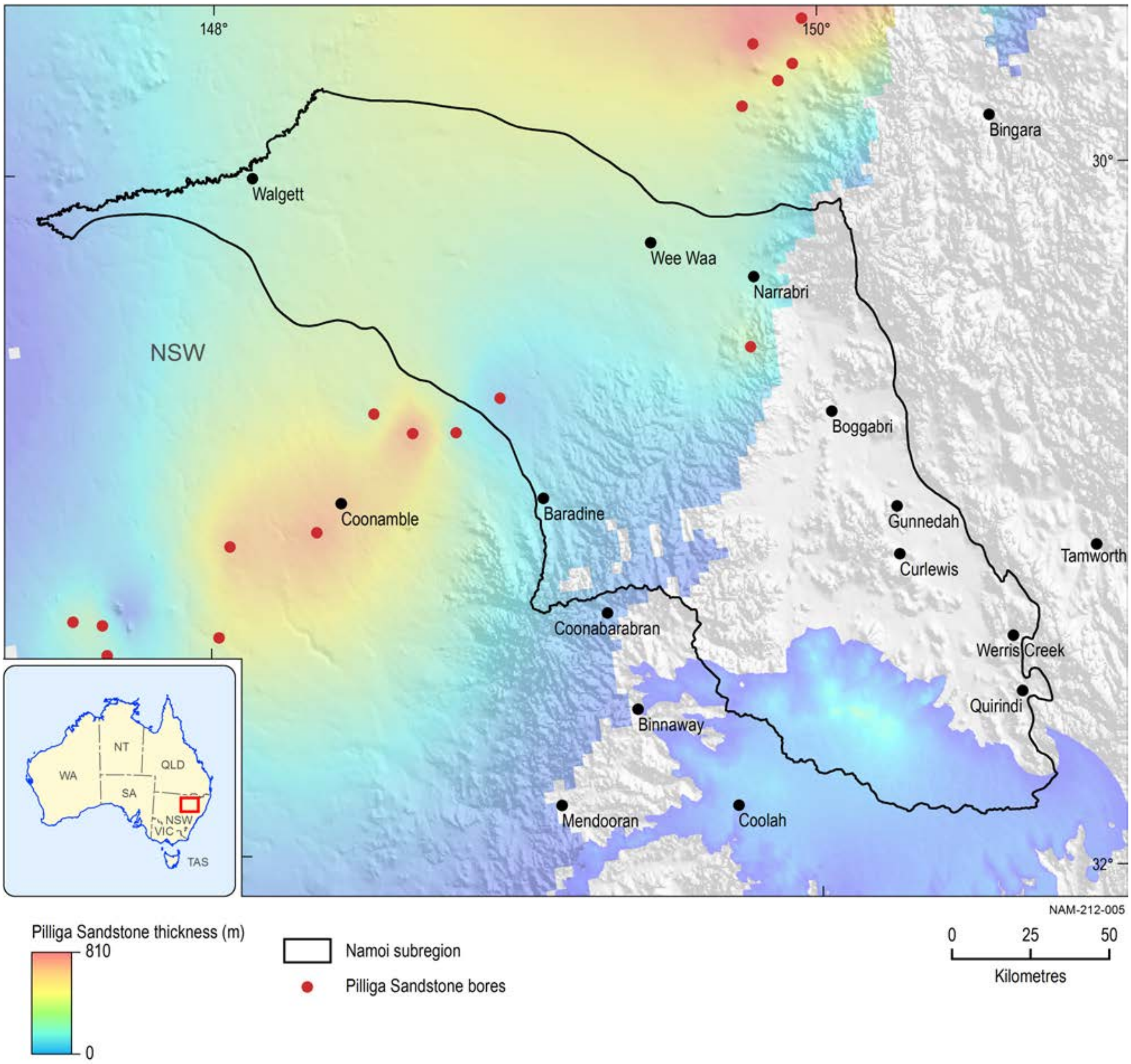

Figure 11 Thickness and extent of the Pilliga Sandstone layer in the Namoi BA geological model

BA = bioregional assessment

Data: CDM Smith (Dataset 4) and Geoscience Australia (Dataset 6)

2.1.2.2.4 Layer 5 (Purlawaugh Formation and Garrawilla Volcanics)

The Purlawaugh Formation and Garrawilla Volcanics are present in the Coonamble Embayment of the Surat Basin and disconformably overlie the Napperby Formation (Tadros, 1993). To the west of the Gunnedah Basin, the Purlawaugh Formation and Garrawilla Volcanics overlie the Lachlan Fold Belt.

The thickness of the Purlawaugh Formation in the Coonamble Embayment is variable, ranging from a presumed maximum of 85 m (Hawke and Cramsie, 1984), thinning to the north and south to about 20 m thick (Radke et al., 2012). However, well completion reports from drill holes near Narrabri indicate the Purlawaugh Formation is significantly thicker than this, up to 190 m (e.g. Bohena 2 (Forcenergy, 1998), Bibblewindi 8 (Eastern Star Gas, 2007), Dewhurst 2 (Eastern Star Gas, 2008)). The western extent of the Purlawaugh Formation is poorly defined because most wells in this part of the Namoi subregion do not penetrate deeper than the base of the Pilliga Sandstone (Hawke and Cramsie, 1984).

The maximum thickness of the Purlawaugh Formation and the Garrawilla Volcanics in the CDM Smith model is approximately 285 m and 485 m, respectively. In some areas, particularly in the south of the subregion, the extent and thickness of the Purlawaugh Formation and Garrawilla Volcanics in the CDM Smith model are not compatible with the surface geology or WCR. Given the availability of more recent data from GABWRA (Smerdon et al., 2012) and the GAB Atlas (Ransley et al., 2015), the Assessment team used this information in the Namoi BA geological model.

The extent and thickness of Layer 5 in the Namoi BA geological model is shown in Figure 12. In the Surat Basin, layer 5 is the combined thickness from the base of the Pilliga Sandstone (Geoscience Australia, Dataset 7) to the base of the Jurassic–Cretaceous sequence (Geoscience Australia, Dataset 8). A regional unconformity at the base of the Purlawaugh Formation in the northern part of the Gunnedah Basin and the Garrawilla Volcanics in the southern and central parts of the Namoi subregion marks the base of the Surat Basin sequence and the top of the Gunnedah Basin sedimentary sequence. This regional unconformity means the base of the Jurassic–Cretaceous sequence is easily identified during drilling. In the western part of the subregion, outside the Gunnedah Basin, the base of layer 5 forms the base of the Namoi BA geological model.

The south-eastern extent of layer 5 in the Oxley Basin was derived from the combined thickness of the Purlawaugh Formation and Garrawilla Volcanics in the CDM Smith model (CDM Smith, Dataset 4).

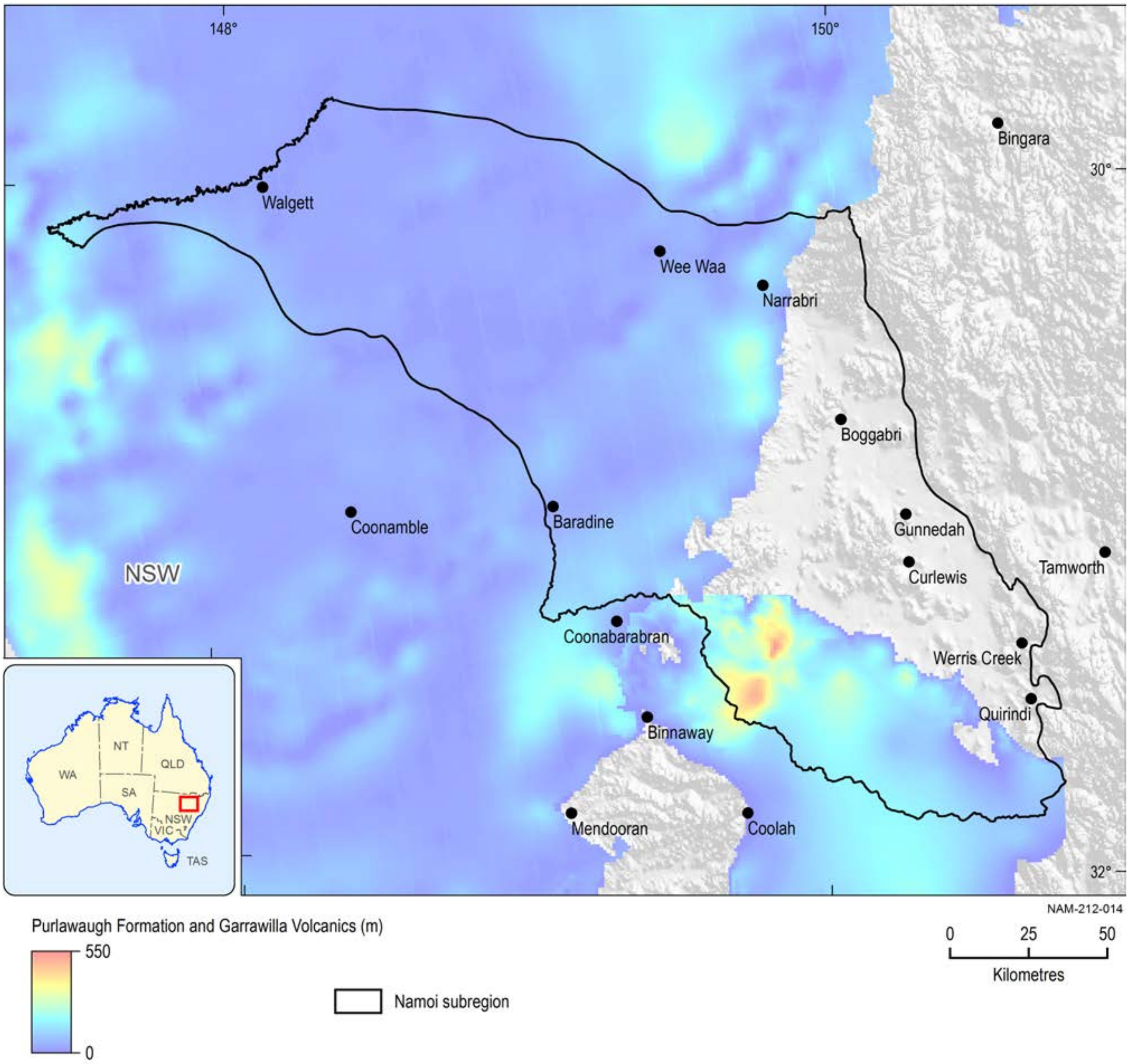

Figure 12 Thickness and extent of Layer 5 in the Namoi BA geological model

BA = bioregional assessment
Data: CDM Smith (Dataset 4), Geoscience Australia (Dataset 7, Dataset 8)

2.1.2.2.5 Interburden 2 (Layer 6)

For consistency with the hydrostratigraphic units in the numerical groundwater model (see companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)) the following layers from the CDM Smith model were amalgamated to create one layer for the Namoi BA geological model, termed Interburden 2:

- Deriah and Napperby formations
- Digby Formation
- Black Jack Group above Coal.

The Deriah Formation overlies the Napperby Formation and is mainly present in the northern part of the Mullaley sub-basin, and to a lesser extent in the south-western and central areas. The

Napperby Formation conformably overlies the Digby Formation and has a relatively wide surface exposure, outcropping in a discontinuous belt extending south from Narrabri to the base of the Liverpool Plains. In the subsurface, the Napperby Formation occurs throughout the Gunnedah Basin, with the exception of the Maules Creek sub-basin (Tadros, 1993; Geological Survey of NSW, 2002). The Digby Formation unconformably overlies the Black Jack Group in the Mullaley sub-basin. Discontinuous outcrops of the Digby Formation extend south from Narrabri to the base of the Liverpool Ranges. In the subsurface, the Digby Formation covers much of the area of the Gunnedah Basin except in the Maules Creek sub-basin (Tadros, 1993). The Black Jack Group above Coal layer in the CDM Smith model is a composite layer of the Nea and Coogal subgroups that lie above the Hoskissons Coal. This layer includes the Clare Sandstone and the Benelabri, Trinkey and Wallala formations.

The thickness and extent of this merged layer is shown in Figure 13. The Interburden 2 layer incorporates the Triassic and Late Permian strata of the Gunnedah Basin above the Hoskissons Coal and includes a range of rock types. Representing multiple Permian and Triassic units in a single layer within the geological model will under-represent the variability within this layer, however, given the regional scale of the model, the relatively coarse model resolution is considered appropriate.

There are thickness errors and modelling artefacts in some of the layers that comprise Interburden 2, and these errors are not consistent between layers or spatially across the region. In some cases, the errors within each unit that makes up Interburden 2 may be additive such that the Interburden 2 layer may be significantly thicker than the data would imply. In other cases, one unit may be thinner than the data indicates and the adjacent unit thicker, resulting in a thickness of Interburden 2 that may represent reality, despite errors in the original layers. These errors will not be consistent or easily discernible. However, the primary purpose of the Namoi BA geological model is to create regional stratigraphic layers that may be translated into the numerical groundwater model. It does not provide the level of lithological information that is represented in local-scale models for smaller areas within the Namoi subregion.

The Interburden 2 layer is intercepted by a large number of wells primarily targeting the Hoskissons Coal. The maximum thickness of the layer is 1038 m at the southern boundary of the subregion (Figure 13). The exaggerated thickness in this area is not likely to impact model outputs as there are no coal resource developments in this area.

There are some inconsistencies between the extent of the strata comprising the Interburden 2 layer in the CDM Smith model and geological mapping (Pratt, 1996, 1998). For example, published geological mapping (Figure 8) shows outcropping Napperby Formation and Deriah Formation in the north-east of the subregion that is not represented in the CDM Smith model and there is a large thickness of Digby Formation in the CDM Smith model to the west of Gunnedah Basin boundary, which is not constrained by any well data. However, given the regional scale of the model and the location of coal resource developments, these discrepancies are not considered to impact model outputs.

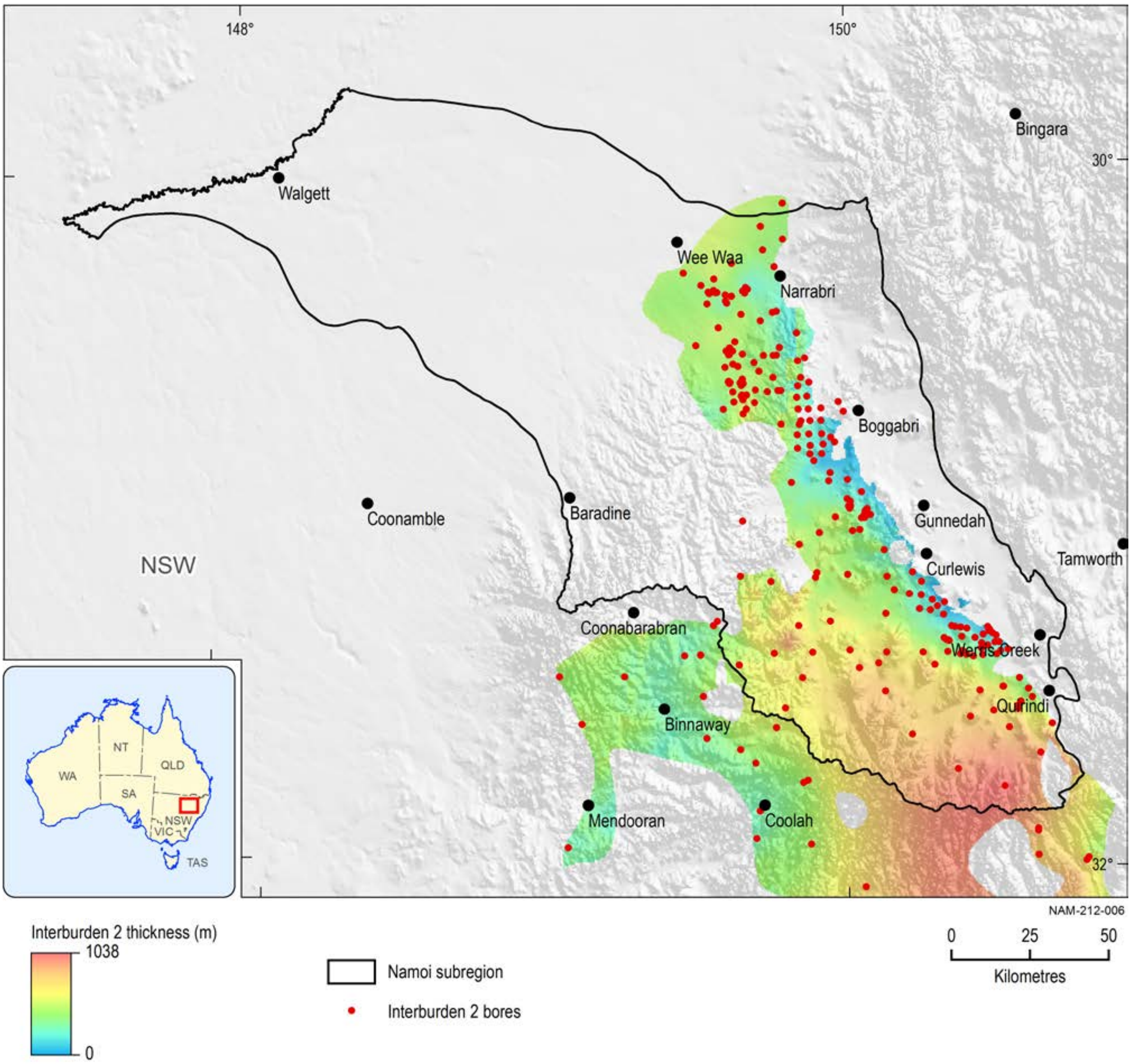

Figure 13 Thickness and extent of the Interburden 2 layer in the Namoi BA geological model

BA = bioregional assessment
Data: CDM Smith (Dataset 4)

2.1.2.2.6 Hoskissons Coal (Layer 7)

The Hoskissons Coal within the Black Jack Group is the major economic seam in the Mullaley sub-basin and extends from Narrabri in the north to beyond the southern boundary of the Namoi subregion (Figure 14). According to Tadros (1993), the thickness of the Hoskissons Coal ranges from less than one metre in the west to up to 13 m in the north and 19 m in the south-east of the Namoi subregion. Maximum recorded thickness of the Hoskissons Coal in the Australian Stratigraphic Units Database is 18 m. The maximum thickness of the Hoskissons Coal layer in the CDM Smith model (within the Namoi subregion) is approximately 130 m, south of Mullaley, however this appears to be due to a single data point being incorrectly interpreted (see Figure 14). There are also areas of significantly thicker Hoskissons Coal to the south-west and west of Narrabri and south-west of Quirindi. The thickness of the Hoskissons Coal in these areas appears to have been incorrectly transcribed from some WCR (e.g. Wilga Park 1 (Hartogen Energy Limited, 1986) and Wilga Park 1, 1C and 2 (Forcenergy, 1999a, 1999b, 1999c)) during geological model development, with the Black Jack Group being picked instead of just the Hoskissons Coal. This results in the Hoskissons Coal layer being thicker than suggested by the publicly available WCR in some areas. Bullseyes are also apparent in the Hoskissons Coal layer thickness map (e.g. south of Mullaley) and other modelling artefacts (e.g. the thicker areas of Hoskissons Coal to the west of Narrabri that does not appear to be constrained by data). To the south-east of the subregion the maximum thickness of the Hoskissons Coal is 354 m. This appears to be a result of a modelling artefact as it is not constrained by data, however given this area is outside the Namoi subregion and not near coal resource developments, this excessive thickness of coal is not considered to be of consequence for the Namoi BA.

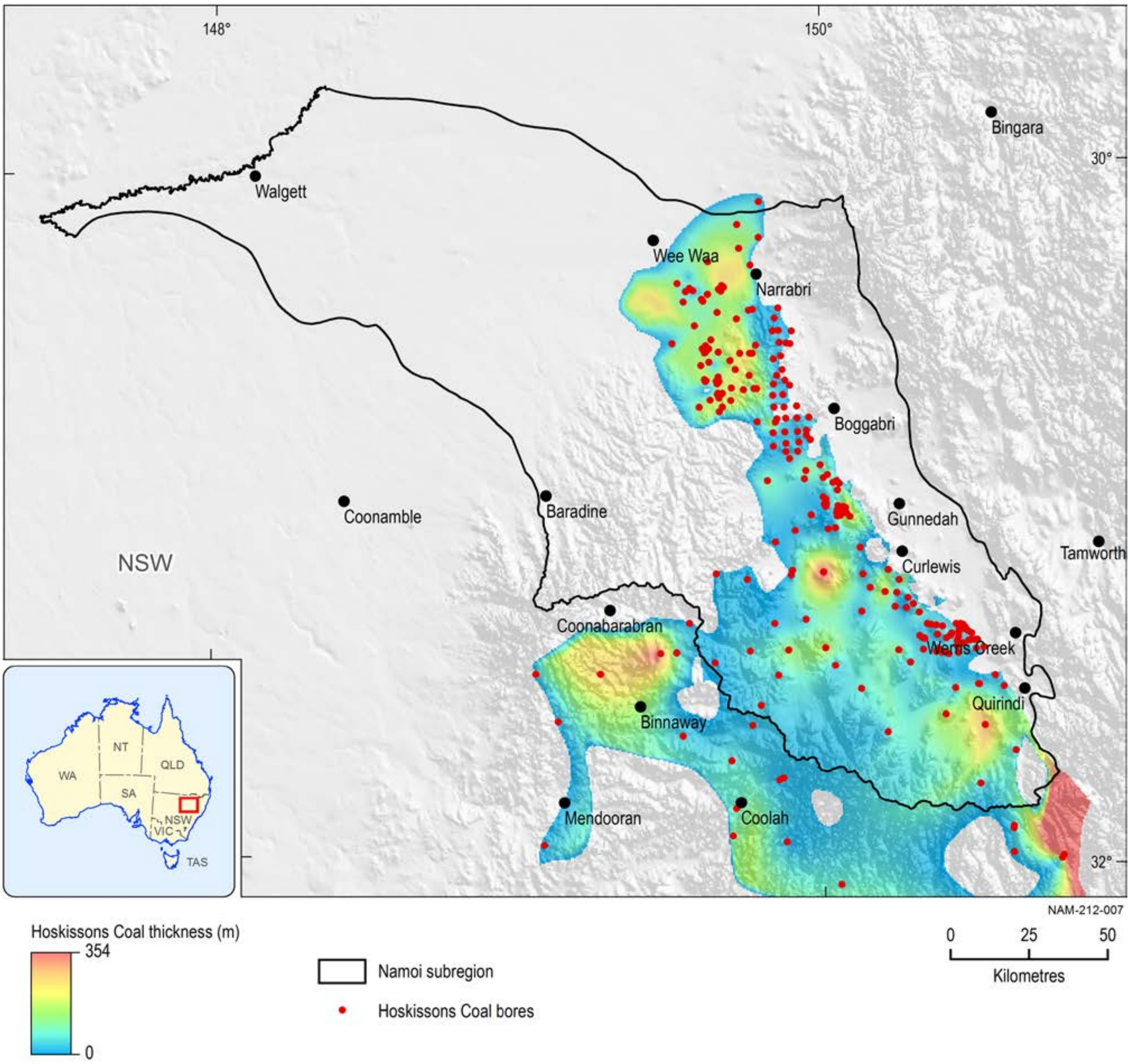

Figure 14 Thickness and extent of the Hoskissons Coal layer in the Namoi BA geological model

BA = bioregional assessment
Data: CDM Smith (Dataset 4)

2.1.2.2.7 Interburden 3 (Layer 8)

The layer described as Interburden 3 in the Namoi BA geological model comprises the Black Jack Group below Coal and the Millie Group layers, as represented in the CDM Smith model. The Black Jack Group below Coal layer in the CDM Smith model comprises the Brothers subgroup, the oldest part of the Black Jack Group. The basal component of the Interburden 3 layer is the Millie Group, which comprises the Porcupine and Watermark formations. The Millie Group is present in the subsurface over much of the Mullaley sub-basin.

The thickness and extent of Interburden 3 is shown in Figure 15 as up to 1026 m thick, with the thickest extent occurring in the south of the subregion. This appears to be an anomalous result in the Black Jack Group above Coal layer in the CDM Smith model and an artefact of model development given this area not constrained by bore data. Along the eastern side of the Mullaley sub-basin the layer is well constrained by bore data.

To the south-west and south of Narrabri, there are areas in the CDM Smith model where the Black Jack Group below Coal layer is either very thin or absent. In some instances, the Black Jack Group below Coal has not been interpreted from the WCR during model development, and instead the entire sequence has been assigned to the Hoskissons Coal, despite many WCR clearly showing the presence of Black Jack Group below Coal (e.g. Dewhurst 5 (Eastern Star Gas, 2008), Strathmore 2 (Eastern Star Gas, 2011) and Wilga Park 2 (Forcenergy, 1999c)). This results in areas where the Black Jack Group below Coal layer is thinner, and the Hoskissons Coal layer is thicker than anticipated.

With the exception of the issue identified above, the geologic interpretation of the Interburden 3 layer is generally sufficiently comparable with WCR and geological mapping (Pratt, 1996, 1998) to suggest the layer is representative of the Black Jack Group below Coal and the Millie Group at a regional scale, especially in the area of coal resource development in the Namoi subregion.

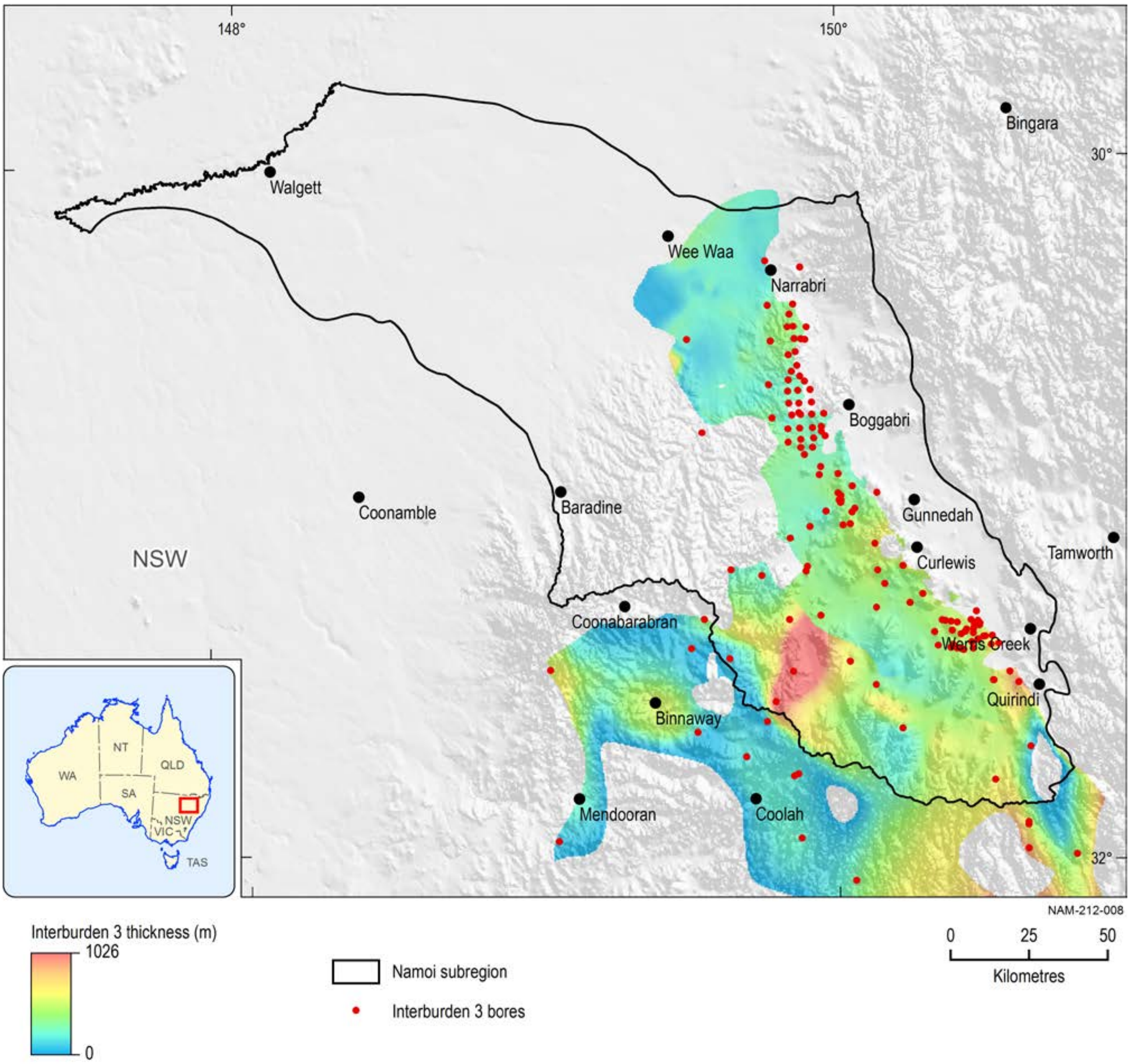

Figure 15 Thickness and extent of the Interburden 3 layer in the Namoi BA geological model

BA = bioregional assessment
Data: CDM Smith (Dataset 4)

2.1.2.2.8 Maules Creek Formation (Layer 9)

The Maules Creek Formation includes several economically important coal seams that are targeted by a number of coal mines, predominantly in the Maules Creek sub-basin adjacent to the Hunter-Mooki Thrust Fault System. The Maules Creek Formation outcrops on the eastern and western sides of the Boggabri Ridge. In the Mullaley sub-basin the Maules Creek Formation outcrops near Gunnedah, and is generally less than 100 m thick. In the Maules Creek sub-basin, the Maules Creek Formation thickens in the east in excess of 800 m (Tadros, 1993; Geological Survey of NSW, 2002).

The Maules Creek Formation layer in the Namoi BA geological model is equivalent to that in the CDM Smith model. The extent of the Maules Creek Formation in the CDM Smith model is in general accordance with surface geology maps (Pratt, 1996, 1998) and geologic intercepts for the Maules Creek Formation in WCR. The extent and thickness in the Mullaley sub-basin is well constrained by data, however less so in the Maules Creek sub-basin (see Figure 16). However, the thickness is consistent with other sources (e.g. Tadros, 1993; Totterdell et al., 2009), so it is considered that the Maules Creek layer is fit for purpose for the Namoi BA geological model.

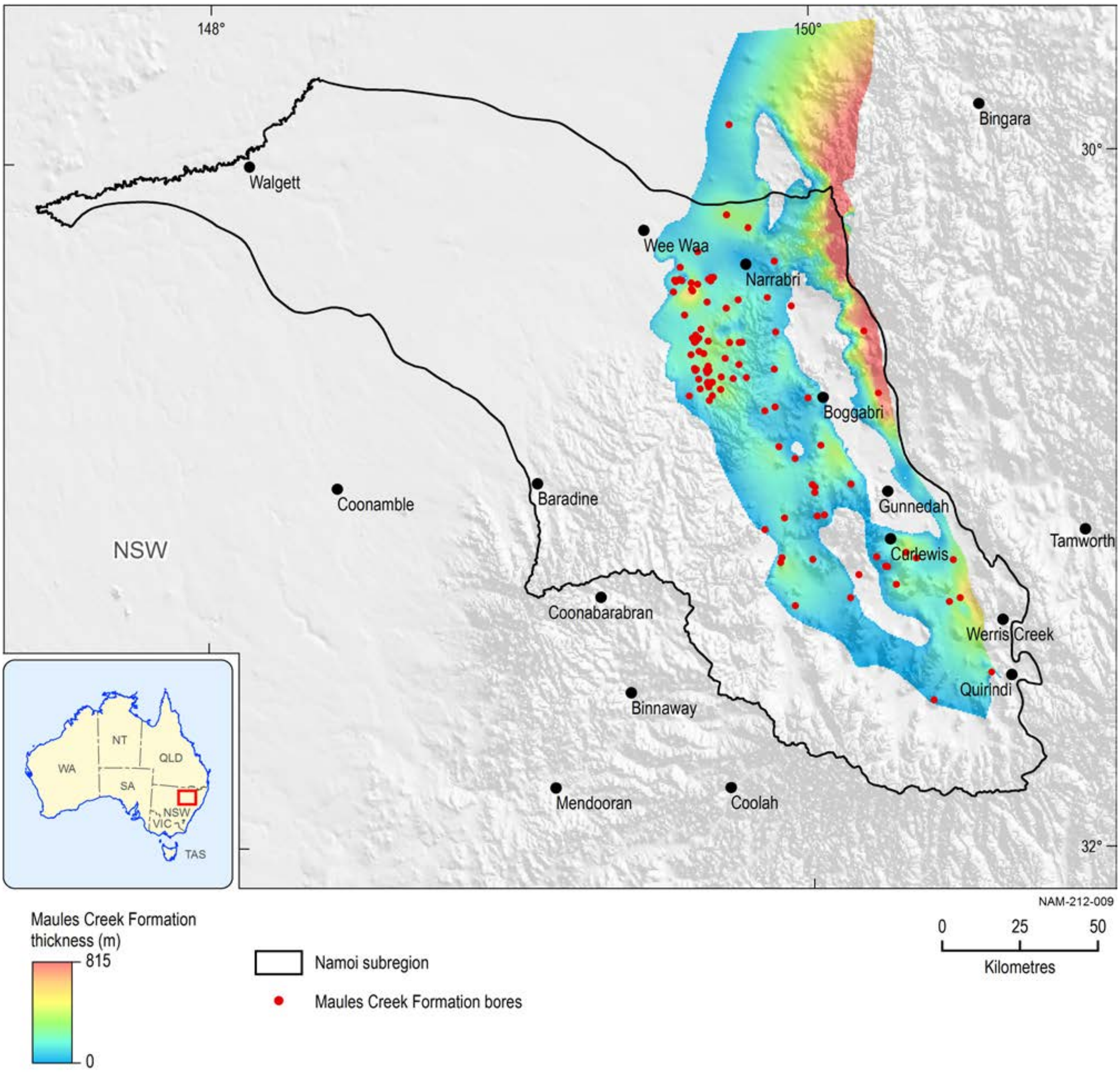

Figure 16 Thickness and extent of the Maules Creek Formation in the Namoi BA geological model

BA = bioregional assessment
Data: CDM Smith (Dataset 4)

2.1.2.2.9 Base of the model

The base of the Namoi BA geological model in the Gunnedah Basin is the upper surface of the Leard-Goonbri Formation, as modelled in the CDM Smith model. Where the Leard-Goonbri Formation is not present, the base of the model is the top of the Boggabri Volcanics and Werrie Basalt. In the west of the subregion the basement comprises the base of the Surat Basin sequence, predominantly the Garrawilla Volcanics.

2.1.2.3 Gaps

This geological model of the Namoi subregion is derived and adapted from pre-existing geological models that cover the Namoi subregion. The geological model is regional scale and therefore has a relatively coarse model resolution. The model was designed to isolate the layers that have important water-dependent assets (the alluvium and the Pilliga Sandstone) and the coal seams that are targeted in the Gunnedah Basin (the Hoskissons coal and Maules Creek Formation), and is considered fit for purpose for the Assessment. However, if the model were to be used for a different purpose, there are a number of geological data gaps that have been identified and would need to be addressed:

- The model does not contain faults and this is a limitation of the model. Depending on fault orientation, type and stress direction, faults can act to compartmentalise groundwater flow or provide a conduit for flow. There are distinct depositional sub-basins (e.g. Maules Creek and Mullaley sub-basins) within the Gunnedah Basin. The depth of these features can be in excess of 1500 m, and this is likely to be associated with faults or folding so a more detailed understanding of structures and inclusion in the model would improve geological modelling.
- There appear to have been some transcription errors between some WCR and the model database, resulting in the Hoskissons Coal in particular, being modelled as thicker than the reports and data indicate. It is recommended that the thickness of the Hoskissons Coal layer be reassessed if this model is to be used for other purposes.
- Access to WCR from other companies operating in the Namoi subregion would greatly improve the accuracy of geological models in the vicinity of coal project areas, particularly in the Maules Creek sub-basin.
- Access to more detailed geological mapping (including structural mapping) and geological models from other companies operating in the Namoi subregion would improve the model.
- The review of the CDM Smith model, which formed the basis of the Gunnedah Basin stratigraphy in the BA model, was limited, and input data to the model was not systematically validated. As the model used some non-open file well information from Santos, not all of the input data are publicly available and could not be verified.
- It is unclear how the tops of formations were picked in some wells. In some cases it appears they have been taken directly from the tabulated stratigraphy in the WCR, and in other cases from an interpretation of the composite logs in the WCR.
- There are some wells in the Namoi subregion that either have limited stratigraphic data, or for which data are not publicly available.
- Where well data is not available, for example in the south of the Namoi subregion, it may be beneficial to use the Phanerozoic OZ SEEBASE™ surface to constrain Gunnedah Basin surfaces.
- A detailed assessment of existing two-dimensional seismic reflection data, and well logs, and further incorporation of data from a variety of sources would improve this model. If available seismic and well log information is considered fit for purpose, it could be used for other purposes such as distribution and variation in lithology, porosity and more detailed structural analysis.

- An integrated geological analysis using regional geophysical datasets, well logs and coal company data is likely to provide further understanding on local-scale structures. A more detailed understanding of structures would improve geological and hydrogeological modelling.

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2.1.3 Hydrogeology and groundwater quality

Summary

This section provides a hydrogeological assessment of the input datasets for the Namoi subregion numerical groundwater model.

There are a large amount of observed groundwater level data that have been collected in recent decades for water resources management. This data collection is focused on the alluvium where the water resources are; there are little observational data outside of the alluvium such as in the Permian formations that host the coal resource.

The focus of data collection of hydraulic properties has been the hydraulic conductivity. The hydraulic conductivities of the coal-bearing formations and interburden have a decreasing trend with increasing depth, and also a zone of enhanced hydraulic conductivity near the surface due to weathering. These relationships have been incorporated into the numerical groundwater model. There is no evidence of a depth-dependent relationship for the hydraulic properties in the Pilliga Sandstone, therefore the groundwater model will not have a depth dependence for the hydraulic properties for the Pilliga Sandstone.

The observed trends in groundwater level at nested piezometers have been used to infer the vertical connectivity in the alluvium. Zones in the alluvium that are well connected have been identified by similar trends occuring in groundwater level at multiple depths. Similarly zones that are poorly connected have been identified where the trends in water levels at multiple depths are different. This analysis of the connection of the alluvium is used in the groundwater model to inform the ratio of the vertical hydraulic conductivity to the horizontal hydraulic conductivity of the alluvium.

The recharge due to rainfall for the groundwater model domain has been determined using the chloride mass balance technique and upscaled using surface geology and mean annual rainfall as covariates.

This section provides a hydrogeological assessment for the Namoi subregion. It informs the conceptualisation that underpins the numerical groundwater model that is used for assessing the groundwater impacts of additional coal resource development in the Namoi subregion. Relevant hydrogeological datasets sourced from the NSW state agencies and groundwater models developed for the Namoi river basin in previous studies were used for this purpose. The Namoi subregion consists of two major aquifer systems: the Namoi Alluvial aquifer (Upper and Lower Namoi) and the Pilliga Sandstone aquifer. The most widely used aquifer in the Namoi subregion is the Namoi alluvium comprising the Quaternary Narrabri and Gunnedah formations. These units contain significant resources of high quality groundwater that is heavily utilised for irrigation, water supply and stock and domestic use. Pilliga Sandstone is a part of the Surat Basin and is a major regional aquifer consisting of medium- to coarse-grained sandstone and conglomerate with minor interbeds of fine-grained sediments.

Hydrogeological data, including aquifers, water levels and hydraulic properties, are required to inform groundwater modelling. In addition, estimates of the extraction of groundwater for use are needed. The hydrogeologic data used in the bioregional assessment (BA) of the Namoi subregion are detailed in Section 2.1.3.1.

2.1.3.1 Observed data

2.1.3.1.1 Groundwater level data

There is an extensive network of monitoring bores in the Namoi subregion that are used for managing the water resources of the subregion. Over the historical period (1983–2012) there were 2934 bores with at least one observation of the groundwater level with over 800,000 total data points. The vast majority of these bores are located in the alluvium where the water resources are being utilised (Figure 17a).

However, the majority of these bores have a low reliability in their coordinates and elevation as recorded in the NGIS dataset (NSW Office of Water, Dataset 1). If the location is estimated from a map, the elevation then read from a digital elevation model (DEM) and the top of casing not measured above ground level then there are three forms of error in the estimate of the groundwater level that could cumulatively add up to over 10 m. In other BA regions (refer to Cui et al. (2016) and Herron et al. (2018b) for groundwater numerical modelling in the Clarence-Moreton bioregion and Hunter subregion respectively) the criterion used for including the bore in observations has been that the observation bore must have either the location or elevation located via surveying or GPS. When this criterion is used in the Namoi subregion there are only 170 observation bores remaining (Figure 17b) (and 33 of these lack a depth attribute). The observation in these bores are used for evaluating the objective function and constrain the model predictions.

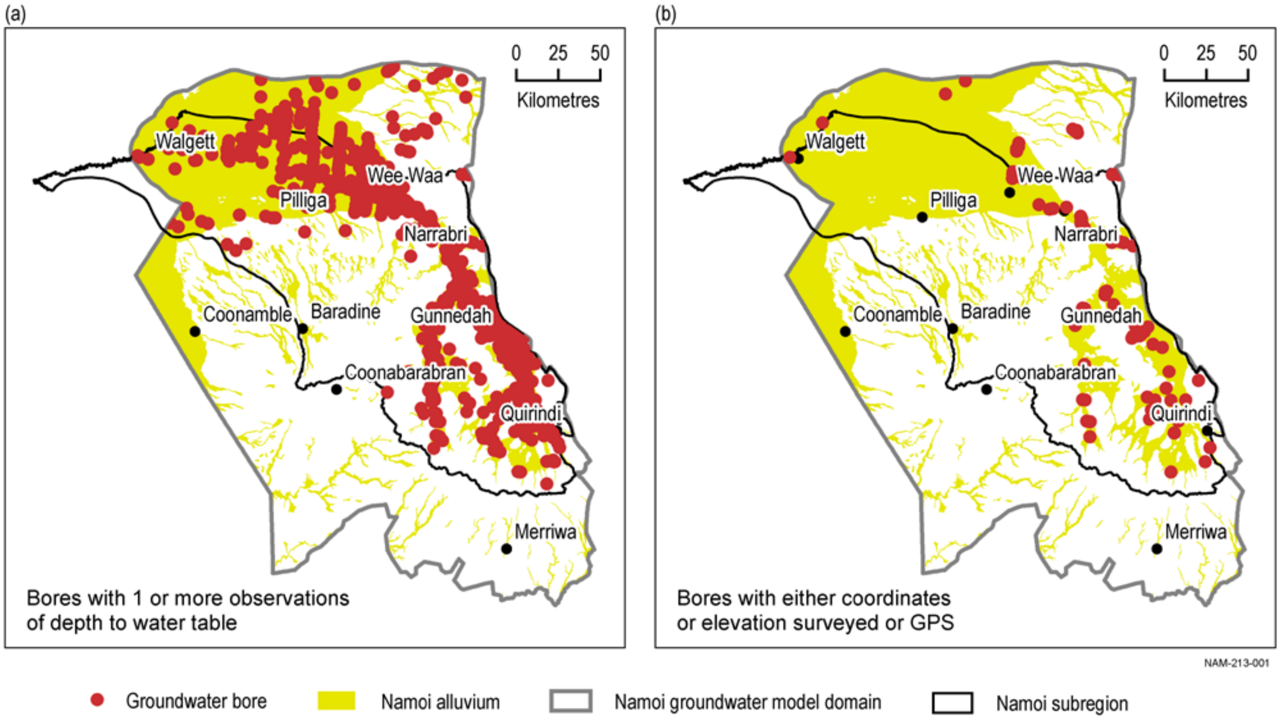

Figure 17 Observation bores within the Namoi subregion also showing the model domain and the alluvium extent

Data: Bioregional Assessment Programme (Dataset 2)

2.1.3.1.2 Hydraulic conductivity data

Each of the coal development proponents has undertaken field investigations into the hydraulic properties of the materials at their site (AGE Pty Ltd, 2010, 2011; Aquaterra, 2009; Douglas Partners, 2010; GeoTerra, 2008; GES, 2012; GHD, 2007; Heritage Computing, 2012; RCA Australia, 2004, 2007, 2010; RPS Aquaterra, 2011; Sigra, 2006). The hydraulic conductivity data has been generated using a variety of methods including core testing, drill stem tests, packer tests, slug tests and pump tests. Other sources of data that have been collated are a study investigating the properties of the aquitards in the region using core data (Esteban et al., 2016) and the pump tests conducted by the NSW Office of Water (now DPI Water) (DPI, 2010). There are 463 measurements of hydraulic conductivity that have been collated and are detailed in Bioregional Assessment Programme (Dataset 2).

These data have been collated by the hydrostratigraphic layer that is used in the numerical groundwater model (in companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)). The numerical groundwater model isolates the layers that have important water-dependent assets (alluvium and Pilliga Sandstone) and significant stresses imposed through coal development (Hoskissions Coal and Maules Creek Formation). All other geological formations have been lumped into interburden layers. The hydrostratigaphic layers used in the numerical groundwater model and some examples of the geological formations that they represent are shown in Table 5.

Table 5 Hydrostratigraphic layers used in the numerical groundwater model and some examples of the geological formations that these layers represent

These are examples and not a complete list

Numerical model layer	Geological units
Alluvium 1	Narrabri Formation
Alluvium 2	Gunnedah Formation Cubbaroo Formation
Interburden 1	Rolling Downs Group Liverpool Range Volcanics Warrumbungle Volcanics
Pilliga Sandstone	Pilliga Sandstone
Interburden 2	Purlawaugh Formation Garrawilla Volcanics Napperby and Deriah formations Black Jack Group – Coogal and Nea subgroup
Hoskissions Coal	Hoskissons Coal
Interburden 3	Black Jack Group – Brothers subgroup Watermark Formation Millie Group
Maules Creek Formation	Maules Creek Formation
Basement	Boggabri Volcanics

The measured hydraulic conductivity data have been plotted against depth for the hydrostratigraphic layers used in the numerical modelling (Figure 18). It has been shown in other regions that hydraulic conductivity decreases with depth (Peeters et al., 2018; Herron et al., 2018b). This is also true for the Namoi subregion where the coal-bearing formations of Hoskissons Coal and Maules Creek Formation and also the interburden layers 2 and 3 show similar depth-dependant relationships. The alluvium and Pilliga Sandstone do not appear to have a depth-dependent relationship and there are insufficient data to assess whether a relationship between depth and hydraulic conductivity exists for the basement and Interburden 1.

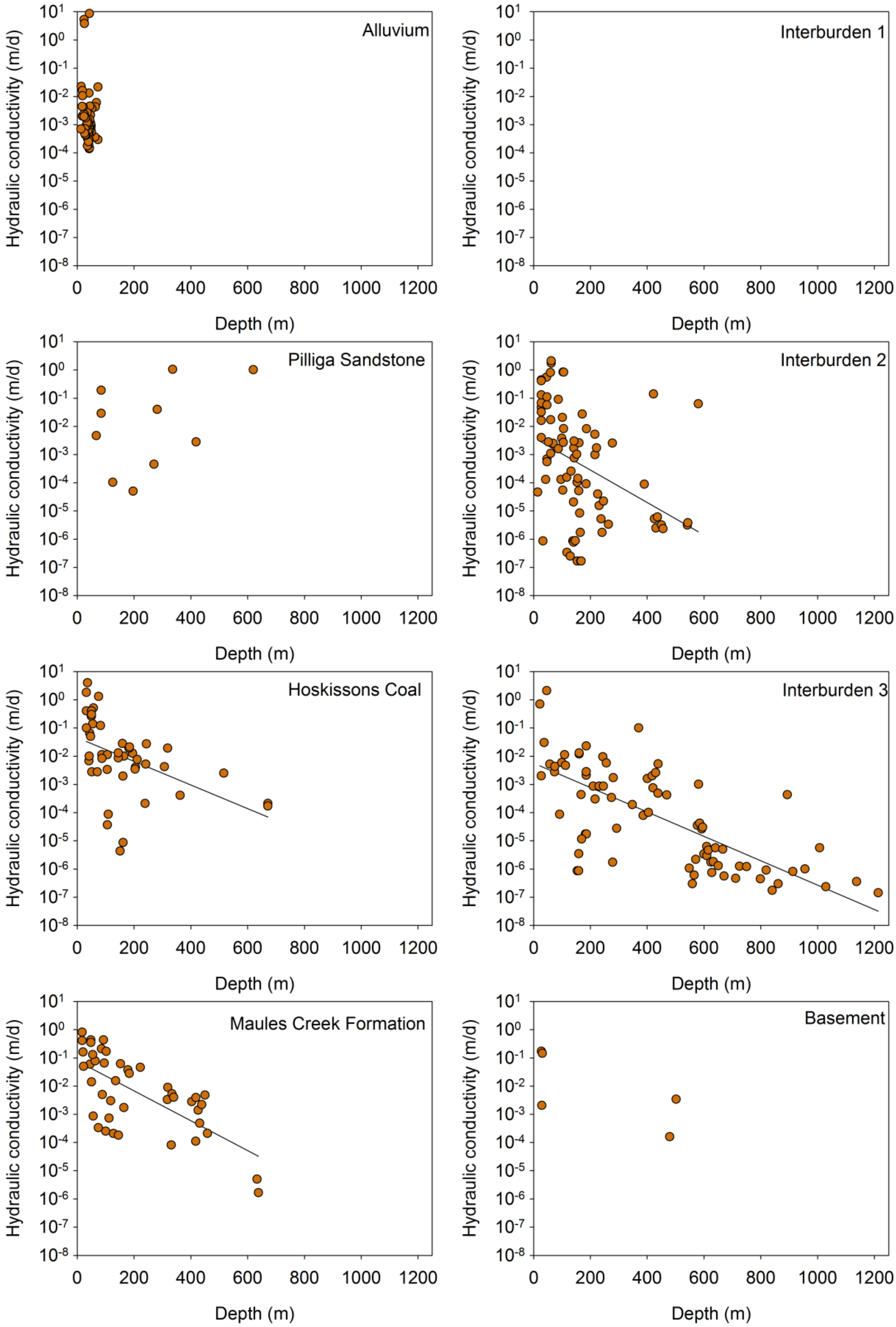

Figure 18 Hydraulic conductivity data from field measurements in the Namoi subregion for each hydrostratigraphic layer used in the Namoi groundwater model

The lines on this plot are a linear regression line through all the data points for illustrative purposes only, it is not used anywhere. Where the line is present it is statistically significant ($p<0.05$), where there is no line present then the line of best fit was not statistically significant.
Data: Bioregional Assessment Programme (Dataset 3)

The relationships with depth for the hydraulic conductivity in the Hoskissons Coal and Maules Creek formations appear to be from the same population, and similarly the Interburden 2 and Interburden 3 layers appear to be from the same population (Figure 18). To simplify the analysis, the datasets for the coal-bearing formations have been grouped together and the interburden layers have been combined with the basement (Figure 19); this shows that the coal-bearing formations generally have a hydraulic conductivity an order of magnitude greater than the interburden for a given depth. The Pilliga Sandstone does not have a depth dependant hydraulic conductivity function implemented in the numerical groundwater model and the alluvium has a uniform hydraulic conductivity for each of its two layers (see Janardhanan et al. (2018) for more details).

The magnitude of the measured hydraulic conductivity also appears to have a dependency on the scale of measurement. The core tests, being the smallest scale, have smaller hydraulic conductivity than the pump test which is at a larger scale (Figure 19). This is the expected result based on other studies (Rovey and Cherkauer, 1995).

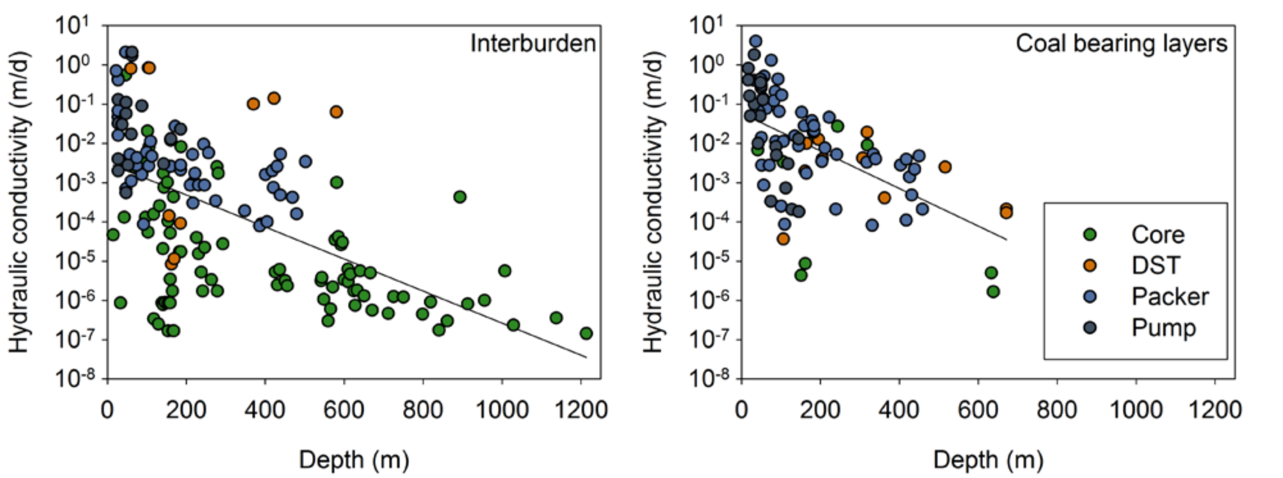

Figure 19 Field measurements of hydraulic conductivity aggregated to coal bearing layers and interburden and separated by measurement technique for the Namoi groundwater model

The lines on this plot are a linear regression line through all the data points for illustrative purposes only, it is not used anywhere.
DST = Drill stem test
Data: Bioregional Assessment Programme (Dataset 3)

The hydraulic properties used in previous numerical groundwater modelling in the Namoi subregion have been collated and aggregated into the hydrostratigraphic layers that are used in the BA model (refer to companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)). The previous models reviewed for their hydraulic properties were the regional-scale models of the Namoi Catchment Water Study (SWS, 2012) and the Gunnedah Basin Regional Model (CDM Smith, 2014) as well as the smaller models for mine environmental impact statements (EISs) (AGE Pty Ltd, 2010, 2011, 2013; Aquaterra, 2009; Douglas Partners, 2010; GeoTerra, 2008; Heritage Computing, 2012, 2013; Hydro Simulations, 2014, 2015; RCA Australia, 2010). These models have used a wide range in hydraulic properties and there is little consistency between them (Figure 20). There are several inferences that can be extracted from this previous modelling:

- The alluvium has the highest median hydraulic conductivity, specific storage and specific yield. This is expected as it is the only unconsolidated layer within the model domain.
- Pilliga Sandstone also has relatively high hydraulic conductivity, specific storage and specific yield. This is expected as it is a productive aquifer.
- The median of the hydraulic conductivities of the coal-bearing formations is higher than the interburden, although the range in both is quite large.
- Some models (Heritage Computing, 2012, 2013; AGE Pty Ltd, 2011, 2013) have been developed using a weathered zone near the surface for some layers that have a higher conductivity and storage than the unweathered properties of that layer.

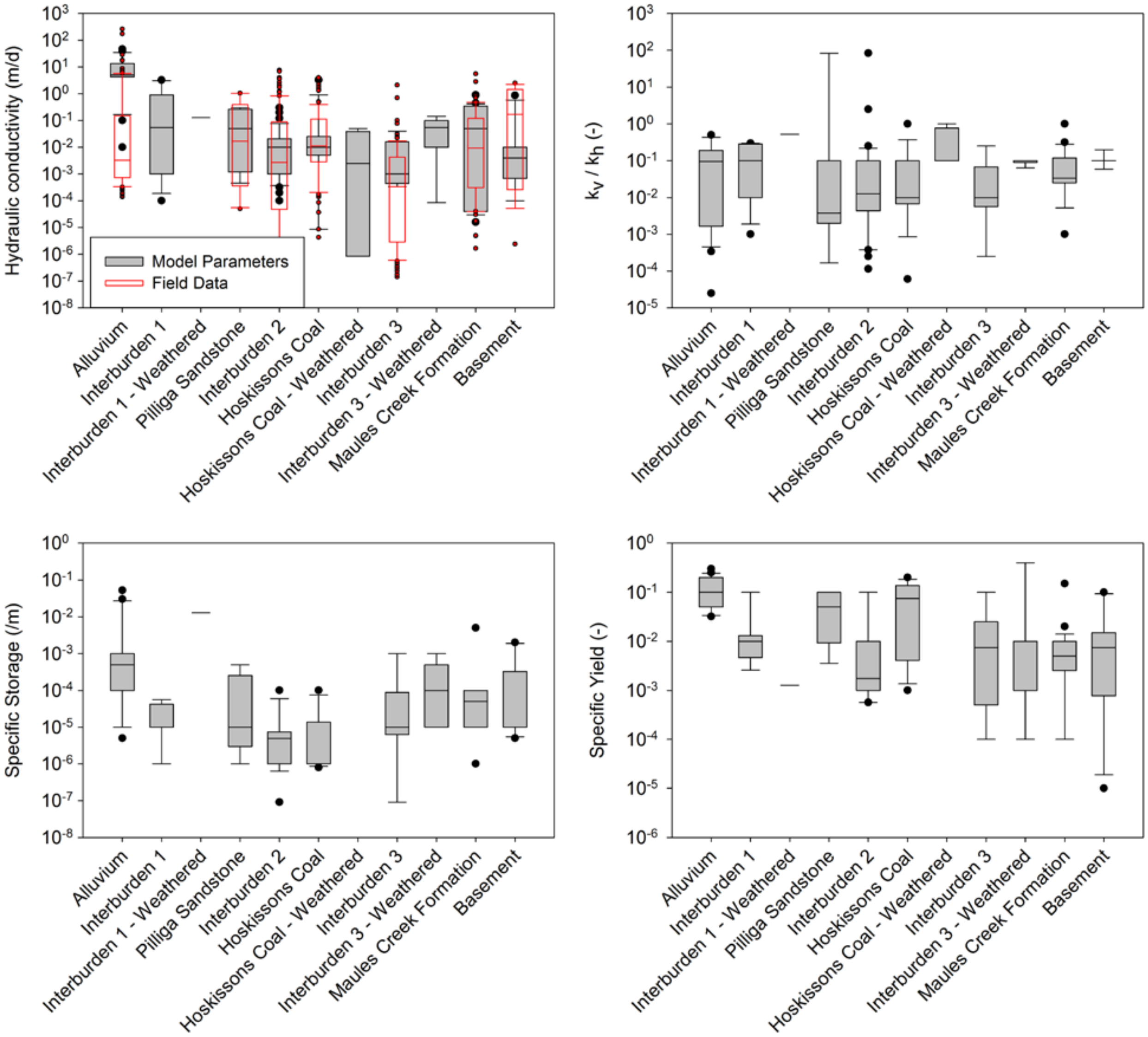

Figure 20 Range of hydraulic parameters used in each hydrostratigraphic layer in previous models in the Namoi subregion

The box contains the interquartile range of the data, the line in the centre of the box is the median, the whiskers contain 95% of the data and the dots are those points that lie outside 95% of the data.
Data: Bioregional Assessment Programme (Dataset 3)

Based on the observed measurements and the previous modelling studies, the following hydraulic properties are used in the current modelling:

- The alluvium has been split into two layers with Alluvium 1 (Narrabri Formation) having lower hydraulic conductivity than Alluvium 2 (Gunnedah and Cubbaroo Formation). The hydraulic properties of the alluvium do not have a dependence on depth.
- The Pilliga Sandstone will use a single parameter range as there is no evidence of a depth dependence in the little observation data that are available.
- The coal-bearing formations (Hoskissons Coal and Maules Creek Formation) have similar hydraulic properties and so will use the same parameter distributions. There is a depth dependence on the hydraulic conductivity and also a zone of enhanced hydraulic conductivity due to weathering near the surface.
- Interburden 2 and Interburden 3 have similar hydraulic properties and so will use the same parameter distributions. There is a depth dependence on the hydraulic conductivity and also a zone of enhanced hydraulic conductivity due to weathering near the surface. Due to a lack of measured data and a lack of differentiation in the previous modelling efforts, the Interburden 1 and Basement hydraulic properties are also drawn from the same parameter space as Interburden 2 and Interburden 3.

The depth dependence of the interburden layers and coal-bearing formation is modelled as an exponential decay (given the linear fit through log-transformed data) with depth, with an enhancement due to weathering in the top 100 m for hydraulic conductivity. For the hydraulic conductivity the model fitted is:

$$k(d) = (1 + 10^{we} * EXP(-0.06 * we^{0.5} * d)) * (k0 * EXP(-\alpha_k * d)) \tag{1}$$

where *k(d)* is the hydraulic conductivity (*k*, m/day) at a certain depth *d*, (m), *we* is the enhancement due to weathering (orders of magnitude), *k0* is the hydraulic conductivity of fresh material at the surface and α_k is the decay constant. The green line in Figure 21 is a least squares fit of the measured hydraulic conductivity data (red dots) for the interburden and coal-bearing layers. The black lines are 64 random realisations of the parameter space that is used in the sensitivity analysis (described in companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)). (The green line fitted to the interburden in Figure 21 sits toward the lower half of the parameter space used as the many core samples give a low bias to the hydraulic conductivity data).

The depth dependence of the specific storage is modelled as:

$$S_S(d) = S_S0 * EXP(-\alpha_S * d) \tag{2}$$

where $S_S(d)$ is the specific storage (S_S, m^{-1}) at a certain depth (*d*, m), S_S0 is the specific storage at the surface and αS is the decay constant. The black lines in Figure 21 are 64 random realisations of the parameter space that is used in the sensitivity analysis (described in companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)).

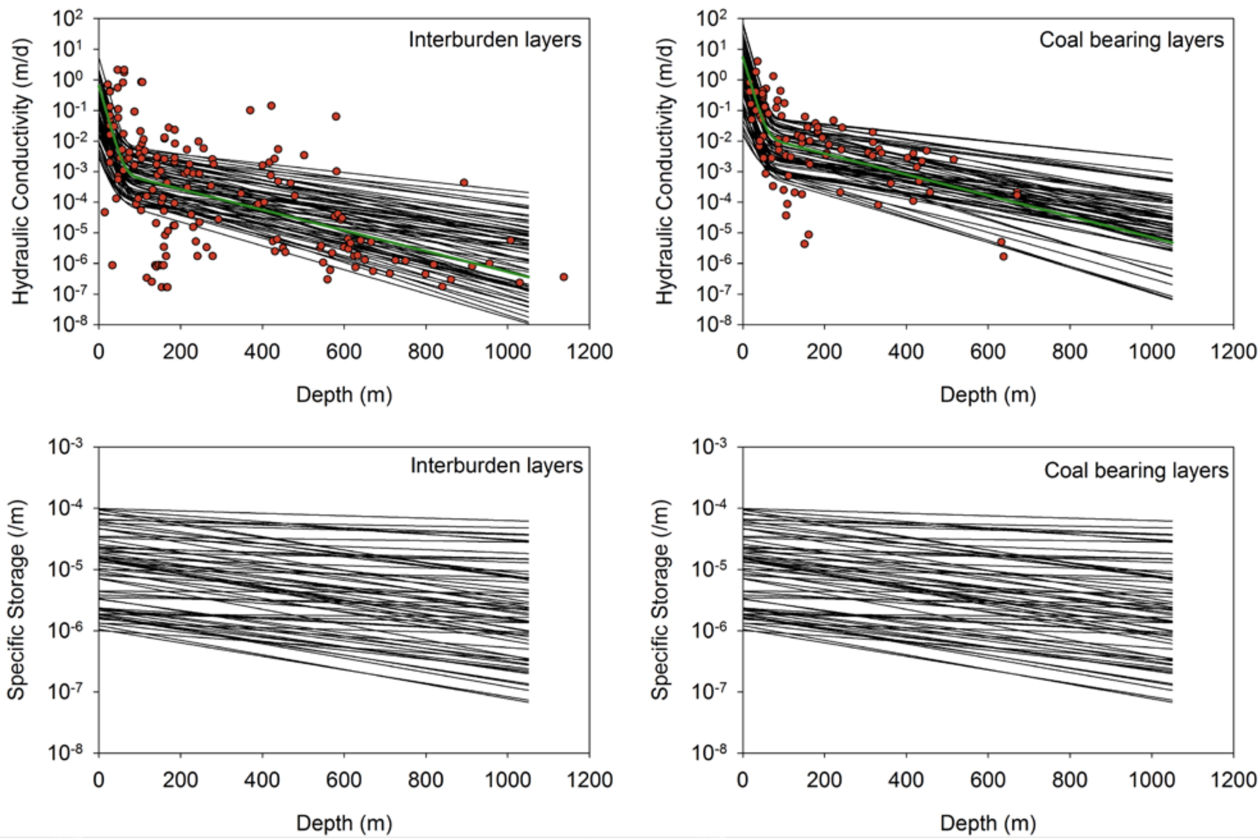

Figure 21 Parameter space explored in the numerical modelling for the hydraulic conductivity and specific storage for the interburden and coal layers

Red dots are measured hydraulic conductivities, the green line is a line of best fit through the measured data and the black lines are selection of parameter sets used in the modelling, each model run get its own black line.
Data: Bioregional Assessment Programme (Dataset 3)

2.1.3.1.3 Alluvium connectivity

The Namoi alluvium has historically been interpreted as a three layer system in the Lower Namoi and a two layer system in the Upper Namoi. The upper layer (Narrabri Formation) has been assumed a fine-textured low-conductivity layer whereas the lower layer (Gunnedah Formation) is a predominantly sandy productive aquifer, and the paleovalley fill in the Lower Namoi (Cubbaroo Formation) is coarse textured sands and gravels (CSIRO, 2007). More recently it has been demonstrated that this is a gross simplification and that the valley fill sediments are representative of a distributive fluvial system and are an upward-fining sequence in response to a drying climate (Acworth et al., 2015; Kelly et al., 2014).

Giambastiani et al. (2009) and Blakers et al. (2011) have demonstrated that the trends in groundwater levels in nested piezometers can be used to establish vertical connectivity in the Namoi alluvium. As the groundwater model developed for BA (in companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)) is using a simplified two layer alluvium, an analysis of the water level trends will enable the spatial variability in the vertical hydraulic conductivity between these two layers to be data-driven rather than uniform across the aquifer.

All of the groundwater level data from the nested piezometers in the Namoi alluvium have been extracted from the National Groundwater Information System (NSW Office of Water, Dataset 1) for the historical period used in BA (start of 1983 to end of 2012). This has resulted in 347 nested piezometer sites with between two and six piezometers. For each piezometer the linear trend in the groundwater levels has been calculated for this 30-year period and the maximum difference in the slope of the trend line between piezometers in the same nest has been recorded.

There is an assumption here that if the aquifer is well connected then there will be little difference in water level trend over this 30-year period, if there are significant differences in the water level trends at a nested site then it is assumed that the aquifer is poorly connected vertically. This is a simplistic analysis as it does not incorporate the stresses on the system (e.g. extraction for irrigation). A high, short-term stress may cause a difference in water level in a well connected nest of piezometers; by using the water level trends over 30 years the short-term impacts should be avoided. What cannot be avoided is that if there is no stress on the system then there is likely to be no difference in water levels even in a poorly connected aquifer.

These point data have been kriged to the alluvium boundary to create a spatial layer of the difference in groundwater level trends within the alluvium and this has been used to infer aquifer connectivity (Figure 22). Where the maximum difference in the groundwater level trend is low (<0.01 m/year) the aquifer is well connected; where the maximum difference in the groundwater level trend is high (>0.1 m/year) the aquifer is poorly connected.

These differences in the groundwater level trends are related to the k_v/k_h ratio that is used in layer 1 of the groundwater model (see companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018) for more details).

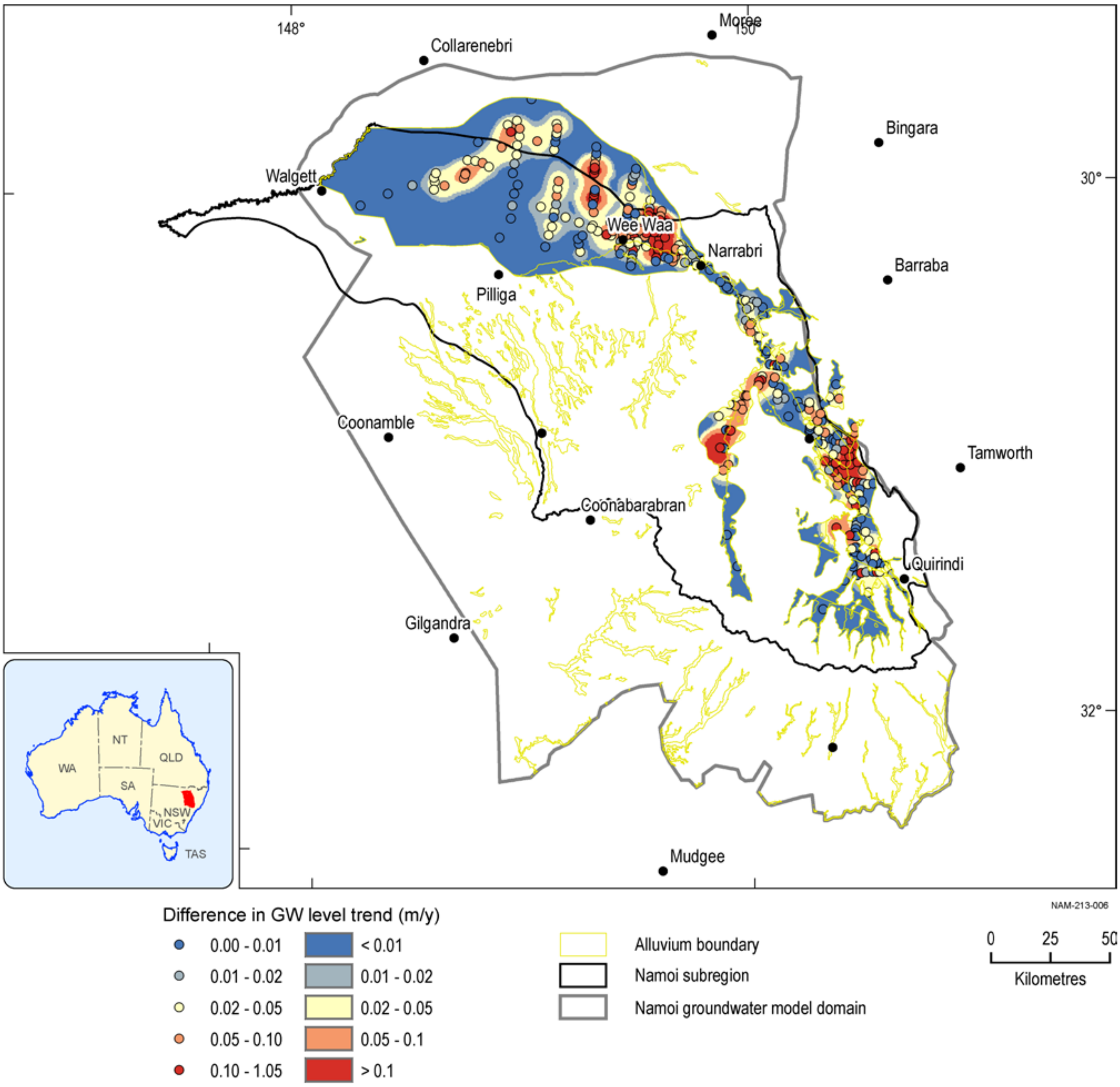

Figure 22 Vertical connectivity of Namoi alluvium used in the Namoi groundwater model

Data: Bioregional Assessment Programme (Dataset 4)

2.1.3.1.4 Dryland diffuse recharge

Groundwater recharge from rainfall is a crucial input into numerical groundwater models. As there have not been previous estimates of recharge in the Namoi subregion at a scale suitable for the BA numerical modelling, a gridded recharge surface has been generated for the Namoi subregion using the chloride mass balance method (Anderson, 1945). This simple and cost-effective method for estimating recharge is the most commonly used method in Australia due to the availability of data to support it (Crosbie et al., 2010).

The assumptions that underpin the chloride mass balance method are summarised (Wood, 1999):

- Chloride in groundwater is only sourced from rainfall (not rock weathering or interactions with streams or deeper aquifers).
- Chloride is conservative in the system (no geological sources or sinks).
- The chloride flux does not change over time (steady-state conditions).
- There is no recycling of chloride in the system (e.g. due to irrigation drainage).

If these assumptions are met, then recharge can be estimated as follows:

$$R = \frac{100\ D}{[Cl^{-}]_{gw}} \quad (3)$$

where recharge (R) is in mm/year, chloride deposition (D) is in kg/ha/year and the chloride concentration of groundwater $[Cl^{-}]_{gw}$ is in mg/L.

As the Namoi model domain is larger than the Namoi subregion and contains parts of the Hunter, Central West and Gwydir subregions (see companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)), the recharge for the Namoi subregion was estimated together with these other regions. The area assessed here contains the outcropping area of the geological Gunnedah Basin, the geological Sydney Basin and a part of the geological Surat Basin.

The chloride deposition over the area of interest was extracted from the national dataset at a resolution of 0.05° (Leaney et al., 2011) (CSIRO, Dataset 5). This dataset was created from 297 field measurements of chloride deposition at point locations and then fitted to the model of Keywood et al. (1997). Figure 23a shows chloride deposition to be much greater near the coast compared to inland areas, which is due to decreasing concentrations of atmospheric salts as distance from the sea increases.

The chloride concentrations of groundwater were obtained from data collected by NSW Office of Water (now DPI Water) (NSW Office of Water, Dataset 6). There are 4786 points covering several decades of chloride data in the area of interest (Figure 23a). A borehole may have one or more observations; where there were multiple observations for a borehole, the geometric mean was used to characterise the chloride concentration, otherwise the isolated value was used. At each location, the chloride data were assigned to a stratigraphic layer based on mapped surface geology (Geoscience Australia, Dataset 8) where better data did not exist. In most cases it was assumed that the bores were completed into the stratigraphic layer representing the surface geology; there were only a few where the information existed to show otherwise (e.g. bores drilled through the Rollings Downs Group to sample the Pilliga Sandstone).

In alluvial areas, the chloride signal reflects not only a contribution from rainfall, but also from streams and upward flow from deeper aquifers, this is illustrated in detail by Raiber et al. (2016) in the Clarence-Moreton bioregion. Consequently, the first assumption of the chloride mass balance method is not met and 3235 data points from alluvial areas were excluded from the analysis. The remaining 1551 measurements of groundwater chloride concentration were used to calculate point estimates of recharge. Figure 23b shows the spatial distribution of these 1551 data points.

They are not uniformly distributed across the area of interest with better spatial coverage of recharge estimates in the Upper Namoi.

The second assumption in the chloride mass balance methodology is that the chloride is conservative in the system. In areas without halite deposits it is generally assumed that there are no geological sources of chloride and the trace amounts of vegetation uptake are recycled to the systems as leaves decay.

The assumption of steady-state conditions is difficult to meet in any area where there has been land use change. This can be mitigated by only using shallow bores as the water sampled would be younger. If deep bores are used then there is the possibility of having a low bias to the recharge estimates. An attempt was made to only include analyses of younger water by only including bores in the analysis that were screened in the same stratigraphic layer as the surface geology (e.g. bores sampled from the Pilliga Sandstone were excluded if they were overlain by the Rolling Downs Group). The median drilled depth of the bores used was 35 m.

The assumption of no recycling of chloride can be achieved by not using bores that are in areas under irrigation.

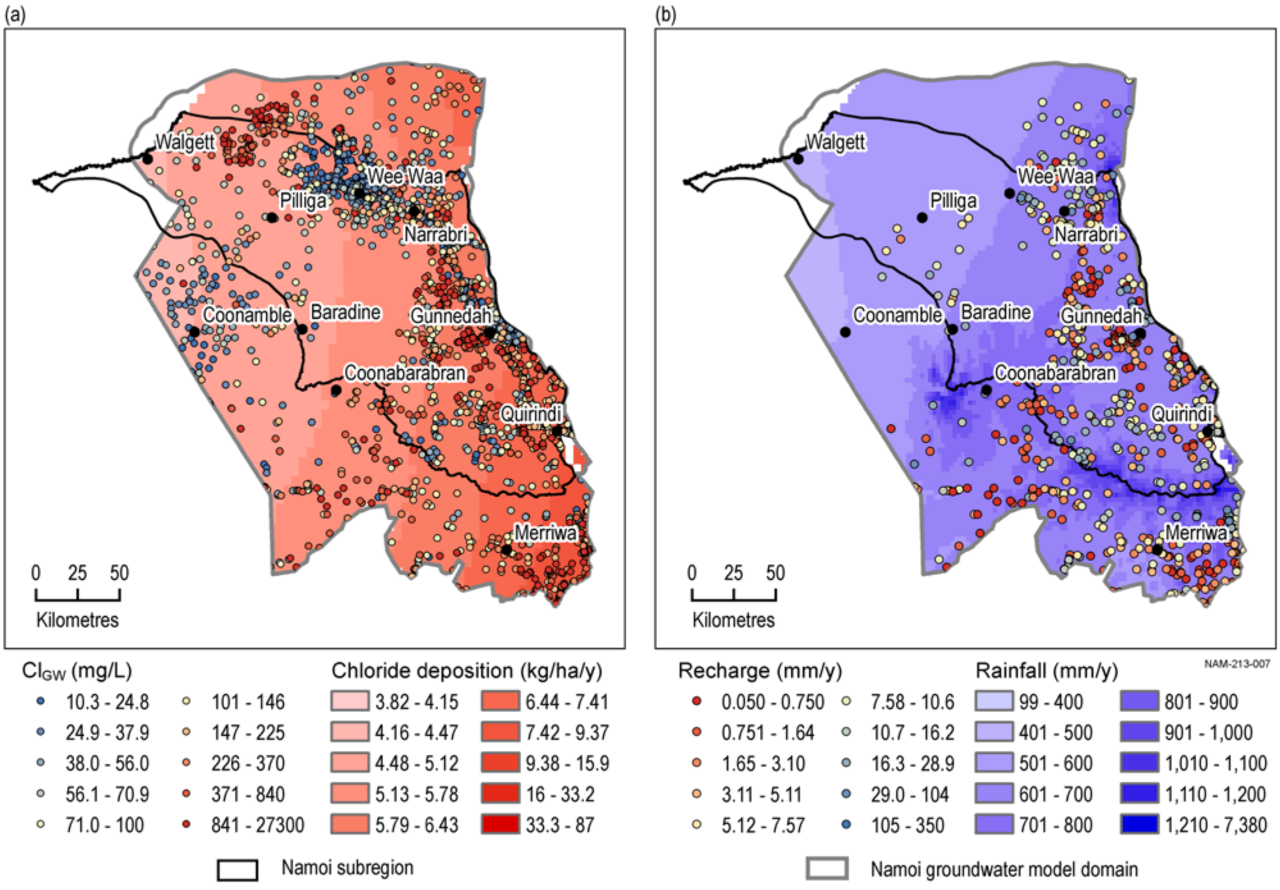

Figure 23 Inputs into the chloride mass balance method of estimating recharge for the Namoi groundwater model

(a) chloride deposition and the chloride concentration of the watertable aquifer (Cl), (b) mean annual rainfall and the point estimates of recharge (excluding points on alluvium)
Data: CSIRO (Dataset 5), NSW Office of Water (Dataset 6), Bioregional Assessment Programme (Dataset 7), Bureau of Meteorology (Dataset 9)

To generate a continuous surface of recharge estimates for input into the groundwater model, the point estimates derived from the chloride mass balance method needed to be upscaled. Crosbie et al. (2010) found that mean annual rainfall, soil type and vegetation type are the key determinants of recharge. Crosbie et al. (2013) used these variables successfully to upscale point estimates to a continuous recharge surface. However, due to the paucity of point recharge estimates under different soil and vegetation types in the area of interest, the mean annual rainfall (Bureau of Meteorology, Dataset 9) and nine different classes of surface geology have been used as covariates (Figure 24). The nine geological classes were generally based on the age of the sediments and sedimentary rocks and are an extension of those used in the Hunter subregion (product 2.1-2.2 for the Hunter subregion (Herron et al., 2018a)). As the Namoi groundwater model also includes parts of the Hunter, Central West and Gwydir subregions, the chloride in groundwater data from these subregions has also been used in generating the relationships used for upscaling.

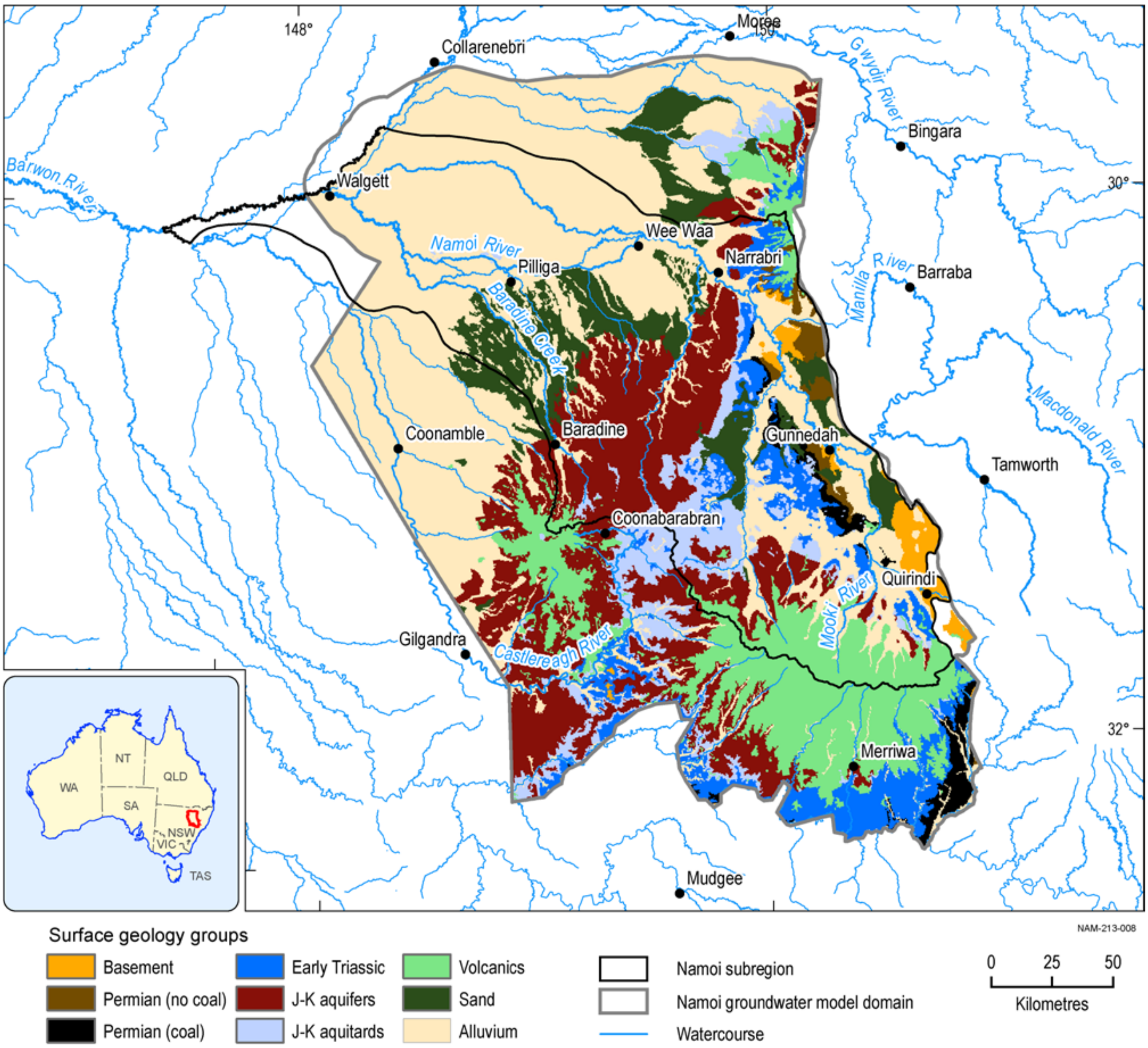

Figure 24 Surface geology groups used in estimating recharge for the Namoi groundwater model

Data: Bioregional Assessment Programme (Dataset 7)

A log-linear relationship was adopted for estimating mean annual recharge from mean annual rainfall. This is similar to relationships developed previously from both field and modelled data (Crosbie et al., 2010, 2013). Use of a log-linear relationship can result in recharge rates at the higher end of the rainfall spectrum that are greater than rainfall (especially when extrapolated beyond the range of the field data). To prevent this, a global maximum recharge rate equal to half the rainfall was imposed, which is approximately the highest recharge estimated from the point scale chloride mass balance estimates. As the chloride mass balance method was not appropriate for alluvial areas, empirical relationships developed from historical field data to predict recharge using mean annual rainfall (Bureau of Meteorology, Dataset 9), soil clay content (CSIRO, Dataset 10) and vegetation (Australian Bureau of Agricultural and Resource Economics and Sciences, Dataset 11) were used (Wohling et al., 2012).

Figure 25 and Figure 26 show the log-linear relationship for estimating mean annual recharge from mean annual rainfall. This shows that for a given rainfall amount the Sand, Volcanics and J-K aquifers classes have comparably more recharge than the other classes; this is consistent with these being the productive aquifers in the region. The coal-bearing formations (Permian (coal)) tend to have recharge that is similar to that of the interburden layers (Permian (no coal), Early Triassic and J-K aquitards).

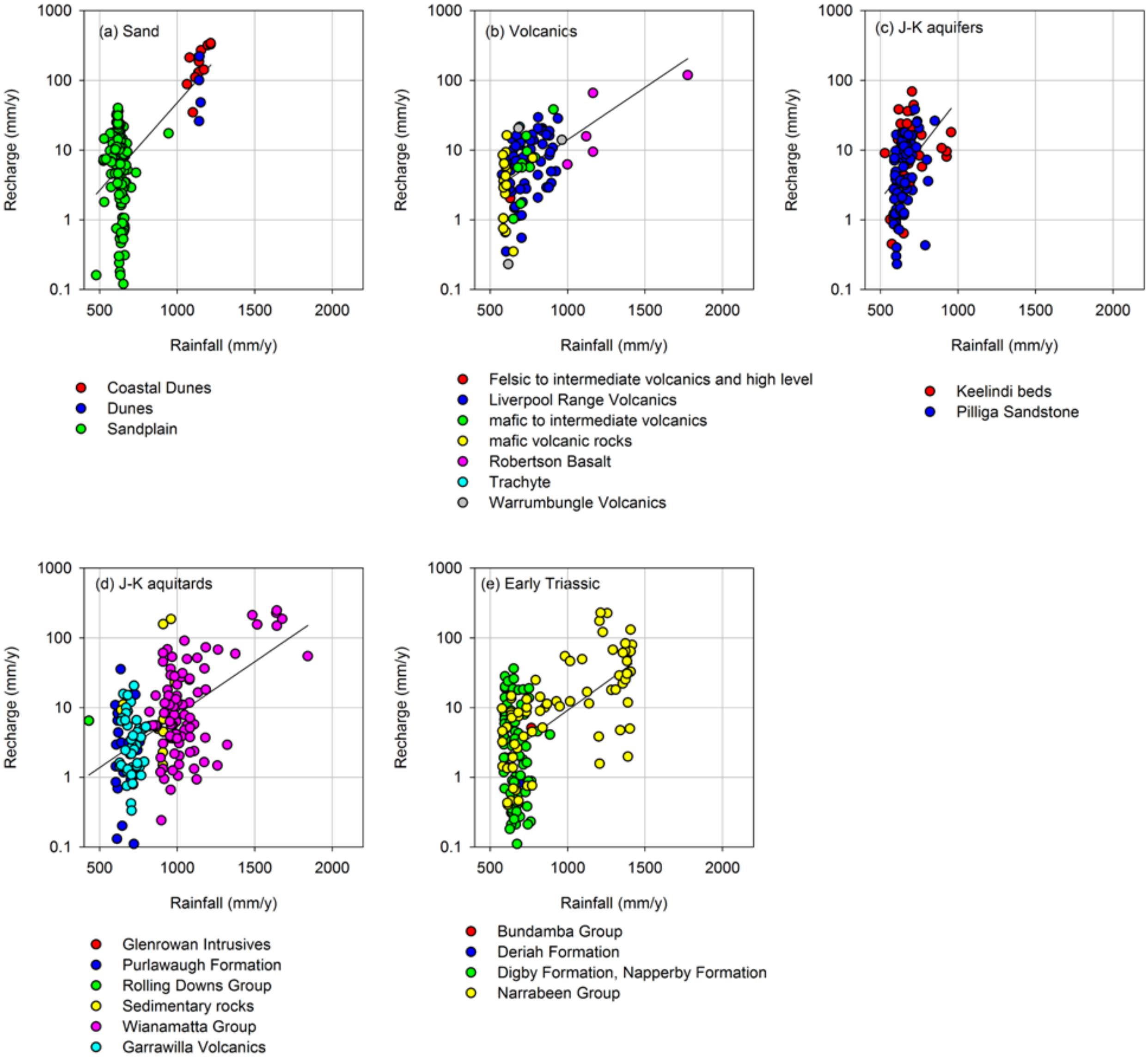

Figure 25 Relationship between mean annual rainfall and mean annual recharge for Triassic and younger groupings of surface geology for the Namoi groundwater model domain

The black line is the line of best fit through the data points, this is one realisation of 1000 used in the upscaling.
Data: Bioregional Assessment Programme (Dataset 7)

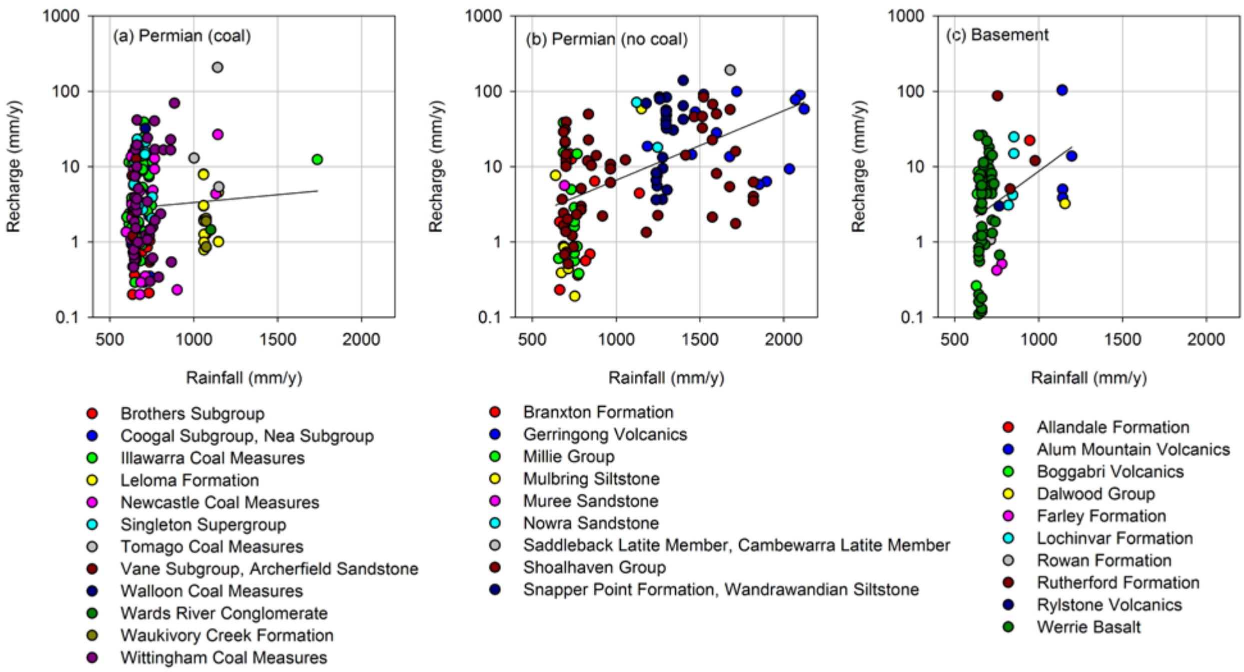

Figure 26 Relationship between mean annual rainfall and mean annual recharge for Permian and older groupings of surface geology for the Namoi groundwater model domain

The black line is the line of best fit through the data points, this is one realisation of 1000 used in the upscaling.
Data: Bioregional Assessment Programme (Dataset 7)

The relationship between rainfall and recharge for each surface geology group would allow a deterministic estimate of recharge to be developed. However, an estimate of the uncertainty around this deterministic estimate is necessary for carrying out the sensitivity and uncertainty analyses in the numerical groundwater modelling. The sources of uncertainty that can be quantified are the chloride deposition and the regression function. The chloride deposition shown in Figure 23 is the best estimate reported by Leaney et al. (2011), who also produced gridded estimates of the mean, standard deviation and skewness from 1000 equally well-calibrated replicates (CSIRO, Dataset 5). These gridded datasets were used to stochastically generate ten alternate chloride deposition grids. Each of these ten deposition grids were used to generate the regression equations between mean annual rainfall and mean annual recharge using bootstrapping (Efron and Tibshirani, 1994) with replacement for ten replicates. This provided 100 replicate regression equations to use in up-scaling. 'Bootstrapping' is a statistical method that involves random sampling with replacement. In this case it has been used by leaving out some of the data points and replacing them with replicates of other data points and then re-calculating the regression equation. This allows for an estimate of the uncertainty in the regression equations developed between rainfall and recharge.

The upscaled recharge estimates across the Namoi groundwater model domain are shown in Figure 27 as the 5th, 50th and 95th percentiles of the 100 replicates. The highest recharge is associated with the alluvium with sandy soils and the volcanics of the Liverpool Ranges and Warrumbungles, the lowest recharge is under the alluvium with fine-textured soils and where the Permian units outcrop. The areally averaged recharge for the 50th percentile of the 100 replicates is 6.9 mm/year, with the 5th and 95th percentiles being 5.8 and 8.6 mm/year respectively for the

Namoi model domain. (Note that large areas are covered by alluvium which does not have any uncertainty associated with the recharge estimates).

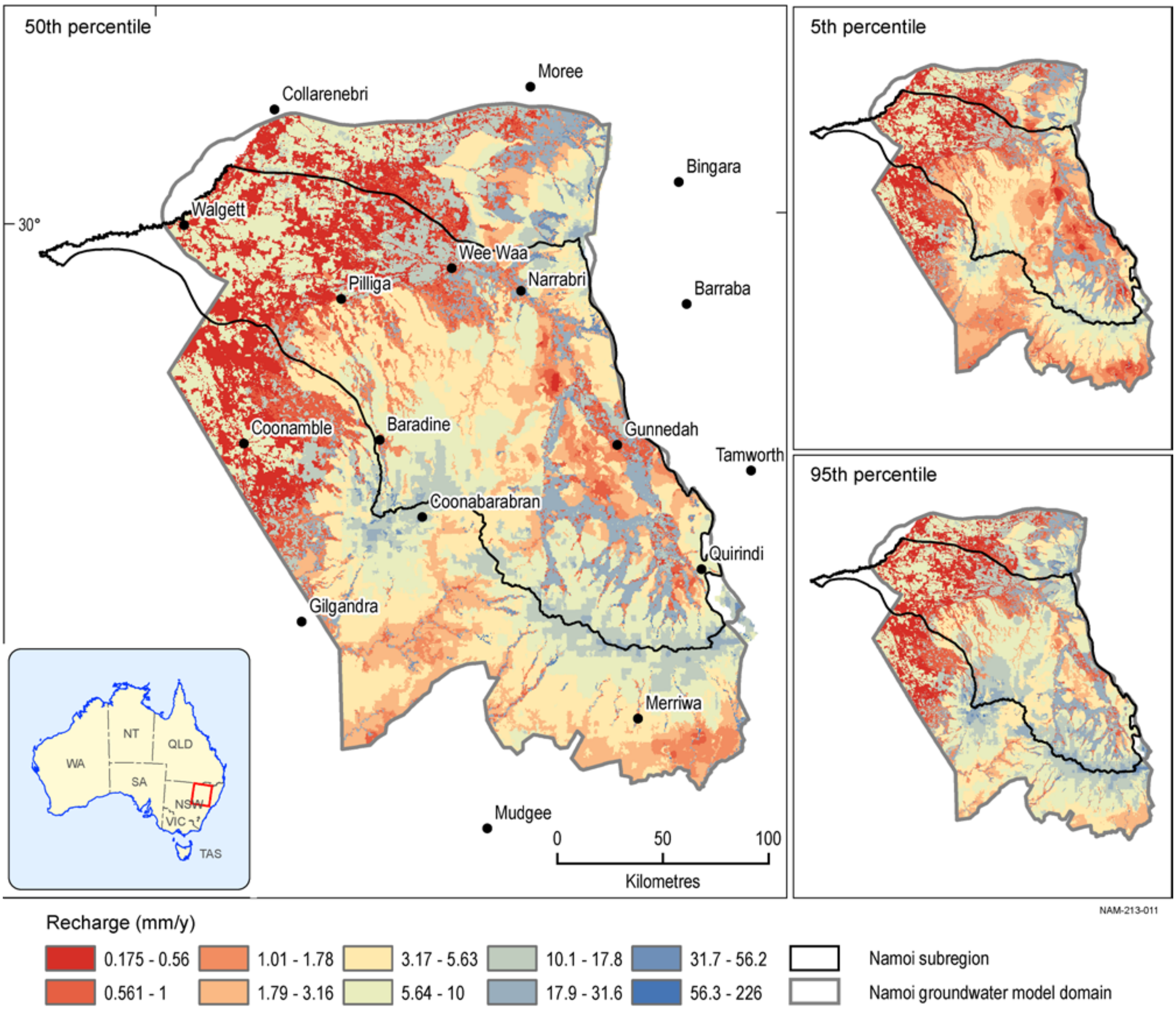

Figure 27 Uncertainty in the recharge estimation across the Namoi groundwater model domain displayed as the (a) 5th, (b) 50th and (c) 95th percentiles from 100 replicates

Data: Bioregional Assessment Programme (Dataset 7)

The limitations of the recharge estimation as applied here relate to the assumptions underpinning the methodology: by not accounting for the chloride that is lost from the system through surface runoff, recharge can be overestimated; whereas not accounting for the enhanced deposition on forested areas leads to underestimating recharge. The assumption of steady-state conditions will be violated in areas that have not attained equilibrium following the clearing of native vegetation for agriculture. The clearing of native vegetation generally leads to an increase in recharge. A chloride in groundwater sample from immediately (~cm) below the water table will be an estimate of current recharge, a very deep (>100 m) sample is likely to be an estimate of historical recharge prior to land clearing. This effect has been minimised by only sampling bores in outcrop areas that are likely to be shallower than bores intersecting confined aquifers, however it is likely that some of the data points will be from recharge prior to land clearing which will likely lead to an underestimation of recharge. No attempt was made to quantify the impacts of such forms of uncertainty.

2.1.3.1.5 Groundwater quality

As groundwater quality was not modelled, no further analysis has been conducted. Contextual information on groundwater quality is provided in companion product 1.1 (Welsh et al., 2014) and product 1.5 for the Namoi subregion (Peña-Arancibia et al., 2016).

2.1.3.2 Statistical analysis and interpolation

The outcome of statistical analysis and interpolation is incorporated in the above section.

2.1.3.3 Gaps

There are gaps in all the datasets used here:

- The observed water level data are predominantly in the alluvium (which hosts the most commonly utilised groundwater resource in the Namoi subregion) and not in the Permian units where the coal resource development is occurring and drawdowns will be greatest.
- The nested piezometers are predominatly in the alluvium, nested piezometers are necessary for monitoring of vertical hydraulic gradients that could be generated by extracting groundwater at depth (e.g. coal seam gas or underground coal mines).
- The measured hydraulic properties are dominated by the hydraulic conductivity with very little information on the storage properties.
- The recharge described here is only the dryland diffuse recharge. No attempt has been made at understanding recharge due to flooding or irrigation, these will be incorporated in the groundwater modelling through outputs of the river modelling (in companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018)).
- The role of faults as conduits or barriers to flow has not been investigated here.
- Groundwater quality has not been assessed in this product.

More information on data gaps will be provided in later products, because the modelling and analysis contributes to identifying further gaps. Likewise, recommendations for monitoring will be reported in later products including the impact and risk analysis (product 3-4) for the Namoi subregion.

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2.1.4 Surface water hydrology and water quality

Summary

This section summarises key datasets that are used in surface water modelling of the Namoi subregion. Streamflow data from 37 gauging stations are used in the rainfall-runoff model Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) and the river routing model (AWRA-R). The available median streamflow data length is 47.5 years while three-quarters and one-quarter of the stations have at least 36 and 71 years of data available, respectively. Only 30 years of data from 1983, available for all but six catchments, were used in the rainfall-runoff modelling. Apart from the Namoi River, all other rivers and creeks are ephemeral with a few flowing for less than 50% of the time. Streamflow data quality for all but four stations is marked as predominately poor, unverifiable or missing. The highest maximum daily flow of 213,340 ML is observed for the Namoi River at Boggabri while the lowest daily maximum flow (1,731 ML) is observed for Pian Creek at Cubbaroo (an anabranch of the Namoi River) west of Wee Waa.

2.1.4.1 Observed data

2.1.4.1.1 Streamflow data

Streamflow data from 37 gauging stations were used in the rainfall-runoff model Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) and river routing model (AWRA-R) in the bioregional assessment (Table 6). Of these, streamflow data from five catchments for AWRA-L calibration were located outside of the Namoi river basin (Figure 28). The following criteria were used in catchment selection for AWRA-L calibration such that they (i) have at least 10 years of data since 1983, (ii) are not impacted by major coal mine or other developments, (iii) have no regulation (e.g. dams, weirs), (iv) are close to the Namoi subregion and (v) are not nested within a larger catchment. All gauging stations used in AWRA-R river routing modelling of the Namoi river basin in an earlier study (Lerat et al., 2013) were also selected.

Although there is some paucity of streamflow gauging stations in the unregulated tributaries, the spatial density of the streamflow gauging stations seems adequate along the Namoi River and its anabranches downstream of Narrabri. Up to December 2012, the available streamflow data length ranges from 14 to 121 years including gaps. The median data length is 47.5 years and the mean is 54.0 years. One-quarter and three-quarters of all the stations have at least 71 and 36 years of streamflow data, respectively, however only 30 years of flow data from 1983 onwards are used in the modelling. Six stations had less than 30 years of data available since 1983.

Table 6 Details of the 37 streamflow gauging stations used in rainfall-runoff model and river routing model for the Namoi subregion

Gauge ID	Catchment name and location	Catchment area (km^2)	Latitude	Longitude	Gauge opened	Gauge closed	Used in AWRA-L calibration
419001	Namoi River at Gunnedah	17100	–30.9720°	150.2556°	Nov 1891	No	No
419003	Narrabri Creek at Narrabri	25120	–30.3272°	149.7802°	Jan 1891	No	No
419005	Namoi River at North Cuerindi	2533	-30.6790°	150.7780°	Dec 2015	No	No
419006	Peel at Corrol Gap	4670	–30.9403°	150.5264°	Dec 1923	No	No
419007	Namoi at D/S Keepit Dam	5700	–30.8928°	150.4949°	Jan 1924	No	No
419012	Namoi River at Boggabri	22600	–30.6682°	150.0578°	Feb 1955	No	No
419015	Peel at Piallamore	1140	–31.1828°	151.0654°	Jul 1936	No	No
419016	Cockburn at Mulla_Crossing	907	–31.0613°	151.1254°	Jul 1936	No	No
419020	Manilla at Brabri (Merriwee)	2020	–30.7089°	150.7022°	Aug 1942	No	No
419021	Namoi at Bugilbone (Riverview)	31100	–30.2726°	148.8206°	Feb 1971	No	No
419022	Namoi at Manilla Railway Bridge	5180	–30.7533°	150.7153°	Mar 1941	No	No
419024	Peel at Paradise Weir	2410	–31.1025°	150.9376°	Nov 1953	No	No
419026	Namoi at Goangra	36290	–30.1429°	148.3873°	Aug 1954	No	No
419027	Mooki at Breeza	3630	–31.2734°	150.4614°	Sep 1957	No	No
419032	Coxs Creek at Boggabri	4040	–30.7734°	149.99°	Jun-1965	No	No
419039	Namoi at Mollee	28200	–30.2595°	149.6817°	Sep 1965	No	No
419043	Manilla at D/S Split Rock Dam	1650	–30.5886°	150.6879°	May 1968	No	No
419045	Peel River D/S Chaffey Dam	411	–31.3415°	151.1437°	Dec 1968	No	No
419049	Pian Creek at Waminda	2440	–29.9221°	148.3873°	Jun 1972	No	No
419059	Namoi at D/S Gunidgera Weir	28500	–30.2033°	149.4361°	Apr 1976	No	No
419061	Gunidgera Creek at D/S Regulator	28400	–30.1962°	149.4287°	Jul 1975	No	No
419068	Namoi at D/S Weeta Weir	29000	–30.2844°	149.3383°	Oct 1978	No	No
419072	Baradine Creek at Kienbri No.2	978	–30.8501°	149.0331°	May 1981	No	No
419088	Pian Creek at Cubbaroo	NA	–30.1667°	149.1333°	Nov 1996	No	No
419089	Pian Creek at Dempseys Brdg	NA	–29.9167°	148.7417°	Nov 1996	No	No
419091	Namoi at U/S Walgett	41600	–30.0268°	148.1544°	Nov 1996	No	No

Gauge ID	Catchment name and location	Catchment area (km^2)	Latitude	Longitude	Gauge opened	Gauge closed	Used in AWRA-L calibration
419029	Halls Creek at Ukolan	357	–30.7040°	150.8270°	May 1965	No	Yes
419033	Coxs Creek at Tambar Springs	1450	–31.3484°	149.8855°	Jun 1965	No	Yes
419035	Goonoo Goonoo Creek at Timbumburri	459	–31.2710°	150.9160°	Jun 1965	No	Yes
419051	Maules Creek at Avoca East	663	–30.4955°	150.0829°	Jul 1975	No	Yes
419053	Manilla at Black Spring	791	–30.4222°	150.6511°	Aug 1972	No	Yes
419054	Swamp Oak Creek at Limbri	391	–31.0380°	151.1700°	May 1975	No	Yes
418014	Gwydir at Yarrowyck	855	–30.4673°	151.3625°	Dec 1954	No	Yes
418027	Horton at Horton Dam Site	220	–30.2065°	150.4292°	May 1967	No	Yes
418033	Bakers Creek at Bundarra	173	–30.2094°	151.0260°	Oct 1978	Feb 1993	Yes
420014	Magometon Creek (site 3) at near Coonamble	540	–30.9957°	148.4790°	Jun 1987	Apr 2002	Yes
420017	Castlereagh at Hidden Valley	1166	–31.4182°	149.3113°	Feb 1980	No	Yes

AWRA-L = Australian Water Resources Assessment landscape model, NA = data not available, D/S = downstream, U/S = upstream
Data: NSW Office of Water (Dataset 1, Dataset 2, Dataset 3)

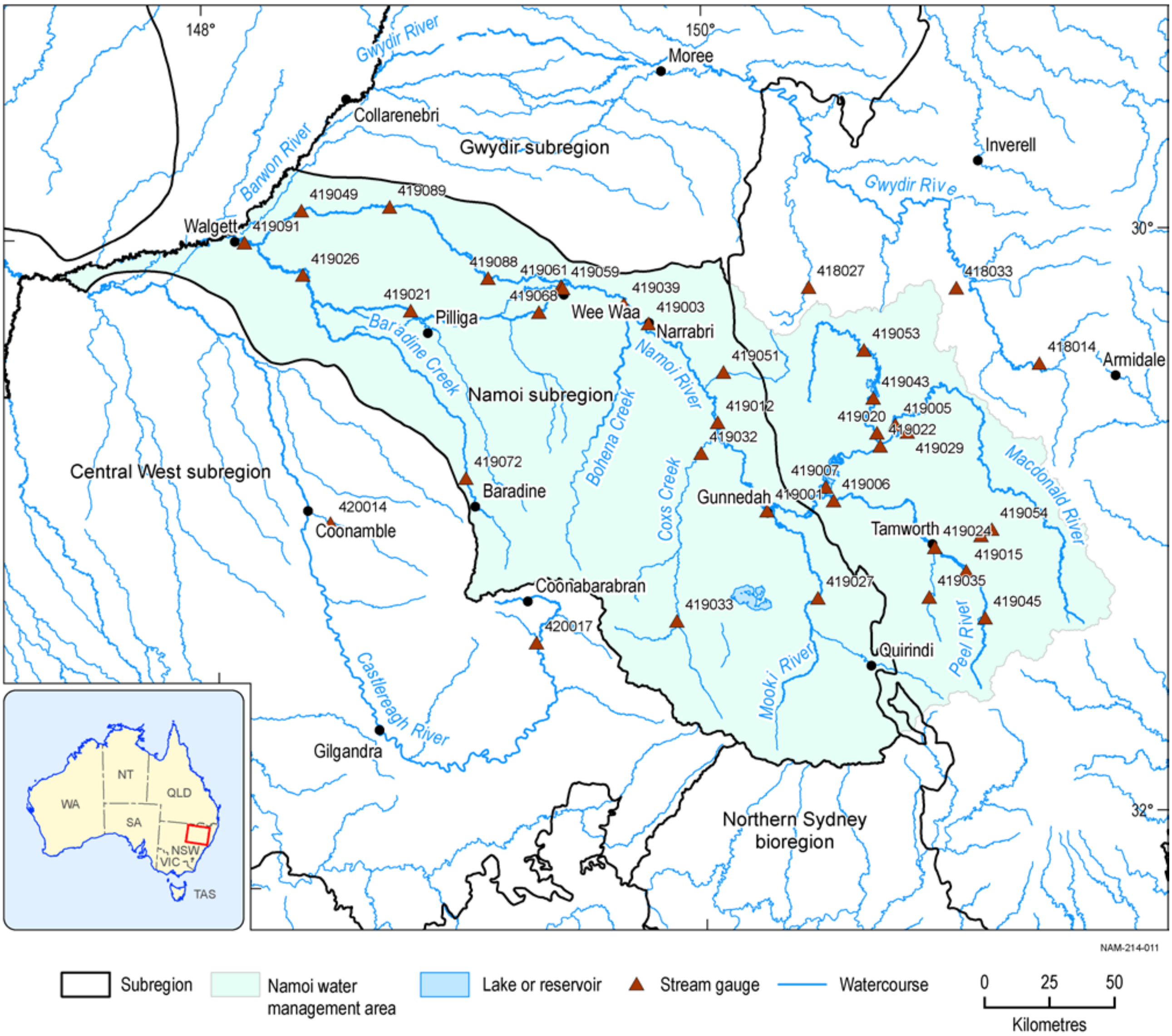

Figure 28 Streamflow gauging stations given in Table 6 for the Namoi subregion

2.1.4.1.2 River cross-sections data

River cross-section data are used in AWRA-R to compute instream evapotranspiration and rainfall, instream capacity and losses to groundwater (Lerat et al., 2013; Dutta et al., 2014). The cross-sections for 23 streamflow gauges used in AWRA-R calibration were obtained from NSW Department of Primary Industries (Bioregional Assessment Programme, Dataset 4). Any potential changes in cross-section due to scour and re-deposition of sediment after peak flows are not considered.

AWRA-R simulations are done at locations where cross-section data are unavailable. Obtaining channel cross-sections requires detailed surveys which are time-consuming and carried out under strict guidelines (Stewardson et al., 2005). Regional hydraulic geometry models can be obtained using proxies that can be readily obtained (e.g. catchment area and mean annual streamflow). Using data from about 400 stations in Queensland, Tennakoon and Marsh (2007) developed functional relationships of modest explanatory value ($r^2 \approx 0.3$) between top width and mean channel depth with catchment area and mean annual streamflow. The cross-section for the remaining 21 streams at the outlet is determined by assuming a trapezoidal shaped cross-section with bottom channel width (*L*) and height (*H*) (Figure 29) able to accommodate AWRA-L simulated maximum streamflow. The 21 stream nodes where the assumed trapezoidal sections were used are: 9, 12, 14, 15, 16, 17, 19, 20, 21, 22, 24, 25, 27, 30, 31, 33, 34, 36, 37, 38 and 39. Figure 4 in companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018) shows the location of these nodes.

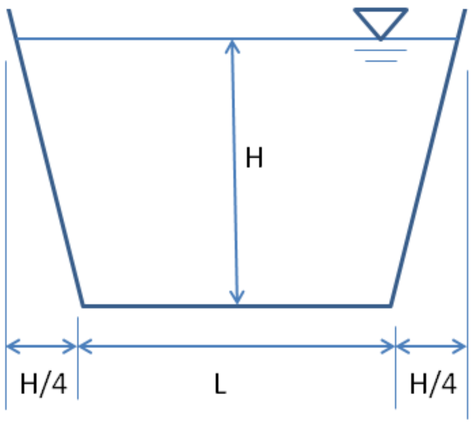

Figure 29 Shape of trapezoidal section assumed for headwater catchments in AWRA-R simulation

AWRA-R = Australian Water Resources Assessment river model, H = height, L = width

The flow equation for a trapezoidal weir with side slopes vertical to horizontal ratio of 4 to 1 estimates height (*H*) for a given flow *Q* as:

$$H = \left(\frac{3}{2} Q \frac{1}{C_d L \sqrt{2g}}\right)^{\frac{2}{3}} \quad (4)$$

where C_d is the coefficient of discharge (assumed as 0.62 for Cippoletti weir; Daugherty and Franzini, 1965) and *g* is gravity acceleration (9.81 ms^{-2}). Using the simulated maximum flow value for the headwater catchment, the high coefficient of discharge for a trapezoidal weir was adjusted to match the maximum flow height for a nearby catchment assuming that the adjusted C_d takes care of roughness of the channel (e.g. Manning's n) and other variables that govern flow and channel cross-sectional area relationship. It is also assumed that cross-sections at a nearby gauging station with a comparable catchment area or at a gauging station with comparable mean annual streamflow provides a reasonable estimate of bottom channel width (Bioregional Assessment Programme, Dataset 4). The Cippoletti weir cross-sections do not incorporate overbank geometry, thus the assumption is reasonable for the stream cross-sections for the headwater catchments which are unlikely to overtop the stream bank.

This process may be simplistic but there are no suitable data to evaluate the approach including data related to calculating the flow using the Manning's equation. Any systematic errors may be compensated through calibration. Furthermore, as the Bioregional Assessment Programme is reporting on the relative difference of hydrological response variables between the baseline and coal resource development pathway (CRDP), any error introduced by the above assumption would cancel out.

2.1.4.1.3 River reach lengths

River reach lengths are used in AWRA-R to compute instream actual evapotranspiration and rainfall fluxes, instream capacity and groundwater recharge from irrigated areas (Lerat et al., 2013; Dutta et al., 2014).

Reach lengths are quantified for all rivers in the reach, including the main channel and tributary channels. River reach lengths are obtained from the River Styles spatial layer for NSW, obtained through digitisation of high resolution aerial or satellite imagery with field validation from different sources (NSW Office of Water, Dataset 5). Visual assessment showed that these data were more accurate than drainage networks derived from the DEM data, particularly in meandering sections of the river. The river reach was clipped using catchment boundaries defined in the AWRA-R modelling domain (see Section 2.6.1.3 in companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018)); and each river reach length was manually computed using GIS software (Bioregional Assessment Programme, Dataset 4). These lengths are planar and can be different from on-ground lengths, particularly in steep areas.

2.1.4.1.4 Irrigation areas and crop types

The AWRA-R river model needs details of irrigated areas and crop types in each river reach in which irrigation is present in order to determine areal extent and crop factors of the most common crop types (Dutta et al., 2014) to calculate water usage by irrigated crop.

Areas and crop types for each reach are sourced from the Namoi Integrated Quantity-Quality Model (IQQM) (Bioregional Assessment Programme, Dataset 6). The information in the Namoi IQQM was summarised by reach in order to determine crop types and associated crop factors (Bioregional Assessment Programme, Dataset 6).

2.1.4.2 Statistical analysis and interpolation

Table 7 shows the maximum and the 10th, 25th, 50th (median), 75th and 90th percentile daily flows for the 37 streamflow gauging stations for data available from 1983 to 2012. Half of the catchments have their 10th percentile flow (a flow that is exceeded 90% of time) less than 1 ML/day. Similarly, 19% of the catchments have their 25th percentile flow less than 1 ML/day. About 8% of catchments also have a median flow of zero or close to it (≤1 ML/day) implying flow in the stream occurs for less than half the time in these catchments. The majority of smaller catchments (<1000 km^2) have their 10th and 25th percentile flows as zero except for the Peel River downstream of Chaffey Dam (407 km^2).

Table 7 Maximum, median, 10th, 25th, 75th and 90th percentile flows for the Namoi subregion using data from 1983 to 2012

Gauge ID	10th (ML/d)	25th (ML/d)	Median (ML/d)	75th (ML/d)	90th (ML/d)	Maximum flow (ML/d)
419001	26	117	416	1338	2661	212,616
419003	15	132	480	1513	2986	137,308
419005	15	50	139	377	1041	93439
419006	19	45	115	305	978	131,450
419007	3	9	26	709	1981	104,397
419012	12	114	426	1397	2844	213,343
419015	29	43	71	133	419	36,637
419016	0	3	19	74	260	23,395
419020	7	13	24	45	185	40,115
419021	5	44	143	425	2510	106,627
419022	35	76	184	543	1521	115,853
419024	16	34	74	232	796	79,426
419026	0	27	109	411	3169	109,948
419027	0	1	12	46	272	134,047
419029	1	2	6	17	81	10,456
419032	0	0	0	4	71	98,478
419033	0	1	5	15	69	31,580
419035	0	1	6	20	70	16,494
419039	20	140	490	1457	3010	182,402
419043	6	12	25	42	115	28,007
419045	4	15	44	92	177	16546
419049	0	0	6	51	229	35,744
419051	0	3	7	15	41	30,239
419053	1	3	13	37	97	57,865
419054	0	0	6	28	116	15,979
419059	7	56	194	559	1726	144,550
419061	0	3	139	425	781	10,719
419068	10	51	171	473	1865	64,038
419072	0	0	0	5	38	16500
419088	0	0	44	158	306	1,731
419089	0	2	11	43	154	25,312
419091	0	3	51	245	2869	159,595
420014	0	0	0	0	1	15,605

Gauge ID	10th (ML/d)	25th (ML/d)	Median (ML/d)	75th (ML/d)	90th (ML/d)	Maximum flow (ML/d)
420017	2	5	13	49	180	34,272
418014	0	3	16	56	217	31,888
418027	0	0	4	28	129	18,204
418033	0	2	5	17	61	5,002

Data: NSW Office of Water (Dataset 1, Dataset 2, Dataset 3)
This table follows BA convention of assigning percentile values which is different to the NSW Policy Advice Note No. 6 at: http://www.water.nsw.gov.au/__data/assets/pdf_file/0010/548848/plans_notes_policy06.pdf

2.1.4.3 Data quality assessment

Since the quality of streamflow data depends on a number of factors including the rating curve, data gaps, methods of flow measurements and measurement errors, it cannot be meaningfully described using a single descriptor. There are also year to year variations.

The gauged data were also examined for any anomaly in the record. It was found that quite a few of the non-zero data points are repeated for many (more than 3 days) consecutive days as though the gauge is stuck at a height. For model calibration these were treated as missing data.

The daily streamflow data were examined and categorised into six generic data quality classes based on the collecting agencies' data quality coding (Viney et al., 2011) (Table 8). The six categories are good, fair, poor, unverified, non-conforming and missing. The categories are defined as follows:

- good: data are an accurate representation of streamflow
- fair: data are a moderately accurate representation of streamflow
- poor: data are a poor representation of streamflow and may be unsuitable for some quantitative applications
- unverified: data quality is not known
- non-conforming: data are unsuitable for most applications requiring quantitative analysis, but may contain useful qualitative information
- missing: data are missing or unusable.

The streamflow data flagged as good, fair, poor and unverified were used while the flow data flagged as non-conforming were excluded in the model calibration. The non-conforming and missing streamflow data are both labelled in the dataset as –9999.

Table 8 Quality codes for the NSW gauges used in the Namoi subregion

Data quality codes	Description
<17, 30, 32–34, 36-39, 94	Good
17, 31, 40–46, 57-58, 82, 95	Fair
26, 51, 54, 60–75, 80, 91, 100, 140	Poor
130	Unverified
35, 52, 77, 152	Non-conforming
153–255	Missing

Data: NSW Office of Water (Dataset 1)

Table 9 shows the proportion of data falling into each data quality category for streamflow, including data gaps, for all 37 stations for the Namoi subregion. Apart from four stations, the data quality for all the stations is labelled as predominately poor, unverified or missing. Nearly 75% of these stations have poor data as a result of a mostly uncertain rating curve (code 140 – 'current rating – may be subject to change'), the remaining unverified data are simply not quality coded. This may result in large (not quantified here) uncertainty in the streamflow data leading to uncertainty in the modelling results.

Table 9 Percentage of data under each data quality category for streamflow data for the Namoi subregion using data from 1983 to 2012

Gauge ID	Good (%)	Fair (%)	Poor (%)	Unverified (%)	Non-conforming (%)	Missing (%)
419001	0.2%	0.0%	76.0%	23.8%	0.0%	0.0%
419003	8.4%	0.0%	89.6%	0.0%	0.0%	2.0%
419005	3.8%	0.0%	14.5%	81.3%	0.0%	0.4%
419006	1.7%	0.0%	71.4%	26.8%	0.0%	0.1%
419007	0.0%	0.0%	75.0%	25.0%	0.0%	0.0%
419012	1.3%	0.0%	77.7%	21.0%	0.0%	0.0%
419015	4.2%	0.0%	39.2%	56.5%	0.0%	0.0%
419016	2.1%	0.0%	31.0%	66.4%	0.0%	0.5%
419020	2.6%	0.2%	73.3%	22.7%	0.0%	1.2%
419021	0.0%	0.0%	82.9%	17.1%	0.0%	0.0%
419022	0.0%	0.0%	79.8%	20.2%	0.0%	0.0%
419024	1.3%	0.0%	49.2%	49.1%	0.0%	0.5%
419026	0.5%	0.0%	75.7%	21.8%	0.0%	2.0%
419027	8.4%	2.6%	61.4%	26.4%	0.0%	0.5%
419029	3.9%	0.4%	14.8%	76.8%	0.0%	4.1%
419032	0.0%	0.0%	76.2%	22.4%	0.0%	1.4%
419033	0.0%	0.0%	98.0%	0.2%	0.0%	1.8%
419035	3.8%	0.1%	44.6%	50.4%	0.0%	1.1%
419039	0.3%	0.0%	77.2%	21.0%	0.0%	1.5%
419043	0.7%	3.1%	71.6%	24.7%	0.0%	0.0%
419045	3.1%	0.0%	0.1%	96.8%	0.0%	0.0%
419049	0.0%	0.0%	97.9%	2.1%	0.0%	0.0%
419051	0.1%	0.0%	75.7%	24.1%	0.0%	0.1%
419053	13.4%	0.1%	59.3%	26.1%	0.0%	1.1%
419054	73.4%	3.6%	0.6%	21.4%	0.0%	1.1%
419059	5.5%	0.1%	74.7%	18.7%	0.0%	1.0%
419061	0.0%	0.0%	77.4%	22.6%	0.0%	0.0%
419068	2.4%	0.0%	73.5%	24.1%	0.0%	0.0%
419072	0.0%	0.0%	79.4%	18.9%	0.0%	1.7%
419088	0.0%	0.0%	99.1%	0.0%	0.0%	0.9%
419089	0.0%	0.0%	99.9%	0.0%	0.0%	0.1%
419091	0.0%	0.0%	86.9%	0.0%	1.4%	11.8%
420014	60.7%	2.4%	2.9%	10.9%	0.0%	23.1%

Gauge ID	Good (%)	Fair (%)	Poor (%)	Unverified (%)	Non-conforming (%)	Missing (%)
420017	0.8%	31.0%	24.0%	30.3%	0.0%	0.6%
418014	32.3%	0.0%	13.3%	53.8%	0.0%	0.7%
418027	1.9%	0.0%	74.0%	22.2%	0.0%	2.0%
418033	12.7%	0.0%	13.1%	66.4%	0.0%	7.8%

Data: NSW Office of Water (Dataset 1, Dataset 2, Dataset 3)

2.1.4.4 Gaps

The stream gauges have a relatively long data record with few missing records. However the majority of the catchments have poor or unverified data making the results of rainfall-runoff modelling less reliable. This will have obvious large implications for uncertainty in the streamflow data leading to uncertainty in the modelling results.

The limited number of stream gauges in unregulated rivers in the Namoi river basin limits the number of catchments that can be used in the calibration, thus it may affect the reliability of the model outcome.

One of the gaps in the surface water modelling relates to the creation of model nodes in the link-node network where there are no observations of streamflow or river geometry. The approach used to derive cross-sections and the estimates of streamflow from AWRA-L should not significantly impact predictions of the differences in hydrological response variables due to the additional coal resource development (ACRD), because they are represented the same way in both baseline and the coal resource development pathway (CRDP).

Water quality data including the salinity data were not analysed in this section as those were not modelled in the BA.

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Dataset 3 NSW Department of Primary Industries (2015) Namoi Surface Water daily streamflow data (additional stations). Bioregional Assessment Source Dataset. Viewed 04 April 2017, http://data.bioregionalassessments.gov.au/dataset/d0ce745c-c573-4cff-8e94-ef2d54d33756.

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Dataset 5 NSW Office of Water (2012) River Styles Spatial Layer for New South Wales. Bioregional Assessment Source Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/06fb694b-d2f1-4338-ab65-a707c02f11d7.

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2.1.5 Surface water – groundwater interactions

Summary

This section presents a baseline assessment of surface water – groundwater connectivity in the Namoi subregion representing June 2012 conditions, or as close as possible. The resultant connectivity map was compared to those previously developed using similar approaches. In previous studies, the surface water resources of the Namoi river basin and the underlying aquifers were mapped as being generally connected upstream of Wee Waa. In comparison, the June 2012 connectivity assessment has highlighted more widespread regions of disconnection between the aquifer and river systems. Areas of increased disconnection are evident in the Mooki river basin, in the region extending from Quirindi downstream to Caroona. Areas transitioning to disconnection are also evident in the mid-section of the Mooki river basin. Other areas in the Upper Namoi showing disconnected and transition classes include reaches around Carroll and a small section upstream of Maules Creek and reaches both upstream and downstream of the previously mapped disconnected reach between Mullaley and Boggabri in the Coxs creek basin.

This section also presents a hydrological assessment of the Mooki river basin for 2003 to 2012 and a comparison with pre-2003 conditions. The data indicate that baseflow is generated in the upper part of the river basin, with a notable decrease in baseflow contributions and flow duration downstream consistent with earlier interpretations. In comparison to pre-2003 conditions, the mean flows (total discharge and baseflow) over the 2003 to 2012 period are considerably reduced. The apparent reduction in flows is likely to be in part due to the drier than average rainfall conditions since 2003, as well as the influence of groundwater extractions on river connectivity and flows, although these associations require further investigation. A comparison of streamflow data for 2006 (dry year) and 2012 (wet year) demonstrates how the river reach varies in its dominant flux, with river losses dominating dry periods and gains over wet periods along the length of the Mooki River. The hydrological data indicate that connectivity is maintained along the length of the Mooki River. The exception is Quirindi Creek, which the hydrological analysis confirms is a disconnected system.

To better understand the changes in depth to watertable over time, and to provide a context to the 2012 baseline connectivity investigation, a comparison has been made to assess changes in depth to watertable between 2006 (dry year) and 2012 (wet year). The comparison shows that there were widespread increases in watertable level throughout the Upper Namoi river basin between 2006 and 2012, coinciding with higher rainfall years. Increases of up to 11 m were measured in some areas of the Upper Namoi river basin. The area between Caroona and Breeza in the Mooki river basin (Upper Namoi groundwater management zone 8), however, shows only modest increases in the watertable level (0.8 m or less) as evidenced by typical bore hydrographs. These smaller increases in watertable level appear to have been insufficient to return sections of the Mooki River mapped as transitional and disconnected reaches in this connectivity investigation, to a previous state of connection (based on earlier interpretations). Bore hydrographs in the area between Caroona and Breeza in the Mooki river basin have shown water level declines by about 11 to 12 m between the

1970s and 2012. These water level declines appear to be impacting on surface water – groundwater connectivity in the Mooki river basin. Downstream of Narrabri there were widespread areas where water levels decreased by up to 6 m over the 2006 and 2012 period. These declines may be as a result of time lag effects from groundwater extractions further up the catchment, over the previous decades, which have had the effect of reducing groundwater throughflow, in combination with the current levels of extraction in this area. The causes of widespread water level decline in the Lower Namoi require further investigation. There are limited data available to characterise the hydraulic properties and groundwater processes of the consolidated sedimentary (and minor volcanic) rocks surrounding and underlying the alluvium in the Namoi river basin. Analysis of a single bore hydrograph in the Mooki river basin suggests that there is an upward vertical hydraulic pressure gradient, most likely from the underlying basalt bedrock aquifer into the overlying alluvial aquifers. This finding is consistent with previous investigations indicating that upward vertical recharge in the Namoi river basin is not uncommon, although the extent of vertical connectivity and upward flow flux is unknown.

The findings presented here will be of value when analysing the results of the surface water and groundwater modelling, and provide a local-scale, detailed analysis to complement the broader regional modelling. The results here provide a means of ‘ground truthing’ the modelling results particularly the direction of surface water – groundwater flux, an important element of the water balance.

A summary of existing knowledge on surface water – groundwater interactions in the Namoi subregion was presented in companion product 1.1 (context statement) for the Namoi subregion (Welsh et al., 2014). This section builds upon that initial contextual information by presenting:

- a more detailed review of several important surface water – groundwater investigations in the Namoi river basin, including summarising their key findings
- the results of new hydrological analysis undertaken for this bioregional assessment (BA).

This section aims to expand on the more detailed findings of several important studies, summarising what the main surface water – groundwater controls are, and then presents new hydrological analysis to better understand surface water – groundwater interaction in the Mooki river basin, an area of Namoi subregion that is of critical importance for this BA due to the high level of expected coal resource development.

In the context of this BA, the review and analysis of surface water – groundwater interactions presented here is critical to inform the conceptual understanding of both the groundwater system, as investigated through the numerical groundwater modelling (see companion product 2.6.2 for the Namoi subregion (Janardhanan et al., 2018)), and the rivers and creeks, investigated through the surface water numerical modelling (see companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018)). Surface water – groundwater interactions in the Namoi subregion are complex, varying spatially and over time, and respond to a range of drivers, both natural and anthropogenic. These factors are further discussed in the sections that follow.

2.1.5.1 Observed data

Surface water – groundwater connectivity has been the focus of several regional investigations in the Namoi river basin. Key findings from the most relevant of these studies for the BA for the Namoi subregion are summarised. In addition, a new baseline assessment of surface water – groundwater connectivity has been made for 2012, and this baseline has been compared to the connectivity assessments made from earlier investigations. The year 2012 was chosen for the baseline connectivity assessment in order to be consistent with companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014), which has been used to establish the development status of coal mines and coal seam gas (CSG) operations in commercial production as of the last quarter of 2012. The 2012 year represents the baseline status by which to compare potential impacts of future coal and CSG development. The methods employed for the surface water – groundwater connectivity 2012 baseline and previous assessments are further described in the sections below, and include approaches based on:

- GIS analysis – analysis and mapping using spatial software and applications to compare groundwater elevations with river stage and/or river bed elevations, and to assess water level changes over time
- hydrological assessments – analysis of streamflow, baseflow separation, flow duration curves, stream and groundwater hydrograph analysis
- hydrogeological field data – analyses of geological and geomorphic datasets, geophysical methods, hydraulic data, temperature, groundwater salinity, and other water chemistry data.

2.1.5.2 Previous catchment-scale investigations on stream-aquifer interactions

2.1.5.2.1 Murray-Darling Basin Sustainable Yields Project

An assessment of surface water – groundwater connectivity for the Namoi river basin was made by CSIRO (2007) as part of the Murray-Darling Basin Sustainable Yields Project using a regional mapping approach. This assessment provided a snapshot in time of the magnitude and direction of hydraulic fluxes to, or from, the major rivers in the Namoi river basin using data from June 2006 (or as close as possible), which was a period of historically low flows in the Namoi River (CSIRO, 2007). The analysis and methods are described in CSIRO (2007). The creek and river reaches in the highland areas of the Namoi river basin, such as the Manilla and Peel rivers (which are east of the Namoi subregion boundary), were assessed as gaining reaches. Further downstream, the river reaches change from predominantly gaining in the upper catchment through to losing and back to gaining in the mid-section of the Namoi River, as shown in Figure 30 (Parsons et al., 2008). The lowest reaches of the Namoi River were reported to form a losing system, and Pian Creek was classified by CSIRO (2007) as 'maximum losing', which the study defined as a river reach where the watertable is separate from the stream due to the presence of an unsaturated zone. These findings are generally consistent with previous regional hydrogeological interpretations, including Ivkovic (2006).

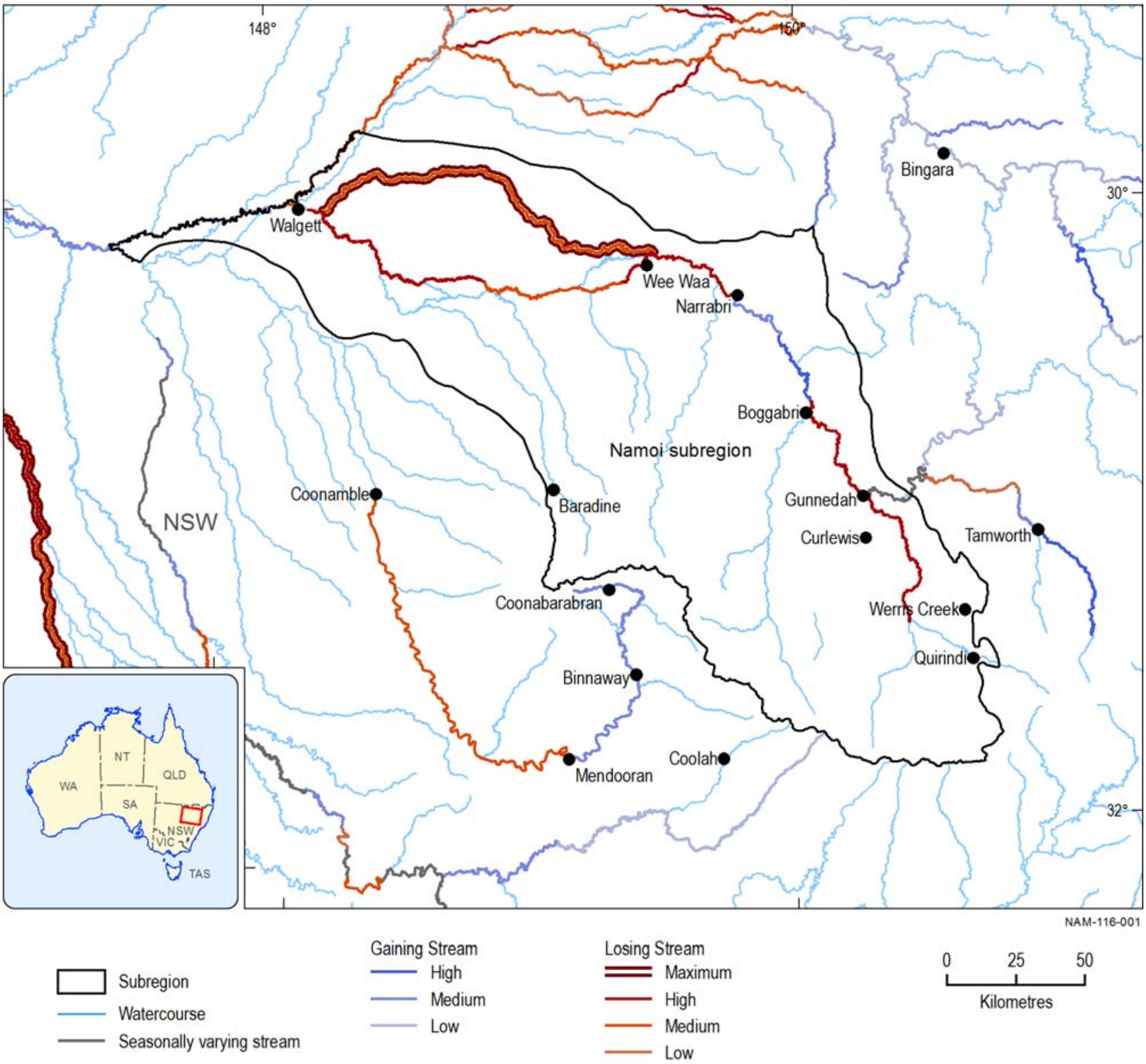

Figure 30 Surface water – groundwater connectivity in the Namoi river basin

Data: CSIRO (2007)

2.1.5.2.2 Modelling groundwater-stream interactions for assessing water allocation options

Ivkovic (2006) employed a combination of hydrological methods to assess surface water – groundwater connectivity and dominant direction of flux at the river reach scale in the Namoi river basin. The data analyses included:

- comparison of groundwater and stream channel base elevations using a GIS
- the shape of the stream hydrograph and application of a baseflow separation filter to streamflow data
- flow duration curves
- vertical aquifer connectivity based on nested piezometer bore hydrographs
- paired stream and bore hydrograph comparisons.

The presence of hydraulic connection between the stream and underlying aquifer was assessed by Ivkovic (2006) through comparing the elevation of the base of the stream channel with the elevation of the groundwater observed within shallow observation bores (<40 m deep) located within 1 km of the stream (Figure 31). In areas without bore data within 1 km of the stream, extrapolations were made based on data points further away from the stream. Connection was assumed to exist where the minimum depth to groundwater over the length of the data record (from the 1970s) was less than 10 m. This depth was used as 10 m was the estimated difference between the elevation of the floodplain, where bore levels would be measured, and the base of the stream in the catchment. The minimum depth to groundwater over the length of the data record (since the 1970s) was intentionally chosen to provide a benchmark of where connectivity had at some point in time existed based on the available data. The value of 10 m as the cut-off for inferred connectivity was derived by comparing streamflow gauging station cross-sections on the major streams to the mean elevation of the surrounding 1 km^2 area determined from the Australian 9 second digital elevation model (AUSLIG, 2001) as reported by Braaten and Gates (2002) (this gives a pixel size of approximately 0.06 km^2 at the latitude of the Namoi subregion). Although the difference in elevation tends to decrease downstream as the topography becomes more subdued and the floodplains larger, this estimate was considered reasonable given the absence of detailed surveys of the riparian zone and the uncertainties of using a nine arc-second digital elevation model.

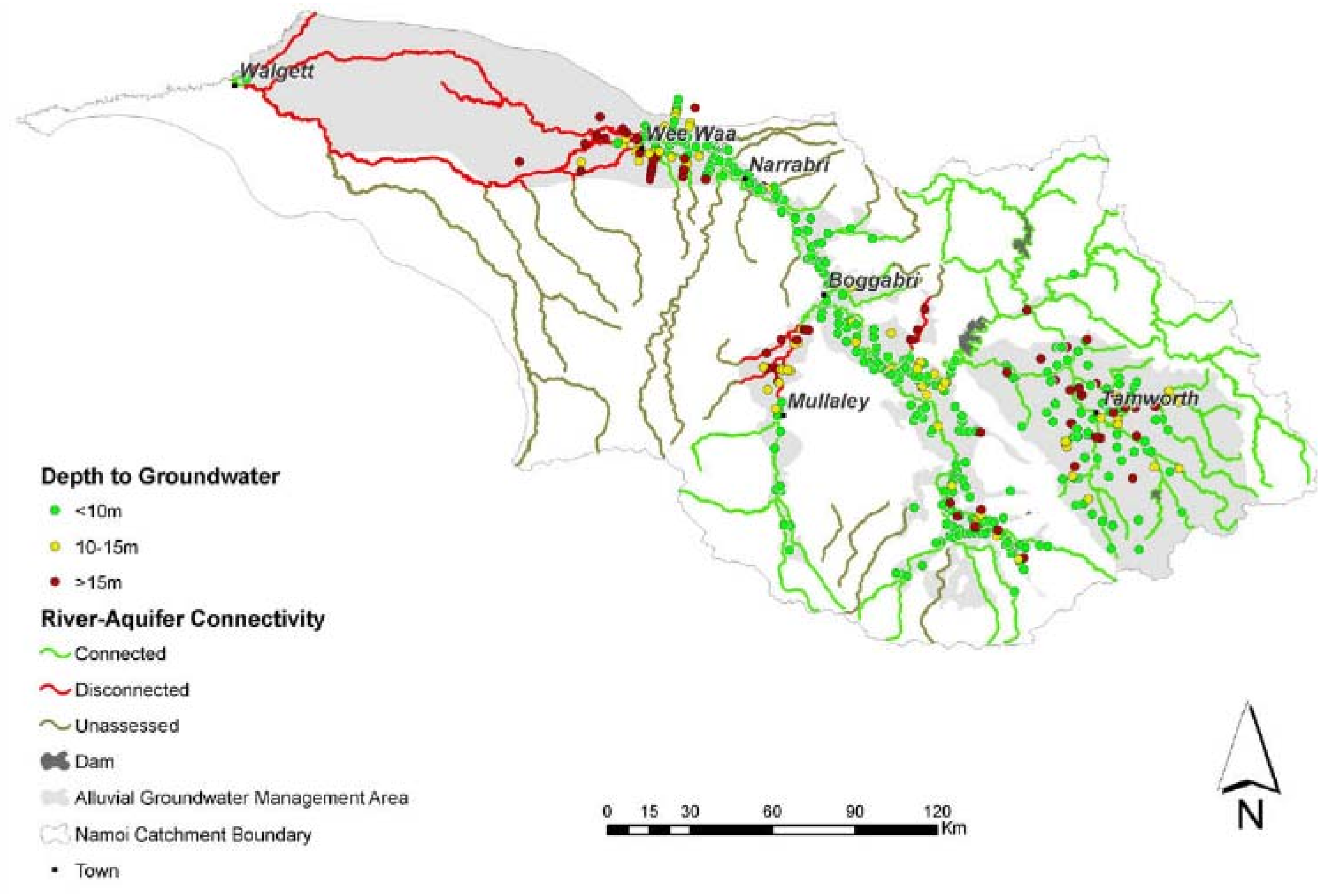

Figure 31 Stream–aquifer connectivity and the minimum depths to groundwater over the data record (from the 1970s through to 2003) for the shallow aquifers in the Namoi river basin

Source: Figure 4-1 in Ivkovic (2006)

Figure 31 shows that the streams upstream of Wee Waa were assessed as primarily connected reaches. One exception is the approximate 30 km length of disconnected (non-contiguous) stream reach in the Coxs creek basin between Mullaley and Boggabri, where groundwater levels were reported to have been declining due to the widespread use of groundwater for irrigation (Brownbill, 2000). The river reaches downstream of Wee Waa were considered to be disconnected (or maximal losing and/or non-contiguous, depending on the classification system used).

Although the groundwater systems in the Lower Namoi river basin were assessed as 'disconnected' from the Namoi River and its tributaries in both the CSIRO (2007) and Ivkovic (2006) investigations, it is important to understand the intent of this term. In this context 'disconnected' is used to describe hydrological systems where the depth to the watertable is more than 10 m below the height of the river bed. CSIRO (2007) also use the term 'maximum losing' for the same situation, to indicate that some degree of connection remains between groundwater and surface water in this condition, through an unsaturated zone between the surface water system and the watertable. Hydraulic connection occurs between the stream and alluvium in many areas mapped as 'disconnected' and stream losses have been shown to play an important role in recharging the underlying aquifers based on the analysis of bore and stream hydrographs and hydrochemical data (Ivkovic, 2006; Lamontagne et al., 2011; McLean, 2003). Groundwater mounds are evident adjacent to the Lower Namoi River and its anabranch, Pian Creek, suggesting that streamflows recharge the underlying aquifers. According to other CSIRO investigations (Rassam et al., 2008), 56% of the Lower Namoi groundwater inputs are from river recharge, mostly associated with flooding inundation, in contrast with the Upper Namoi where only 4.5% is derived from flood recharge. Connectivity is, however, variable and Kelly et al. (2014) have postulated that the vertical connectivity between the river and the underlying aquifers is poor in some areas, reflecting the migration of the Namoi River channel and associated floodplain deposits, which tend to form low permeability layers.

After assessing surface water – groundwater connectivity, the dominant direction of flux was inferred from hydrometric data obtained from 35 streamflow gauging stations on the unregulated stream systems in the Namoi river basin. The results of the analyses are shown in Figure 32. A hydrometric approach was required to infer the direction of flux because of the absence of surveyed field data in the riparian areas of the Namoi river basin, which meant that near-river groundwater elevation and river stage relationships could not be reliably established. A baseflow filter was applied to the streamflow data to estimate the proportion of baseflow using the Lyne and Hollick (1979) digital recursive filter, as described in Nathan and McMahon (1990). In addition, the characteristics of the stream hydrograph, based on visual inspection, and flow duration data were analysed. The complete temporal data record was used to assess the dynamic changes in surface water – groundwater interactions over time, as using only synchronous streamflow records would have severely limited the available data pool. This approach was considered appropriate given the objective of characterising changes in surface water – groundwater interactions over the length of the available hydrological record.

Ivkovic (2006) found that relatively larger baseflow indices (meaning that baseflow is a higher proportion of streamflow) and streamflow of longer duration occur in the uppermost reaches of the Namoi river basin. In this area baseflow is contributed from the fractured rock aquifers into which the streams are incised. A decrease in baseflow index in the downstream reaches was associated with a decrease in flow duration, suggesting that groundwater input maintains streamflow in the upper catchment reaches.

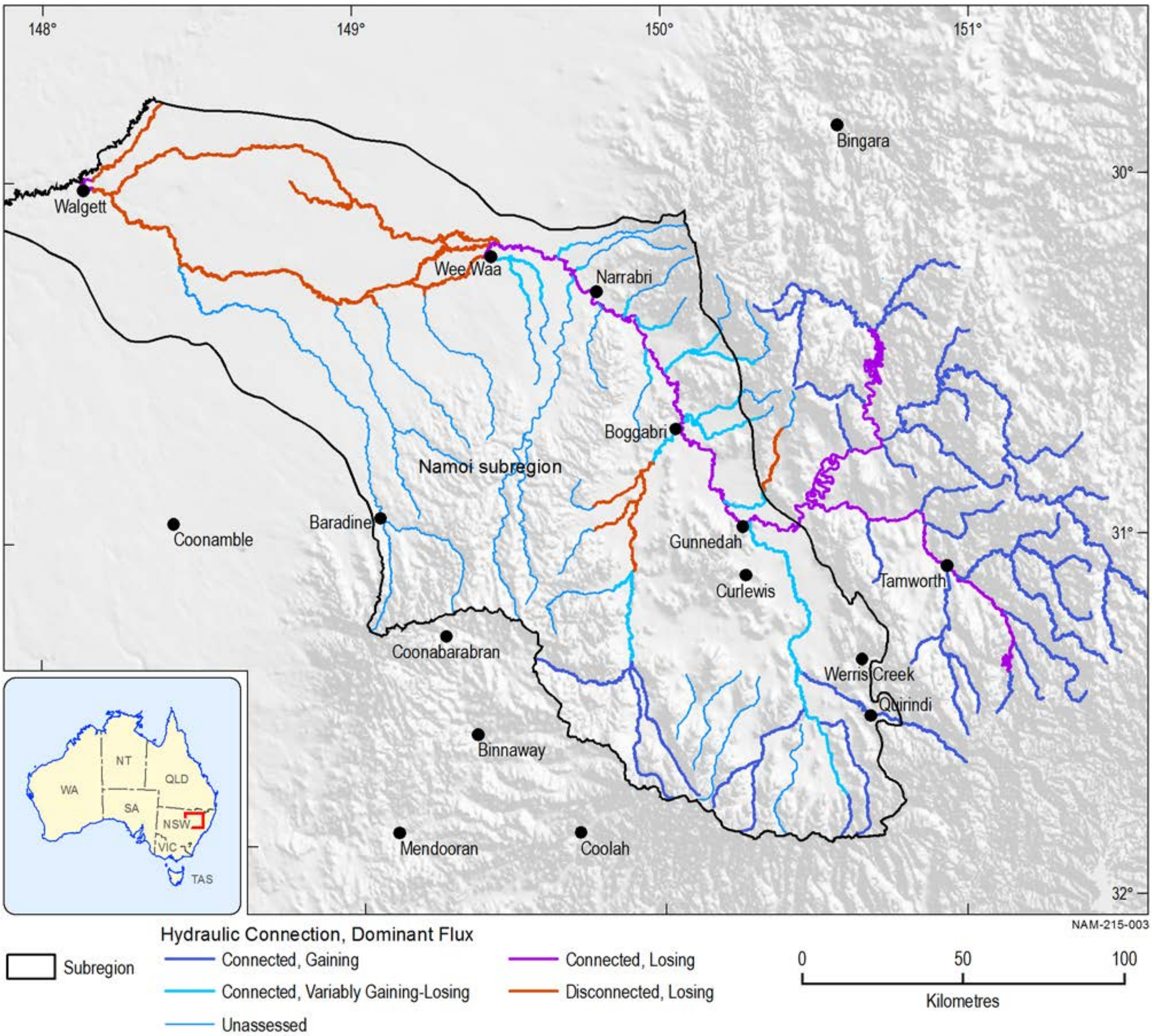

Figure 32 Stream–aquifer connectivity and dominant flux in the Namoi river basin over the length of the available hydrological data record through to 2003

Mapping is at the river-reach scale. Disconnected reaches are where the watertable depth is greater than 10 m from the surface. Data: Ivkovic (2006)

The hydrometric data were used to infer the dominant direction of flux for the unregulated streams. The dominant direction of flux for the connected regulated streams was classified as losing due to the artificially high stream stage as a consequence of stream regulation throughout the irrigation season (September to March).

The inferred connectivity between the stream and underlying aquifer based on the hydrometric data was cross-validated through the assessment of paired bore and stream hydrograph data and other previous hydrochemical investigations, such as Lavitt (1999) and McLean et al. (2000). These details are further discussed in Ivkovic (2006).

Importantly, Ivkovic (2006) observed that connectivity status and flux commonly changed over the length of the data record, depending on the timing of the analysis. For example, stream reaches mapped as predominantly connected also exhibited variable connectivity. Gaining streams also interchanged with losing streams. The variability in connectivity and flux was found to respond to natural (e.g. changing climate and rainfall-recharge dynamics) and human induced factors (e.g. groundwater extraction, stream regulation and water extraction).

There were some differences in the interpretation of the flux direction between the CSIRO (2007) and Ivkovic (2006) investigations, but these differences can largely be attributed to the use of datasets spanning different observational periods. In particular, the CSIRO (2007) investigation used data obtained circa June 2006, whereas Ivkovic (2006) used the full length of the available hydrological data record (from the earliest data available through to 2003), thus encompassing a broader spectrum of hydrological conditions. Ivkovic (2006) also included a class for variably gaining-losing for the connected aquifer – stream reaches, which the CSIRO (2007) study did not include since they were assessing a snapshot in time. Despite the differences in the CSIRO (2007) and Ivkovic (2006) assessments in relation to the direction of flux, the connectivity mapping is broadly similar, and provides credibility to both mapping efforts at the regional scale.

2.1.5.2.3 University of New South Wales – Maules Creek region investigations

Additional investigations into surface water – groundwater connectivity in the area of Maules Creek and the Namoi River between Boggabri and Narrabri (Namoi groundwater management zones 11 and 5, shown in Figure 33) were carried out by the University of New South Wales. They used a combination of geological data, geophysical methods, hydraulic data, and groundwater salinity, temperature and water chemistry data (Andersen and Acworth, 2007, 2009; Andersen et al., 2010; Giambastiani et al., 2012; McCallum et al., 2013; Rau et al., 2010). The results were consistent with CSIRO (2007) and Ivkovic (2006) and indicated that there is spatially and temporally varying degrees of connectivity between surface water and groundwater resources along the river reaches between Boggabri and Narrabri, with predominantly losing conditions during high flows and gaining conditions at low flows. However, McCallum et al. (2013) have noted that there has been a reversal in the aquifer–stream gradient in the Maules Creek catchment as a consequence of groundwater extraction, with the river now tending to lose water at low flows, rather than gain water.

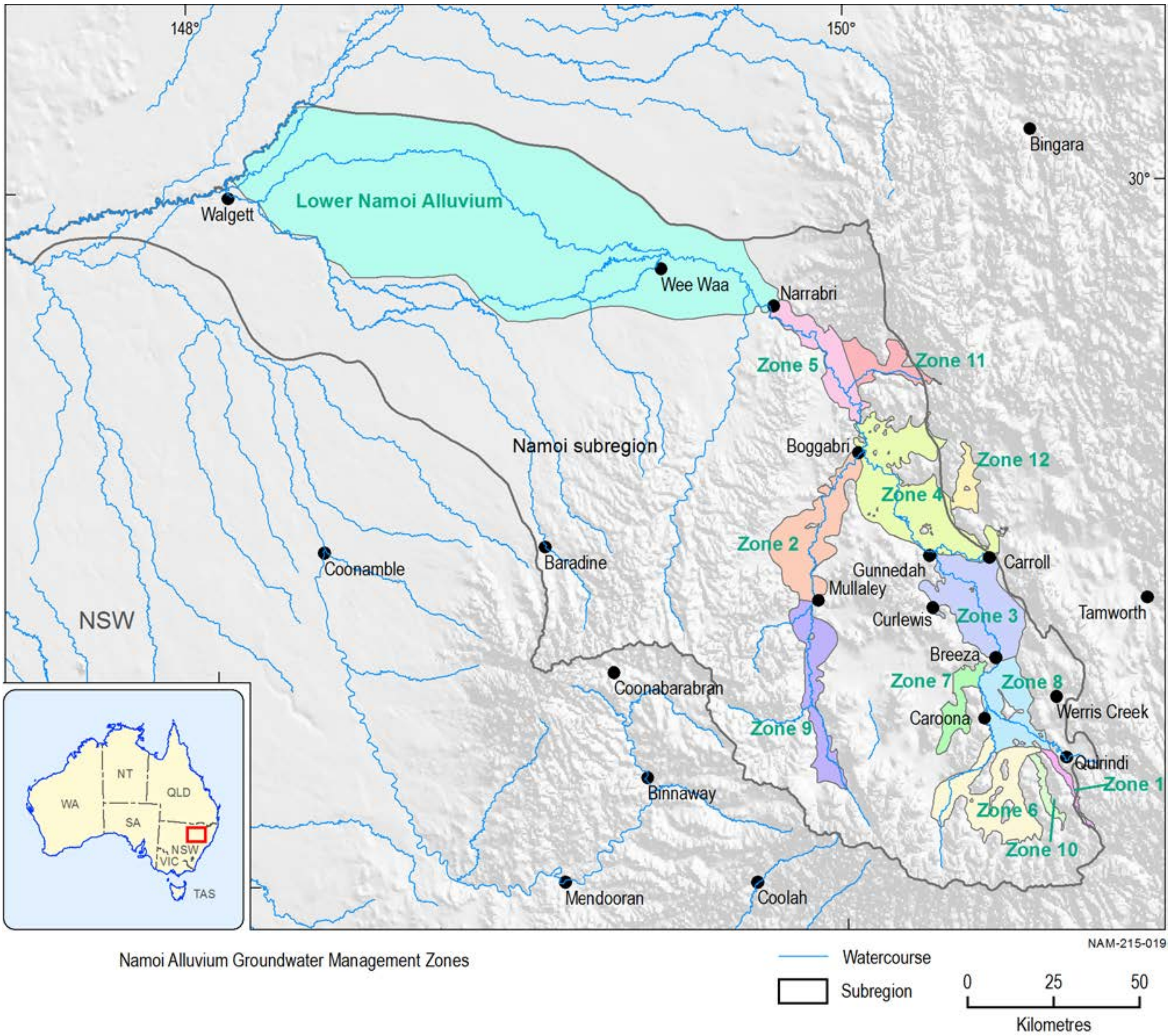

Figure 33 Groundwater management zones within the Upper and Lower Namoi Alluvium Groundwater Source

Data: NSW Office of Water (Dataset 11)

2.1.5.3 Overview of controls on surface water – groundwater connectivity based on previous investigations in the Namoi river basin

There is a degree of subjectivity in categorising a stream reach as connected or disconnected and a flux as gaining, variably gaining-losing or losing due to the dynamic variations in both groundwater and stream stage elevations that change temporally and spatially in response to a range of natural and human factors, some of which are listed below.

2.1.5.3.1 Natural controls

Hydrologic fluxes between surface water and groundwater systems are partly controlled by:

- the depth of the unconsolidated alluvial sediments
- the difference in elevation between the watertable adjacent to the stream and the corresponding stream stage
- the permeability and hydraulic conductivity of aquifer and streambed sediments

- the subsurface extent of transmissive versus confining layers existing between the upper aquifer and stream sediments
- aquifer–stream geometry
- climate and hydrological factors which influence the rainfall–runoff and recharge–discharge dynamics (including droughts and flooding), which in turn control groundwater and stream stage elevations.

2.1.5.3.2 Human controls

Human factors will have a measurable control on groundwater and stream stage elevations, with hydraulic gradients continually responding to these factors. Human factors include:

- river regulation
- surface and groundwater extractions
- land and water use.

The shallow aquifers of the Upper Namoi and Peel rivers have been identified by Barrett (2012) as highly connected to the adjacent streams, with more than 70% of the groundwater extraction volumes estimated to be derived from streamflow (Broadstock, 2009). In these areas groundwater recharge and resource availability is highly dependent on surface water flows (Green et al., 2011), and groundwater extraction bores are commonly located within a few kilometres of connected aquifer–stream systems.

Groundwater extraction from aquifers in hydraulic connection with a stream may result in a reversal of flux direction, with the direction of flow dependent on the difference between the groundwater elevation and stream stage. Gaining streams may become variably gaining-losing streams as groundwater elevation and stream stage relationships fluctuate under the influence of groundwater extractions. A lowered watertable, relative to stream height, results in the loss of streamflows to the underlying groundwater system (induced recharge). Eventually, a gaining stream may become a losing reach if the watertable continues to be lowered and there are insufficient volumes of groundwater recharge to compensate for the volumes of groundwater extracted. A time lag exists between the commencement of groundwater extraction and the impact on streamflow. As the distance between an extraction bore and stream increases, so does the lag in the timing between the start of pumping and the impact on streamflow (CSIRO and SKM, 2012b). A time lag also exists between the onset of groundwater extractions upgradient, and the resultant impact on throughflow down gradient, at the end of a river basin.

The impact of groundwater extractions on the adjacent stream was demonstrated by Ivkovic et al. (2009), who used a lumped parameter model to simulate the influence of groundwater extractions in the Coxs creek basin using 15 years of streamflow data. The model indicated that groundwater extractions from 1988 to 2003 had the effect of reducing baseflow discharges by approximately 82% of the volume of groundwater extracted (for rates up to 9000 ML/year), although the actual yearly reductions might be more or less depending on the particular climatic period. The remaining 18% of the total volume of groundwater extraction was assumed to affect the available volumes of subsurface throughflow, ultimately impacting on downstream flows. At extraction rates above 9000 ML/year, the model findings indicated that the stream would transition to a disconnected stream reach. Similar findings have been made for the Lower Namoi river basin. CSIRO (2007) reported that the Lower Namoi River has changed from a substantial gaining river prior to irrigated agricultural development to now become a largely losing river. They estimated that the current level of groundwater extraction in the Namoi river basin (as of 2007) would eventually reduce mean streamflow by a total of 99 GL/year.

2.1.5.4 Statistical analysis and interpolation

A new surface water – groundwater connectivity assessment representative of 2012 baseline conditions in the Namoi subregion was undertaken to help inform the surface water and groundwater numerical modelling components of the BA. The datasets and data processing methods that were used to develop the 2012 baseline assessment of surface water – groundwater connectivity and key findings are presented in the following sections.

2.1.5.4.1 Methods

A basin-scale surface water – groundwater connectivity assessment was undertaken for June 2012, and included the following:

- development of potentiometric surface of watertable aquifers
- determination of depth to watertable
- assessment of surface water – groundwater connectivity based on groundwater levels.

The basin-scale connectivity analysis was followed by a hydrological analysis of the Mooki river basin to provide additional process understanding of surface water – groundwater connectivity in this area. The hydrological analysis utilised streamflow data over the 2003 to 2012 period. Flow characteristics (stream hydrograph, baseflow component and flow duration data) were used to infer the dominant direction of flux over the assessment period and the findings were compared with pre-2003 conditions. Differential gauging results in the Mooki river basin for 2006, representing a dry period, and 2012, representing a wet period, were assessed and compared. Finally, in order to better conceptualise the changes in the watertable over time and provide greater context to the 2012 baseline surface water – groundwater connectivity assessment, the changes in the depth to watertable between 2006 and 2012 were evaluated. Further details and discussion follow in the sections below.

2.1.5.4.2 Namoi region basin-scale connectivity assessment

Raster surfaces representing the potentiometric surface and depth to groundwater were created using ArcGIS based on data obtained from monitoring bores screening the shallow alluvial aquifers (less than or equal to 45 m deep) using data for June 2012, or as close as possible (Bioregional Assessment Programme, Dataset 1). The month of June was chosen to enable comparison to the CSIRO June 2006 (CSIRO, 2007) investigation, with June typically being a low-flow month outside of irrigation season influences that commonly occur during the September to March period.

The water elevation point data for the shallow alluvial aquifers were used to create an interpolated potentiometric surface (groundwater level) (Figure 34), and shows that groundwater flows from the eastern margins in a north and westerly direction within the Namoi subregion, generally consistent with the surface water flow direction. Groundwater gradients are steeper, with contours located closer together, in the upper catchment where the topography is more elevated and steep and in areas of bedrock highs which constrict groundwater flow.

Figure 35 shows the locations of monitoring bores in the shallow alluvium (less than or equal to 45 m) together with the associated depth to watertable in June 2012, or as close as possible. These point data were used to create an interpolated depth to watertable raster surface using ArcGIS (Figure 36).

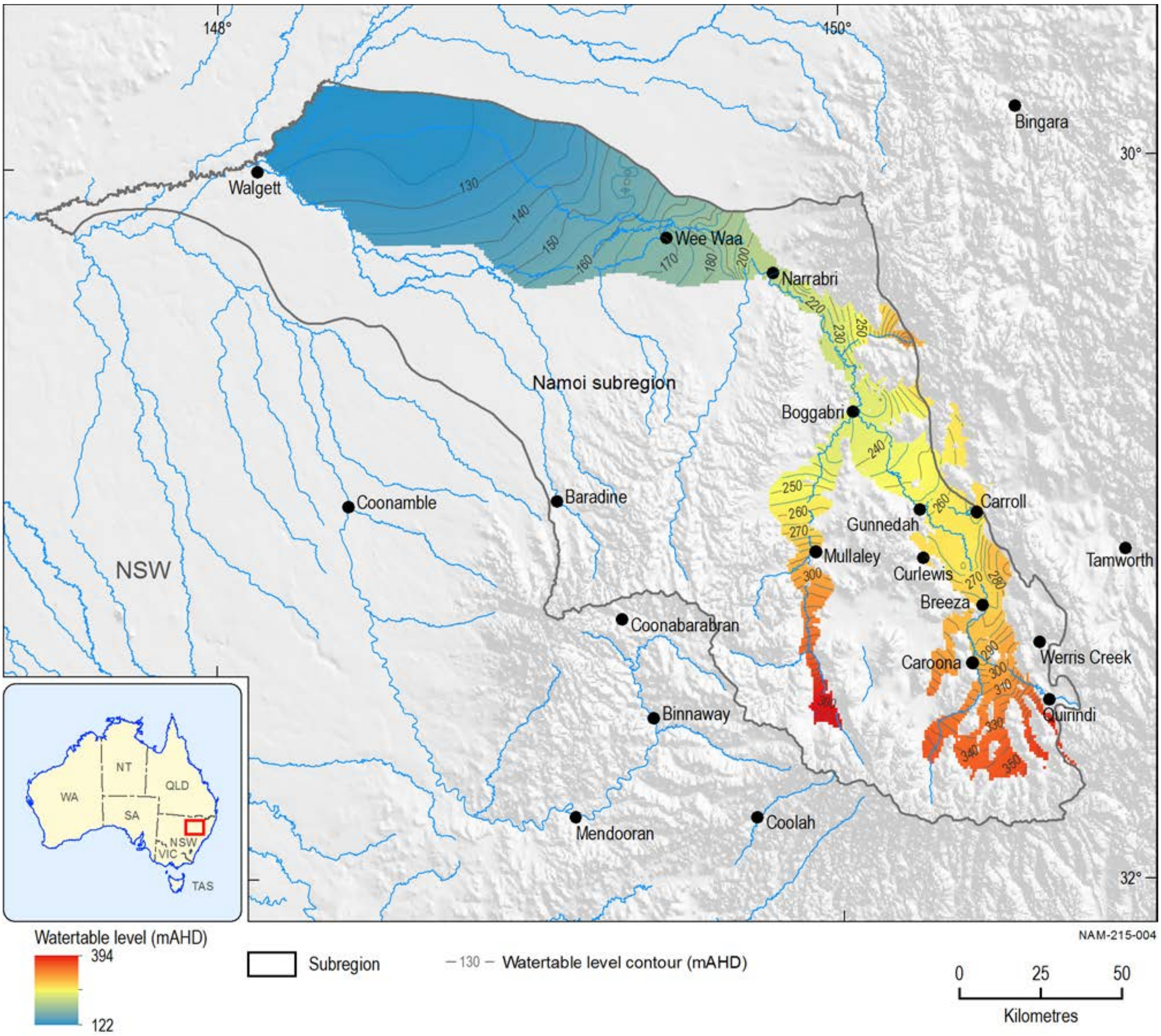

Figure 34 Watertable level interpolated surface for the Namoi subregion, June 2012

Data: Bioregional Assessment Programme (Dataset 2)

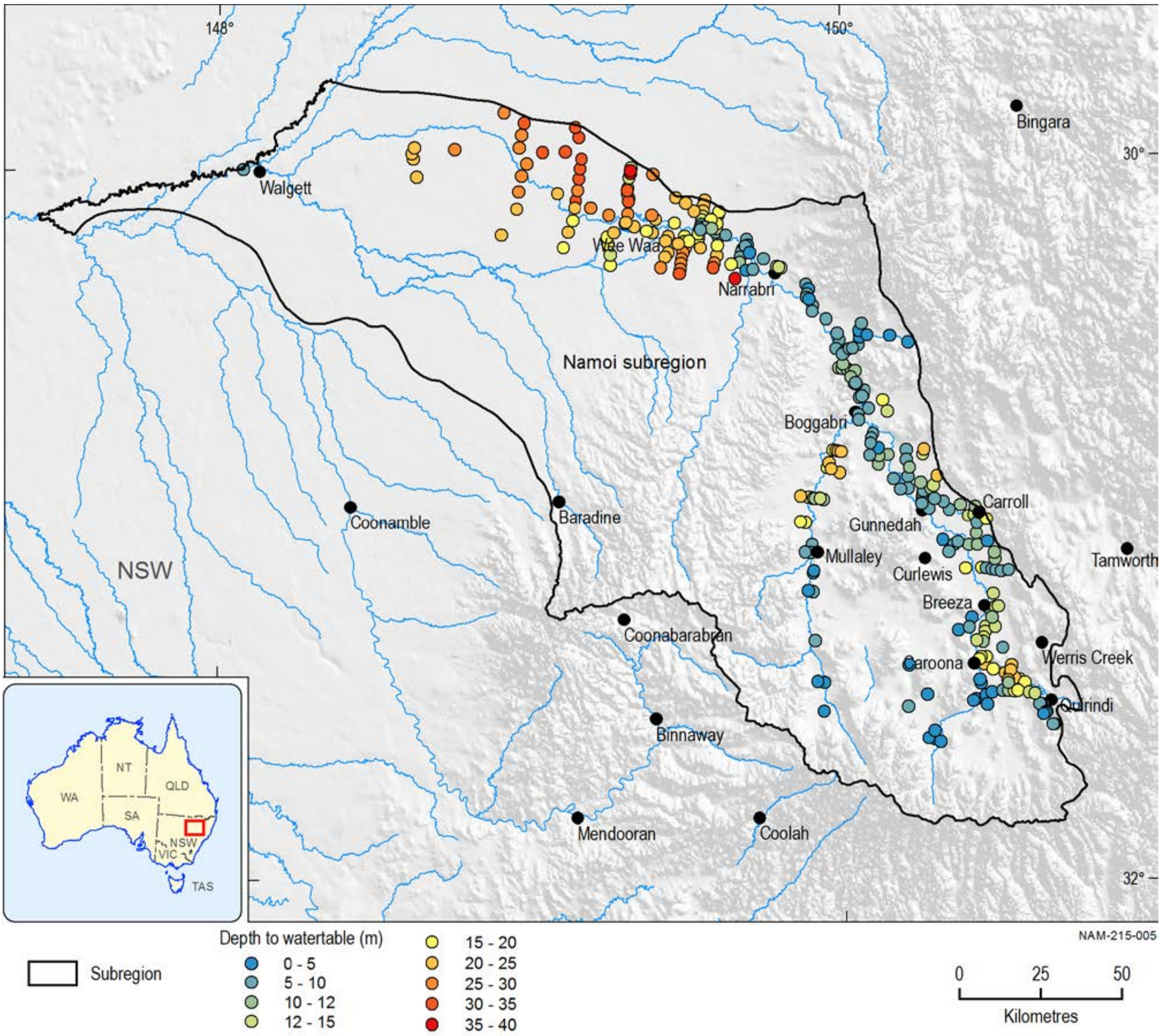

Figure 35 Monitoring bore locations and measured depth to watertable for shallow alluvial aquifers, June 2012

Data: Bioregional Assessment Programme (Dataset 3)

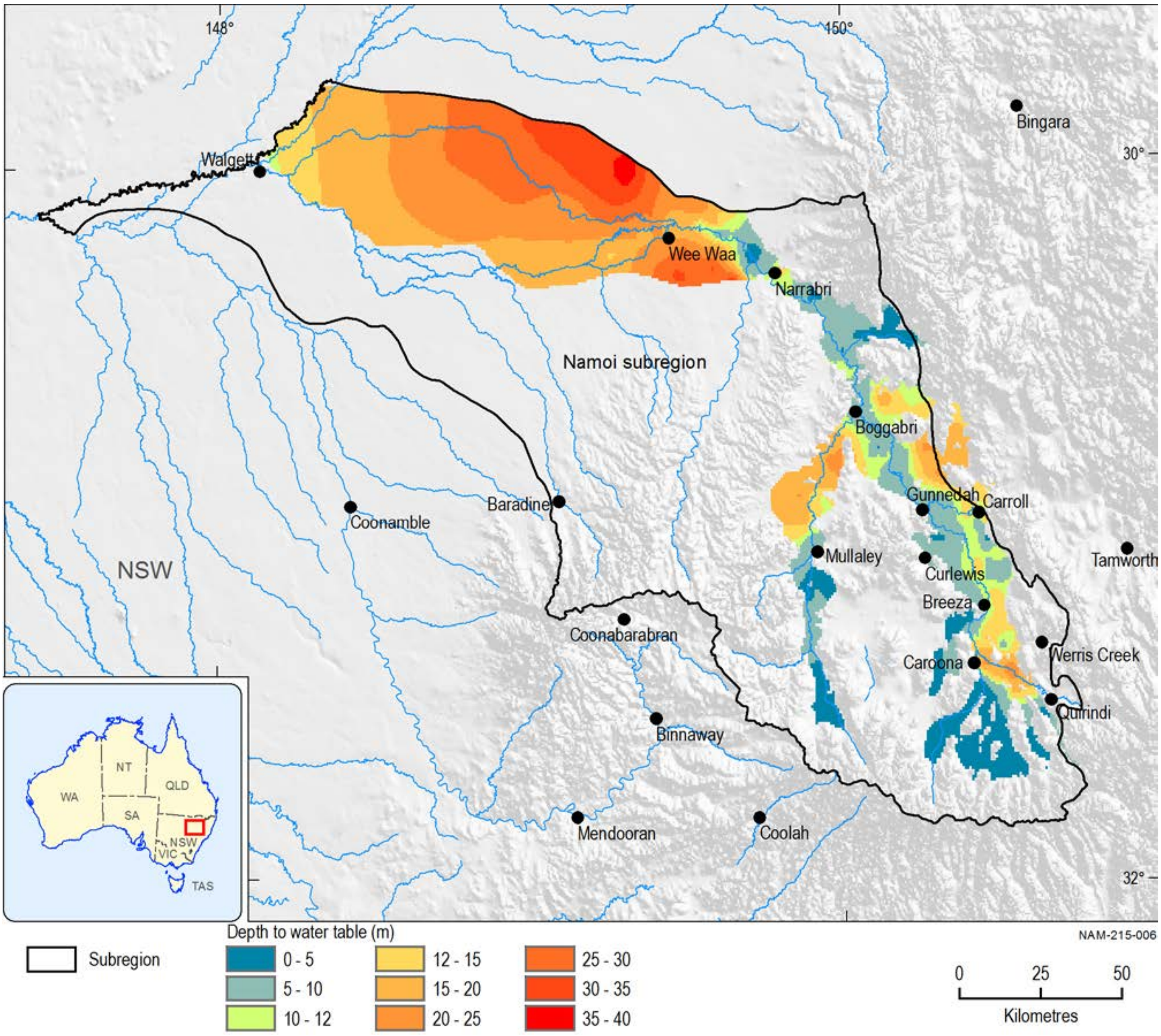

Figure 36 Depth to watertable interpolated surface for the shallow alluvial aquifers, June 2012

Data: Bioregional Assessment Programme (Dataset 2)

2.1.5.4.3 Inferring surface water – groundwater connectivity from groundwater levels

Monitoring bore data from within 1 km of the streams in the Namoi subregion were used to create a near-stream watertable raster surface representing June 2012 conditions (Figure 36). The data are summarised in Table 10. The same methodology used by Ivkovic (2006) to assess surface water – groundwater connectivity was employed, using a depth of 10 m as the cut-off point at which connectivity was inferred (Figure 38). Using a similar methodology allowed for a direct comparison of the changes in connectivity between the time of the Ivkovic (2006) investigation, representing groundwater level data from a time when there was less agricultural and coal resource development, relative to June 2012.

Recent field studies by Brownbill et al. (2011) in the Murray-Darling Basin, including two small field sites in the Lower Namoi river basin (Old Mollee and Yarral East), have suggested that subsurface depth of surface water – groundwater connectivity may be less than 10 m. The Brownbill et al.

(2011) study indicated that a cut-off of 6 m depth to water in the riparian zone may be more appropriate for determining connectivity status at lower elevations, where the topographic variation is relatively subdued. However, there is an absence of catchment-wide data in the riparian zone to confirm this depth more generally. Therefore, the use of 10 m for regional-scale mapping was considered appropriate for the BA for the Namoi subregion.

An additional class representing depths to groundwater in the range of greater than 10 to 12 m has been added to the connectivity map (Figure 38) to highlight stream reaches that are interpreted to transition from connected to disconnected. Although the addition of a transition class is somewhat arbitrary with respect to the depth to watertable range selected, this class was added to emphasise that streams transition from a state of connectivity to disconnection, rather than there being an abrupt change in the state of connection at some point along a stream reach. Moreover, an additional depth of 2 m over the 10 m connectivity cut-off depth allows for the importance of subsurface storages of water in the unsaturated zone in maintaining connectivity, where capillary effects are commonly reported to 2 m thickness (Kuo, 1999). Also, a transitional class is useful for indicating areas where the infiltration rate, or stream loss, to the underlying groundwater system may still be influenced by changes in watertable depth (Brownbill et al., 2011). Importantly, the transition to disconnection class also attempts to account for the sparse monitoring networks along the streams, which may not adequately represent underlying recharge mounds beneath the streams. These recharge mounds are critical to maintaining connectivity in losing stream systems (Lamontagne et al., 2014). These assumptions regarding the relationship between depth to groundwater and connectivity are made in the absence of more detailed peri-stream aquifer–streambed surveys that would allow for more robust assessment of connectivity in the Namoi river basin.

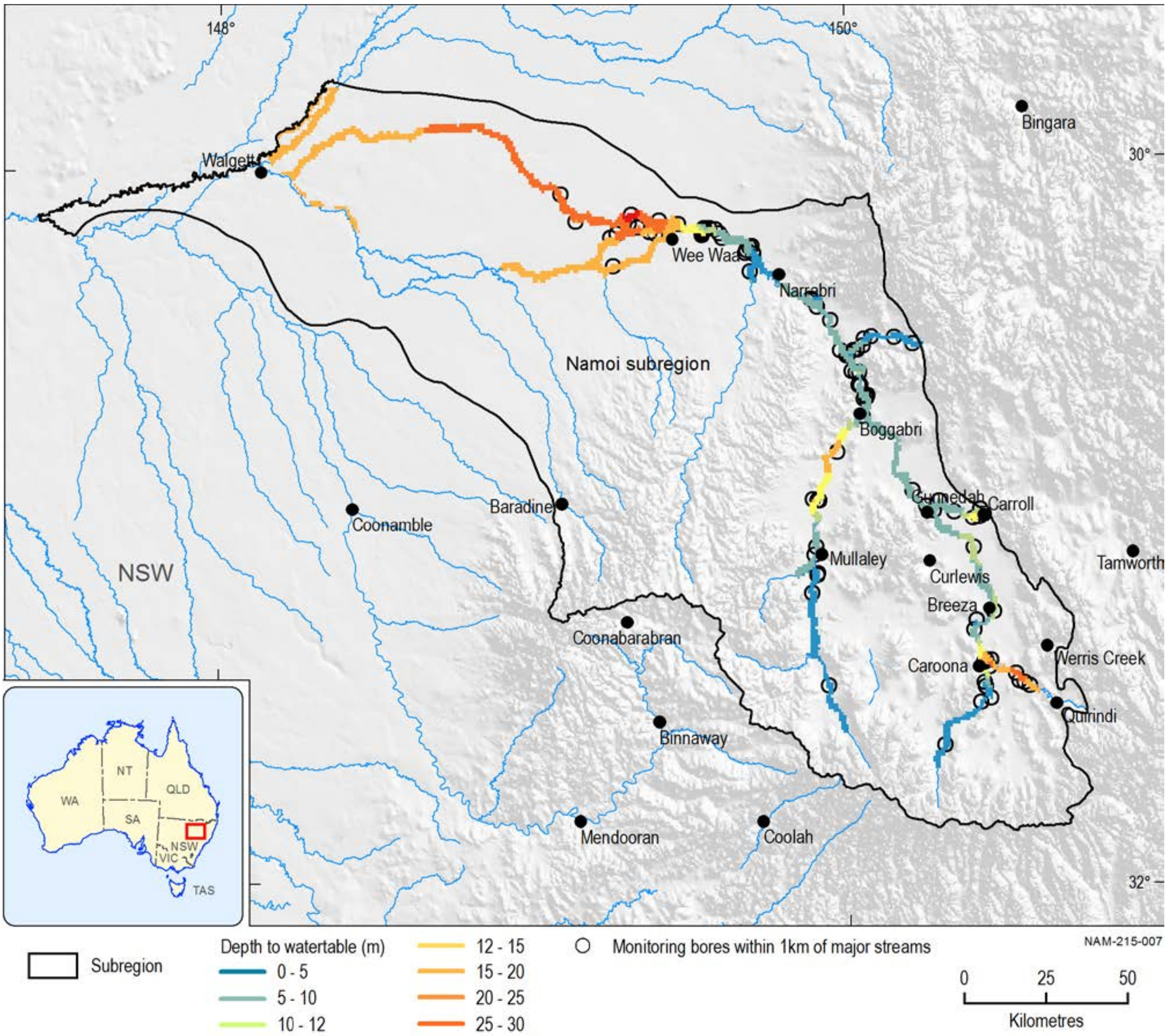

Figure 37 Depth to watertable interpolated raster surface based on monitoring bore data within 1 km of the river, June 2012

Data: Bioregional Assessment Programme (Dataset 2)

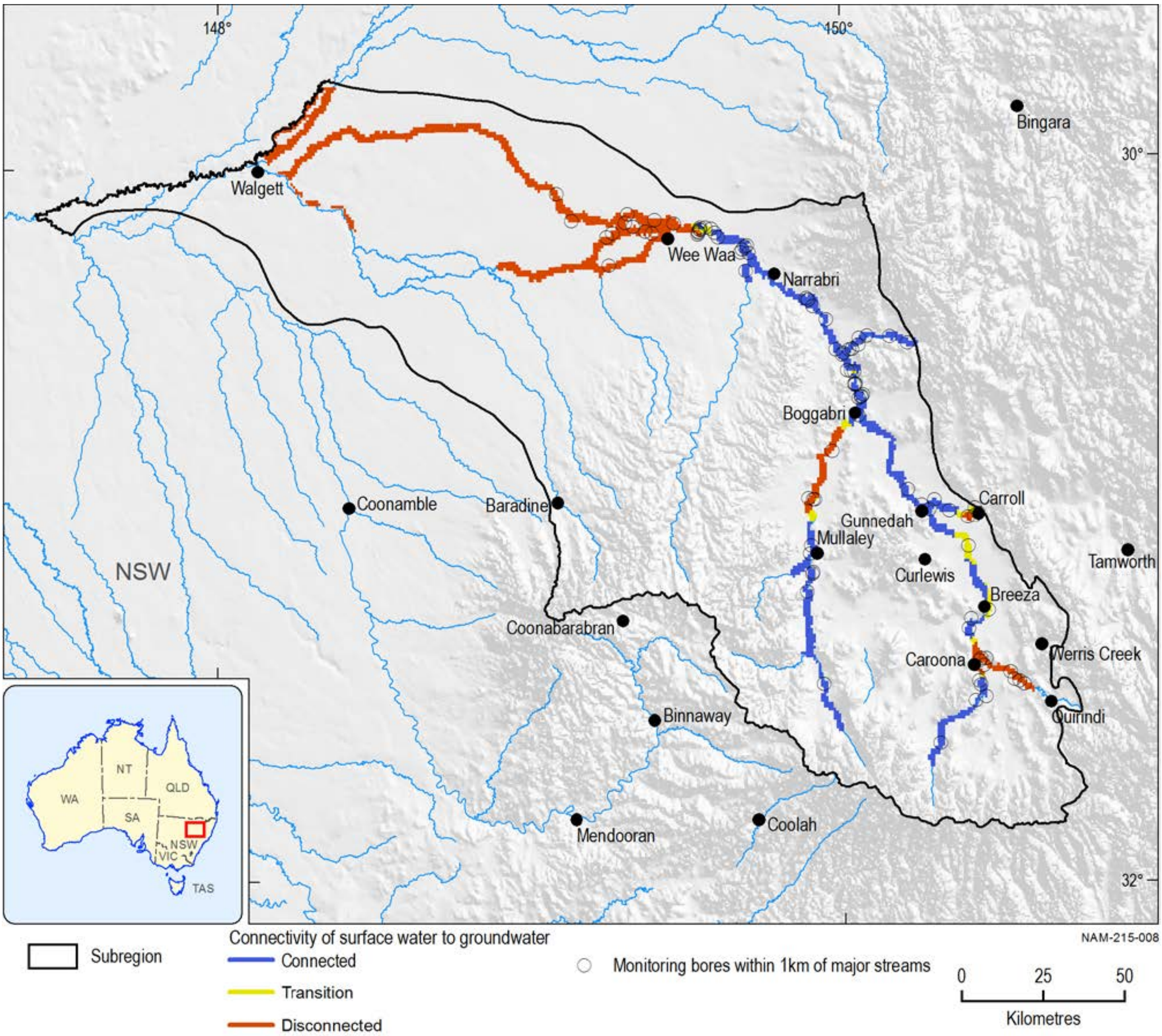

Figure 38 Inferred shallow alluvial aquifer–stream connectivity in the Namoi subregion based on the interpolated depth to watertable raster within 1 km of the stream, June 2012

Connected surface water – groundwater reaches (< or = 10 m); transition reaches (>10 m to 12 m); disconnected reaches (>12 m)
Data: Bioregional Assessment Programme (Dataset 2)

Table 10 List of shallow monitoring bores located within 1 km of the stream and their water levels in June 2012, or as close as possible

Registered number	Latitude	Longitude	Depth to watertable (m)	Date measured	Distance from stream (m)	Stream name
GW021412.1.1	–30.2245420°	149.6011410°	6.99	23 May 2012	683	Namoi River
GW025107.1.1	–30.2112090°	149.5916970°	8.1	23 May 2012	21	Namoi River
GW025138.1.1	–30.1576000°	149.3089230°	27.66	28 Jun 2012	593	Pian Creek
GW025216.1.1	–30.2470420°	149.6958620°	4.89	17 May 2012	846	Namoi River
GW025218.1.1	–30.2581530°	149.6797510°	9.21	21 May 2012	256	Namoi River
GW025219.1.1	–30.2667640°	149.6744740°	8.65	21 May 2012	787	Namoi River
GW025330.1.1	–30.2017650°	149.5425310°	7.94	23 May 2012	175	Namoi River
GW025332.1.1	–30.2084320°	149.5391980°	12.76	23 May 2012	75	Namoi River
GW025333.1.1	–30.2103760°	149.5386420°	15.19	23 May 2012	288	Namoi River
GW025419.1.1	–30.2156540°	149.5366980°	17.73	23 May 2012	899	Namoi River
GW030000.1.1	–31.2553700°	150.4747480°	10.81	27 Jun 2012	114	Mooki River
GW030054.1.1	–30.1967650°	149.5436420°	8.12	23 May 2012	489	Namoi River
GW030081.1.1	–31.4067600°	150.4597510°	21.28	17 Jul 2012	978	Quirindi Creek
GW030086.1.1	–31.4456480°	150.5580830°	20.59	17 Jul 2012	545	Quirindi Creek
GW030087.1.1	–31.4587030°	150.5908600°	17.44	19 Jul 2012	177	Quirindi Creek
GW030099.1.1	–30.1975980°	149.5611420°	11.5	23 May 2012	298	Namoi River
GW030116.1.1	–30.2500970°	149.6878070°	5.79	17 May 2012	536	Namoi River
GW030129.1.1	–30.5223170°	150.0522470°	6.05	31 May 2012	727	Maules Creek
GW030131.1.1	–30.5037060°	150.0561350°	4.19	31 May 2012	514	Maules Creek
GW030147.1.1	–31.4617600°	150.4489180°	3.77	18 Jul 2012	220	Mooki River
GW030152.1.1	–31.4503710°	150.4439180°	3.48	18 Jul 2012	314	Mooki River
GW030153.1.1	–31.5037050°	150.4322520°	0.99	18 Jul 2012	838	Mooki River
GW030175.1.1	–31.4937040°	150.4658630°	0.11	18 Jul 2012	66	Mooki River
GW030188.1.1	–30.1850990°	149.4591990°	15.09	29 May 2012	22	Pian Creek
GW030227.1.1	–30.3937070°	149.8858600°	5.55	30 May 2012	794	Namoi River
GW030229.1.1	–30.4162070°	149.9058590°	6.17	31 May 2012	513	Namoi River
GW030231.1.1	–30.4528730°	149.9486370°	5.27	31 May 2012	251	Namoi River
GW030255.1.1	–30.3164860°	149.6897510°	4.07	21 May 2012	187	Bohena Creek
GW030274.1.1	–31.4250920°	150.5458600°	22.53	17 Jul 2012	93	Quirindi Creek
GW030278.1.1	–30.3973180°	149.8919710°	4.47	31 May 2012	95	Namoi River

Registered number	Latitude	Longitude	Depth to watertable (m)	Date measured	Distance from stream (m)	Stream name
GW030297.1.1	–30.9756490°	150.2814150°	6.04	7 Jun 2012	105	Namoi River
GW030300.1.1	–30.9795380°	150.3478030°	8.38	21 Jun 2012	644	Namoi River
GW030304.1.1	–30.9975930°	150.4083570°	13.59	21 Jun 2012	101	Namoi River
GW030305.1.1	–30.9950930°	150.4283570°	12.02	21 Jun 2012	187	Namoi River
GW030306.1.1	–30.9873290°	150.4421680°	9.72	21 Jun 2012	529	Namoi River
GW030343.1.1	–30.9637210°	150.2573650°	7.83	7 Jun 2012	775	Namoi River
GW030380.1.1	–31.3875930°	150.4491950°	17.54	30 Apr 2012	7	Quirindi Creek
GW030381.1.1	–31.3939820°	150.4430840°	17.97	17 Jul 2012	785	Mooki River
GW030468.1.1	–30.6687060°	150.0541930°	7.42	7 Jun 2012	178	Namoi River
GW030469.1.1	–30.6645390°	150.0633590°	7.85	7 Jun 2012	644	Namoi River
GW036004.1.1	–30.5345400°	149.9800260°	8.38	6 Jun 2012	193	Namoi River
GW036007.1.1	–30.6312060°	150.0389150°	6.89	6 Jun 2012	297	Namoi River
GW036008.1.1	–30.6314840°	150.0433590°	6.47	6 Jun 2012	103	Namoi River
GW036014.1.1	–30.5928730°	150.0164150°	9.43	6 Jun 2012	969	Namoi River
GW036015.1.1	–30.5950950°	150.0291920°	10.01	6 Jun 2012	909	Namoi River
GW036016.1.1	–30.5964840°	150.0403030°	10.5	6 Jun 2012	363	Namoi River
GW036021.1.1	–30.2109330°	149.3872560°	20.46	29 May 2012	676	Gunidgera Creek
GW036022.1.1	–30.2067660°	149.3672560°	17.31	29 May 2012	149	Gunidgera Creek
GW036023.1.1	–30.1931550°	149.3283670°	22.36	29 May 2012	618	Gunidgera Creek
GW036036.1.1	–30.1814890°	149.3011450°	24.51	29 May 2012	952	Pian Creek
GW036047.1.1	–30.2673190°	149.7011360°	2.35	21 May 2012	102	Namoi River
GW036057.1.1	–30.6295390°	150.0422480°	7.11	6 Jun 2012	231	Namoi River
GW036060.1.1	–30.1753770°	149.3975330°	23.66	29 May 2012	564	Pian Creek
GW036062.1.1	–30.2987110°	149.2480920°	16.3	29 May 2012	33	Namoi River
GW036065.1.1	–30.2212110°	149.2411470°	19.79	29 May 2012	795	Gunidgera Creek
GW036066.1.1	–30.2092670°	149.2614240°	21.37	29 May 2012	462	Gunidgera Creek
GW036092.1.1	–30.6664830°	150.0614150°	5.57	7 Jun 2012	377	Namoi River
GW036093.1.1	–30.5448170°	150.0047480°	4.19	6 Jun 2012	540	Namoi River
GW036096.1.1	–30.5498170°	149.9997480°	6.68	6 Jun 2012	228	Namoi River
GW036149.1.1	–31.0781480°	150.4105810°	11.77	26 Jun 2012	440	Mooki River
GW036154.1.1	–30.1742670°	149.1269810°	19.96	29 May 2012	553	Pian Creek

Registered number	Latitude	Longitude	Depth to watertable (m)	Date measured	Distance from stream (m)	Stream name
GW036186.1.1	–30.5353730°	150.0228030°	5.55	6 Jun 2012	37	Maules Creek
GW036187.1.1	–30.5334280°	150.0333580°	5.18	6 Jun 2012	699	Maules Creek
GW036232.1.1	–30.0989900°	149.0794820°	24.6	29 May 2012	616	Pian Creek
GW036239.1.1	–30.9489820°	150.2989150°	8.13	18 Jun 2012	354	Namoi River
GW036434.1.1	–30.8145400°	149.9669740°	18.67	2 Jul 2012	966	Coxs (Turrabeile) Creek
GW036475.1.1	–30.9206500°	150.2122490°	5.75	7 Jun 2012	403	Namoi River
GW036495.1.1	–30.9445410°	149.8869770°	16.08	4 Jul 2012	907	Coxs (Turrabeile) Creek
GW036499.1.1	–30.9467630°	149.9019770°	12.82	4 Jul 2012	216	Coxs (Turrabeile) Creek
GW036506.1.1	–31.0762070°	149.8964240°	6.55	5 Jul 2012	7	Coxs (Turrabeile) Creek
GW036507.1.1	–31.0975960°	149.8917020°	6.28	5 Jul 2012	646	Coxs (Turrabeile) Creek
GW036512.1.1	–31.1534300°	149.8997580°	4.48	5 Jul 2012	428	Coxs (Turrabeile) Creek
GW036544.1.1	–30.9473180°	149.9083660°	11.79	4 Jul2012	544	Coxs (Turrabeile) Creek
GW036565.1.1	–30.7164840°	150.0511380°	7.18	28 Jun 2012	497	Namoi River
GW036569.1.1	–31.2025960°	149.8817030°	3.38	5 Jul 2012	67	Coxs (Turrabeile) Creek
GW036593.1.1	–31.1486160°	149.9012830°	3.58	5 Jul 2012	460	Coxs (Turrabeile) Creek
GW036654.1.1	–31.4561660°	149.9337550°	1.23	5 Jul 2012	159	Bundella Creek
GW036882.1.1	–30.0163020°	148.0624190°	8.42	28 May 2012	208	Barwon River
GW040822.1.1	–31.5186110°	150.4683330°	0.76	18 May 2012	696	Big Jack's Creek
GW041027.1.1	–30.5179130°	150.2148160°	3.87	31 May 2012	188	Maules Creek
GW093105.1.1	–31.2792820°	150.4180110°	2.32	9 Jul 2012	948	Mooki River
GW093106.1.1	–31.3060850°	150.4108710°	7.56	9 Jul 2012	60	Mooki River
GW967137.1.1	–30.4975910°	150.0812160°	4.25	31 May 2012	181	Maules Creek
GW967138.1.1	–30.4995080°	150.1556750°	2.82	31 May 2012	58	Maules Creek

Data: Bioregional Assessment Programme (Dataset 4)

The surface water – groundwater connectivity assessment in Figure 38, when compared to the assessments previously made by CSIRO (2007) (Figure 30) and Ivkovic (2006) (Figure 32), indicates an increase in regions of disconnection where the interpolated depth to watertable is greater than 10 m. Areas of increased disconnection occur in the Mooki river basin, in the region from Quirindi downstream to Caroona, and a small portion of the river reach between Breeza and Gunnedah. Reaches classed as transitional occur in the mid Mooki river basin downstream of Breeza and small areas in the Coxs creek basin, both upstream and downstream of the disconnected reach between Mullaley and Boggabri. This suggests a greater proportion of stream reach is becoming disconnected with a lowering of the watertable. Another area in the Upper Namoi river basin with disconnected and transition to disconnection reaches is the region around Carroll. The assumptions in this assessment include:

- a depth to watertable of less than or equal to 10 m indicates an area of probable hydraulic connection between the aquifer and stream
- a class of greater than 10 to 12 m indicates a transition to disconnection class
- a depth to watertable of greater than 12 m indicates an area of probable disconnection
- the interpolated surface obtained from monitoring bores located within 1 km of the streams accurately represents the watertable level adjacent to the stream in June 2012, or as close as possible.

2.1.5.4.4 Hydrological analysis of Mooki river basin

The Mooki river basin hosts a number of historical and proposed coal mines including the Caroona and Watermark projects (refer to companion product 1.2 (coal and coal seam gas resource assessment) (Northey et al., 2014) and product 2.3 (conceptual modelling) for the Namoi subregion (Herr et al., 2018)). The more detailed analysis here is undertaken to assess surface water – groundwater interactions in this catchment and to inform hydrological modelling, both surface water and groundwater (refer to companion product 2.6.1 (Aryal et al., 2018) and product 2.6.2 (Janardhanan et al., 2018) for the Namoi subregion).

In order to further assess connectivity in the Mooki river basin, hydrometric data were analysed to cross-validate the interpolated depth to watertable surface and connectivity interpretation. Figure 38 shows the Mooki river basin and the locations of the streamflow gauging stations used in this analysis. The streamflow gauging station data were analysed over the period May 2003 to July 2012 (9.1 years) to assess how surface water – groundwater interactions during this period differed to the pre-2003 (Ivkovic, 2006) investigation. This date range was selected because data were available across all streamflow gauging stations without any gaps. It is noted that the pre-2003 period does not represent an undisturbed system, as declines in groundwater levels were already being observed at this time. For example CSIRO (2007) showed increasingly losing conditions over the period 1997 to 2007.

The observed streamflow was filtered using the Lyne and Hollick (1979) baseflow filter using a filter parameter of 0.925. Flow characteristics were assessed according to the shape of the streamflow hydrograph (an example hydrograph is shown in Figure 40) as well as flow duration data (Figure 41) using the methods described in Section 2.1.5.2.2 to determine the dominant direction of flux over the assessment period, with characteristics summarised in Table 11.

It is noted that baseflow analysis contains a number of assumptions (Halford and Mayer, 2000) and further investigation of the baseflow characteristics of the Namoi river basin would be a useful contribution to future studies.

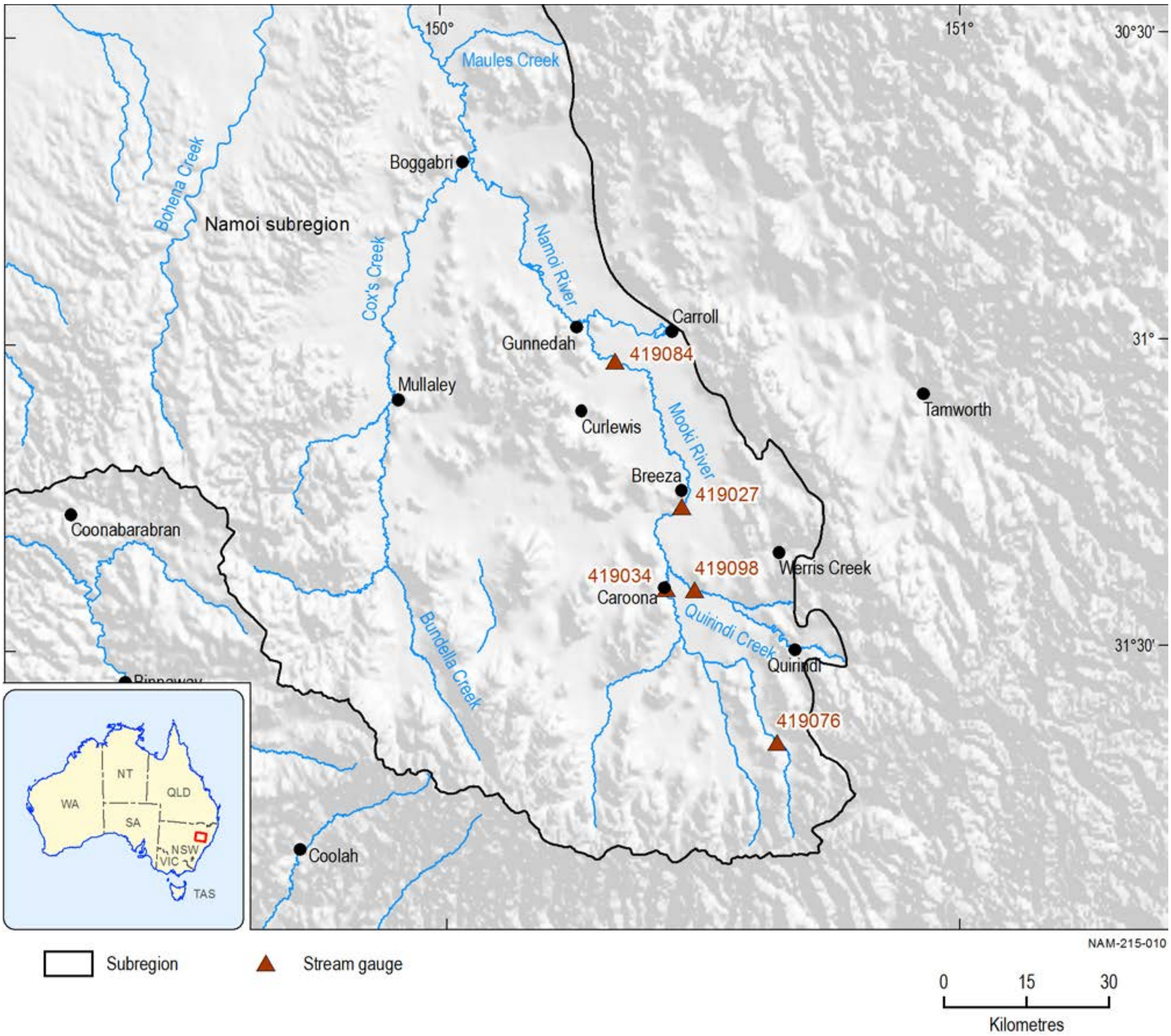

Figure 39 Streamflow gauging stations analysed in the Mooki river basin

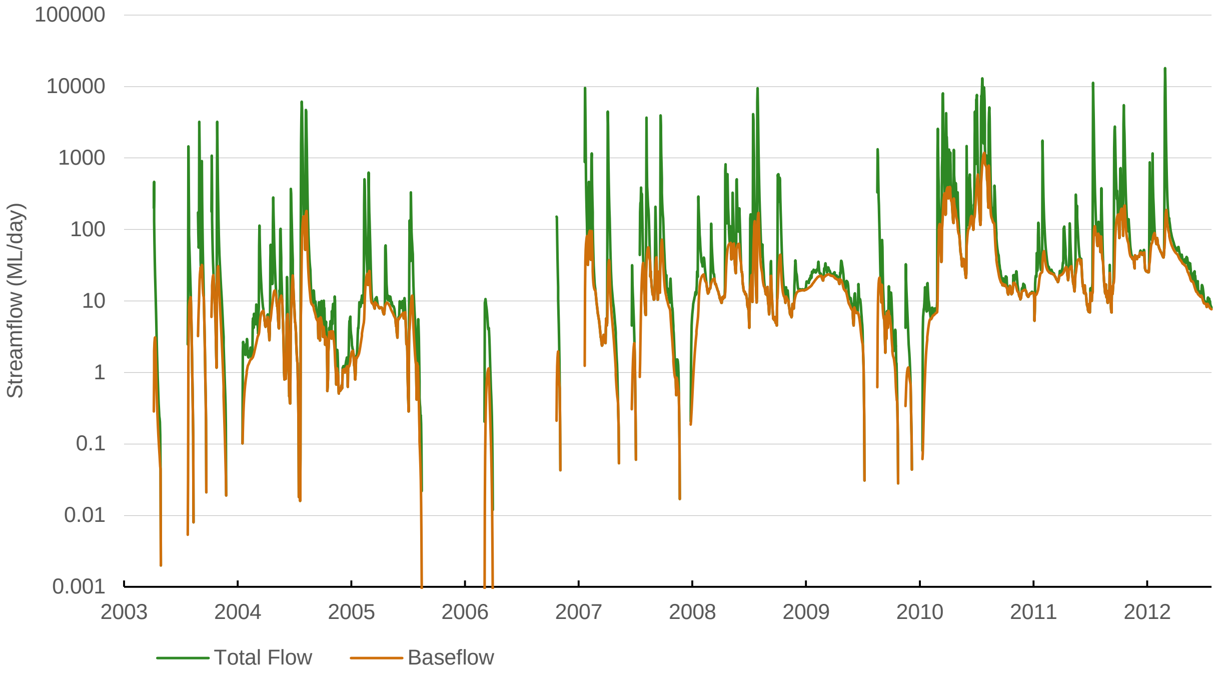

Figure 40 Example stream hydrograph, for streamflow gauging station 419076: Warrah Creek @ Old Warrah (2003 to 2012) exhibiting predominantly connected-gaining characteristics

Connected-gaining stream reaches are classified (in this study) as those with flow measured over 90% of the streamflow record, and where analysis of groundwater levels and stream height indicate connection (Figure 38).
Data: Bioregional Assessment Programme (Dataset 5)

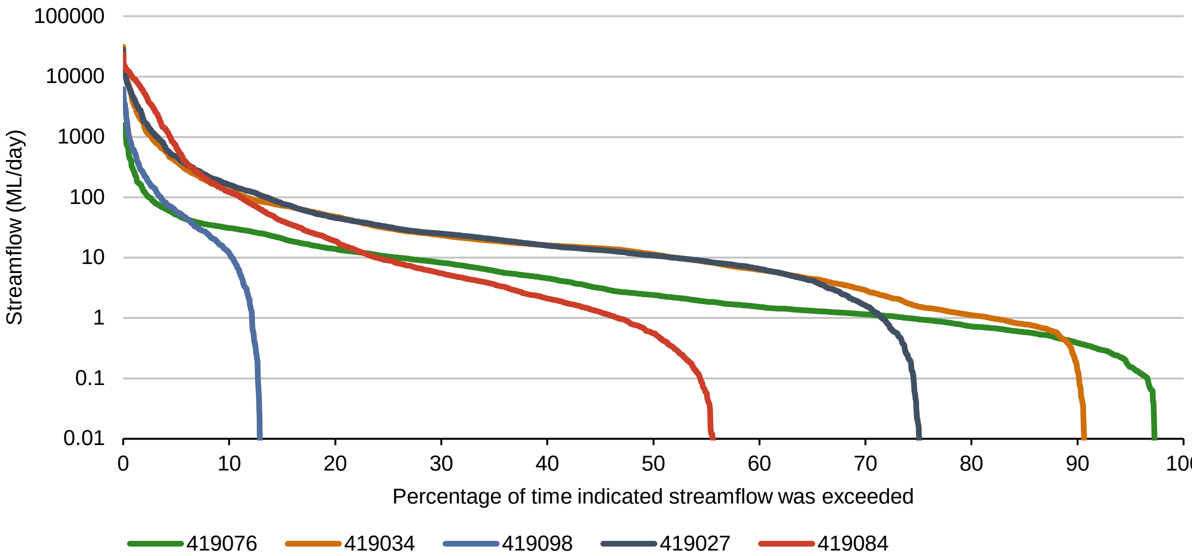

Figure 41 Flow duration curves representing the percentage of time that indicated streamflow was exceeded at selected Mooki river basin stream gauges (2003 to 2012)

Data: Bioregional Assessment Programme (Dataset 6)

When compared to the pre-2003 period, the mean flows (total discharge and baseflow) between 2003 and 2012 are considerably reduced (Table 11). The percentage difference reductions in mean baseflow of the order of 62% and 20% were calculated for gauging stations 419027 and 419084 respectively. The reduction in flows is likely to be in part due to the lower than average rainfall since 2003, as well as the influence of groundwater extractions on river connectivity and flows. Overall, there is a similar pattern as described by Ivkovic (2006) with baseflows generated in the upper catchment, with a decrease in the baseflow index (BFI) and flow duration down the catchment.

Some sections of the Mooki River between gauging stations 419027 and 419084 were mapped as transition to disconnected reaches, based on the interpolated depth to watertable (Figure 38). The streamflow data suggest that this section of the river has maintained variable connection as a mostly losing reach between 2003 and 2012, and this represents a change from being identified as a mostly gaining reach over the length of the hydrological data record prior to 2003.

Table 11 Flow characteristics at unregulated streamflow gauging stations in the Mooki river basin

Gauge ID	Catchment name and location	Date range	Mean discharge (ML/d)	Mean baseflow (ML/d)	Baseflow index	Percentage of time stream flows	Dominant direction of flux[a]
419076	Warrah Creek at Old Warrah	1982–2003	32	7	0.23	97%	Connected gaining
		2003–2012	18	6	0.32	97%	Connected gaining
419034	Mooki River at Caroona	1965–2003	210	28	0.13	87%	Variably connected-disconnected; variably gaining and losing-mostly gaining
		2003–2012	158	24	0.15	91%	Connected gaining
419098	Quirindi Creek at Greenacre	2003–2012	27	2[b]	0.07[c]	13%	Disconnected losing
419027	Mooki River at Breeza	1957–2003	322	53	0.17	88%	Variably connected-disconnected; variably gaining and losing-mostly gaining
		2003–2012	171	28	0.16	75%	Variably connected-disconnected; variably gaining and losing-mostly losing
419084	Mooki River at Ruvigne	1994–2003	462	60	0.13	53%	Variably connected-disconnected; variably gaining and losing-mostly losing
		2003–2012	288	49	0.17	56%	Variably connected-disconnected; variably gaining and losing-mostly losing

[a]Based on visual inspection of the stream hydrograph and flow duration data using Ivkovic (2009) methodology
[b]No baseflows are expected at this site because the river is disconnected from the underlying groundwater.
[c]The estimated BFI of 0.07 gives an indication of the range of error possible when using the Lyne and Hollick filter using a filter parameter of 0.925 in this subcatchment.
Data: Bioregional Assessment Programme (Dataset 7)

There are few monitoring bores near the streamflow gauging stations along the Mooki River by which to confirm groundwater levels adjacent to the river. Further assessment of surface water – groundwater connectivity between Caroona and Breeza or groundwater management zone 8 more generally is warranted given the water resource pressures in this zone.

The current hydrological assessment confirms the connectivity mapping in the river around gauging station 419098, as a disconnected section along Quirindi Creek, between Caroona and Quirindi (Figure 38), as suggested by the absence of baseflow periods in the stream hydrograph, and the steep slope of the flow duration data (Figure 41). This area had been previously mapped as a connected aquifer–river system by Ivkovic (2006).

Differential gauging results for 2012 and 2006 in the Mooki river basin

The differences in mean river discharge between gauging stations 419034, 419027 and 419084 were calculated for the 2012 (wet year) and 2006 (dry year) assessment periods to estimate the mean volume of water lost or gained along the river reach (between the streamflow gauging stations). It was assumed for this estimation that evapotranspiration effects and inflows from the ephemeral Quirindi Creek and other minor tributaries were negligible. The flow summary statistics presented in Table 11 and Table 12 suggest that while this is a simplification of the system, it is not unreasonable. Quirindi Creek flowed only 13% of the time in the period 2003 to 2012, and mean discharge over this period was less than 20% of the mean discharge in the Mooki River upstream of the confluence of the two streams.

The results for the 2012 wet year show transmission losses of around 1.2 ML/day/km between gauging stations 419034 and 419027, followed by a subsequent gain of approximately 20 ML/day/km between gauging stations 419027 and 419084 (Table 12). Overall, there was a cumulative gain of 12.9 ML/day/km between the upstream gauge (419034) through to the catchment outlet as measured at Ruvigne (419084).

Table 12 Differential gauging results for mean flows in the Mooki river basin for 2006 (dry year) and 2012 (wet year)

Gauge ID	Distance between gauging stations (river km)	Cumulative distance (river km)	Year	Mean discharge (ML/d)	Segment loss (ML/d/km)[a]	Cumulative loss (ML/d/km)[a]
419034	0	0	2006	3.8	na	na
			2012	408	na	na
419027	22.8	22.8	2006	1.6	0.1	0.1
			2012	380	1.2	1.2
419084	44.9	67.7	2006	0.3	0.03	0.05
			2012	1280	–20.0	–12.9

[a]minus = gain, na = not applicable
Data: Bioregional Assessment Programme (Dataset 8)

The results for the 2006 dry year show transmission losses along the length of river from gauging station 419034 through to 419084 (Table 12). The mean losses estimated at gauging station 419084 are very low due to the extremely dry conditions in 2006, resulting in the river being dry throughout much of the year.

The differential gauging results demonstrate how the Mooki River reaches vary in their dominant flux, with river losses dominating over dry periods and gains over wet periods. River losses between gauging stations 419034 and 419027 now occur during wet periods as well as dry, with data from gauge 419027 indicating a change from a variably connected, mostly gaining system to a mostly losing system as an aggregate upstream response. The data from gauging station 419084 suggest a variably connected mostly losing river reach as an aggregate upstream response, consistent with pre-2003 conditions.

This analysis could be further refined using data for the metered extraction bores and river off-takes in the area of analysis. This would enable a more detailed analysis of the losses between gauges, to take account of extractions. However, the required data were not available for this bioregional assessment.

2.1.5.4.5 Groundwater level changes between 2006 and 2012

To better understand the changes in depth to watertable over time, and to provide context to the 2012 baseline connectivity investigation, groundwater level (depth to watertable) changes were assessed between 2006 and 2012. The year 2006 was used as a comparison year with 2012 for several reasons, including:

- The CSIRO (2007) investigation represents a snapshot in time for the June 2006 period.
- The year 2006 was when the Water Sharing Plans for the *Upper and Lower Namoi Groundwater Sources* were initially implemented (NSW Department of Primary Industries Office of Water, 2013), so the influence of these plans between 2006 and 2012 can be assessed, to some extent.
- The 2006 period represents a period of drought, which lasted through to 2009. This dry period was subsequently followed by drought breaking conditions between 2010 through to 2012, when annual rainfall totals were significantly and consistently higher than average across the entire Namoi river basin (Burrell et al., 2013).

The residual mass rainfall curve for data from the Boggabri Post Office (gauging station 55007) between 1970 and 2012 is shown in Figure 42. The residual mass represents the cumulative deviation from the mean monthly rainfall (blue line) over the length of the rainfall record assessed (orange line), with the falling sections of the residual mass (green line) indicating periods of below average rainfall.

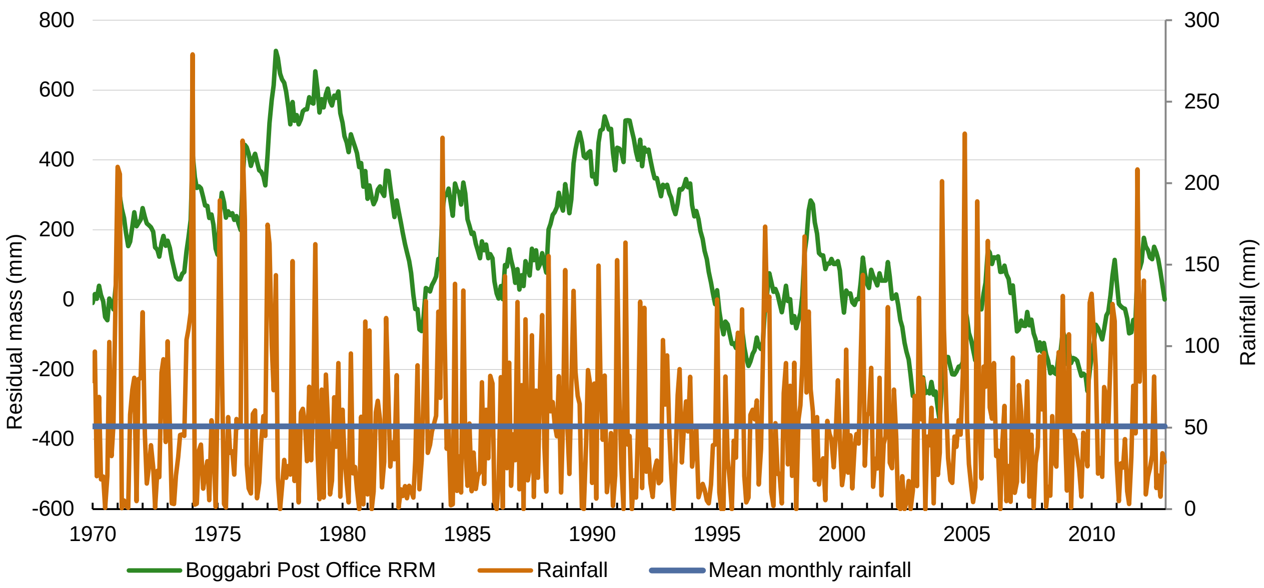

Figure 42 Residual rainfall mass curve (1970 to 2012, using monthly data), Boggabri Post Office gauging station 55007

Data: Bureau of Meteorology (Dataset 9)

A comparison of the 2006 and 2012 conditions allows for an assessment to be made on how groundwater storages have changed during the 2010 to 2012 high rainfall years from the previous drought years. The difference between the 2012 and 2006 depth to watertable interpolated raster surfaces for the shallow aquifer is shown in Figure 43. The figure also shows the locations of monitoring bores used to create the interpolated surfaces, highlighting areas where input data are limited (for example upstream of Caroona), or single data points have a strong influence on the predicted surface (for example in the lower Namoi). Figure 43 shows widespread increases in watertable level over large areas of the Namoi river basin, likely indicating replenishment of groundwater resources during higher rainfall years. Large increases in the watertable level, by up to 11 m in some areas, are shown in areas of the Mooki river basin (between Breeza and Gunnedah) and the Coxs creek basin (just to the north of Mullaley), where the streams have been mapped (in the 2012 assessment) as transition to disconnection and disconnected reaches (Figure 38). Despite the evidence of considerable increases in watertable level between 2006 and 2012, the increases in groundwater storage have not been sufficiently high to return transitional and disconnected stream reaches to the previous state of connection (based on earlier interpretations).

The area between Caroona and Breeza in the Mooki river basin (groundwater management zone 8, refer to Figure 33) shows only modest levels of groundwater recovery (0.8 m or less) between 2006 and 2012, as evidenced by a typical bore hydrograph GW030008 (located about 3 km south-east of the Mooki River) (Figure 44). One can see from this figure that the water levels exhibit a pattern indicative of regular perturbation that appears to reflect groundwater extraction events, as well as a response to rainfall trends. It is evident from this hydrograph that groundwater levels were at their highest in the 1970s, and that there has been a decline in water levels by more than 10 m within the shallow aquifer (Pipe 1) since then. These declines in the regional watertable level are likely to have impacted on surface water – groundwater connectivity in groundwater management zone 8.

Further analysis of Figure 44 suggests that extractions from the deeper (Gunnedah Formation) aquifer appear to be inducing downward flows from the upper (Narrabri Formation) aquifer. Barrett (2012) reported that extraction from the Gunnedah Formation was inducing downward leakage from the overlying Narrabri Formation in many parts of the Upper Namoi river basin, and that in some areas, this was resulting in dewatering of the upper aquifer. Ivkovic (2006) also reported on the apparent widespread incidence of induced downward leakage as a consequence of groundwater extraction from deeper aquifers based on the analysis of nested bore hydrographs.

The pressures in the deepest aquifer represented by Pipe 3 (50.6–56.7 m screened interval; Figure 44), are typically more elevated than those in Pipe 1 and 2 during recharge/water level recovery events, indicating an upward vertical pressure gradient. This agrees with the research of Lavitt (1999), who analysed water samples from the Mooki river basin and found that the samples from the deeper alluvial units were more similar in composition to the surrounding fractured rock aquifer than the upper alluvium. Based on the hydrochemical data, Lavitt (1999) reported that the deeper alluvium and shallow fractured rock aquifers appear to be hydraulically connected.

Widespread areas of groundwater level decline, shown in orange and red in Figure 43, occur in the *Lower Namoi alluvial groundwater source* downstream of Narrabri. These declines may be a result of a range of factors, including time lag effects associated with groundwater extractions from the Upper Namoi aquifers over previous decades, which have resulted in reduced throughflow volumes into the Lower Namoi aquifers, in combination with the current levels of extraction in the Lower Namoi. These factors warrant further investigation.

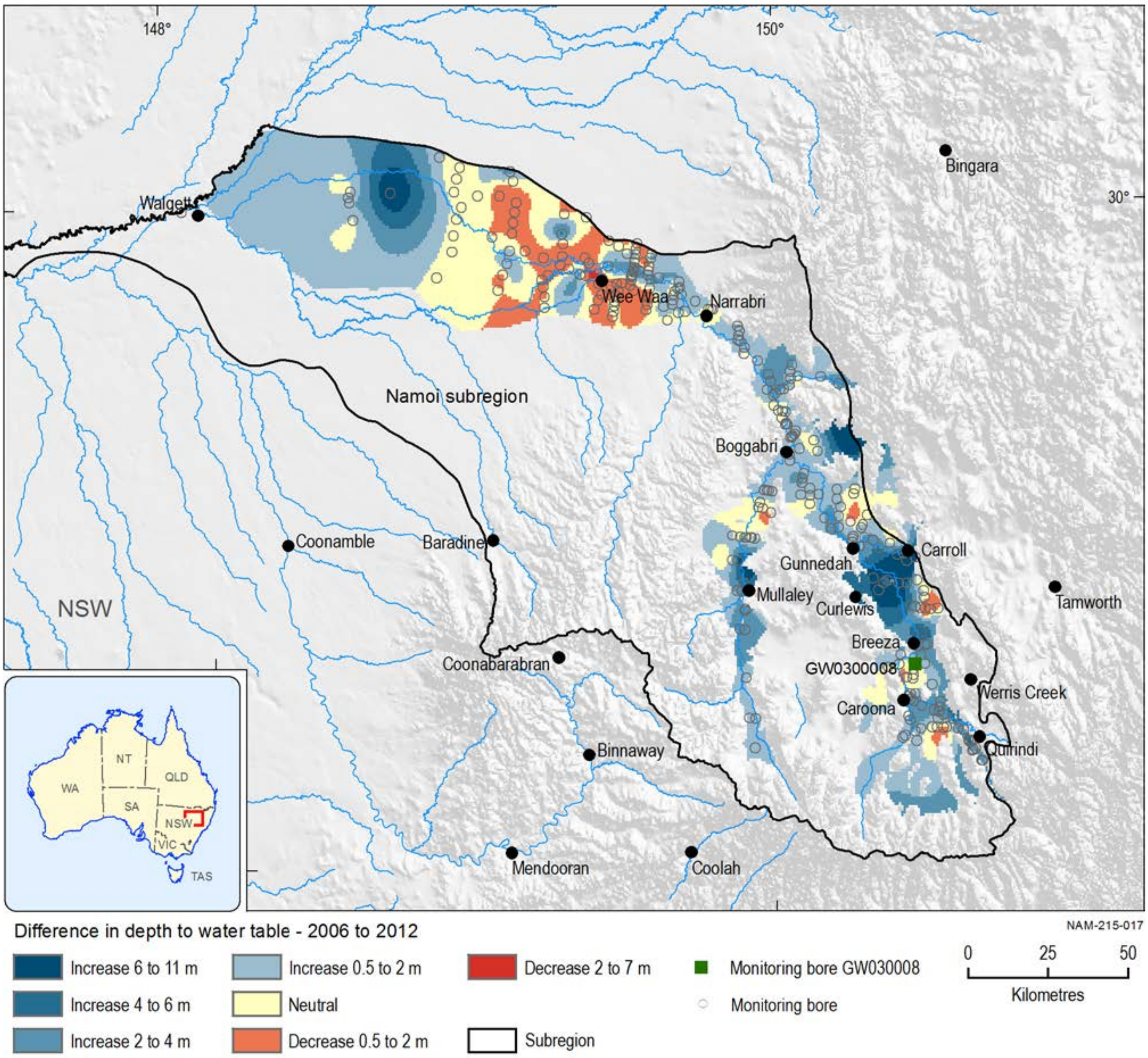

Figure 43 Change in depth to watertable in the Namoi subregion between 2006 and 2012, and location of monitoring bore GW0300008

Data: Bureau of Meteorology (Dataset 2)

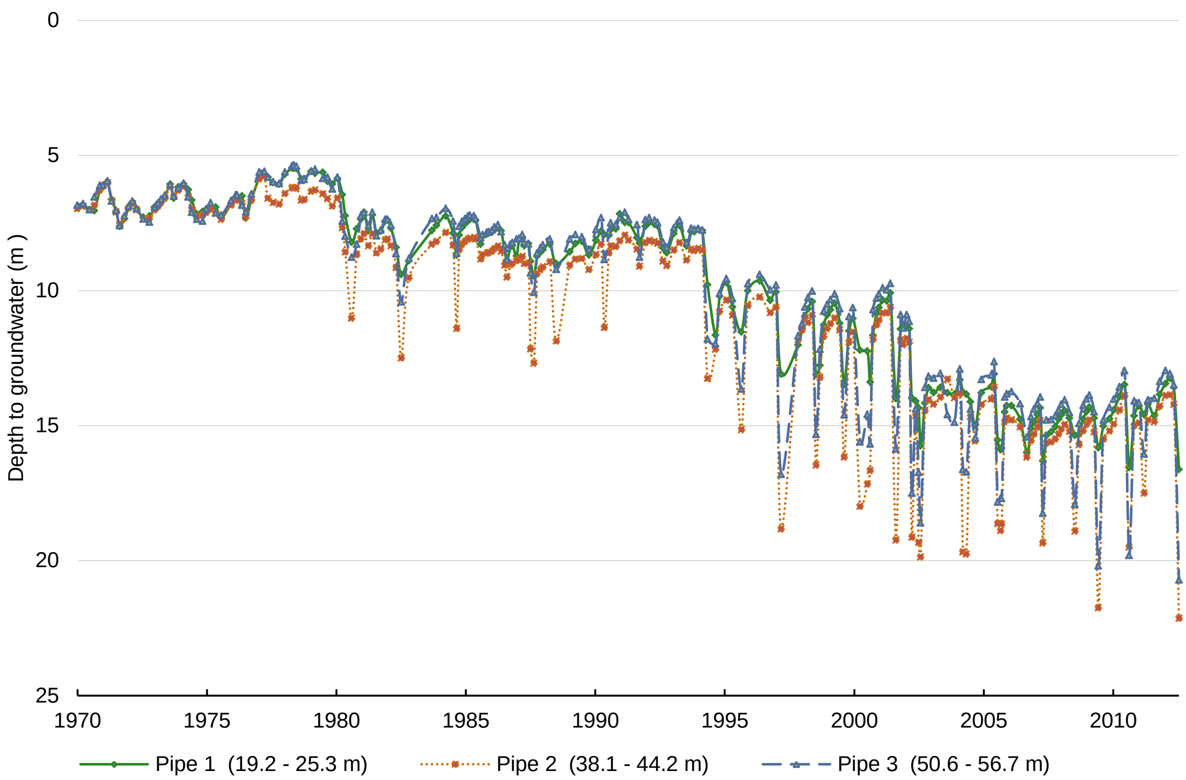

Figure 44 Bore hydrograph for monitoring bore GW030008, typical of the Mooki river basin (showing an example of interaquifer connectivity)

This figure shows water level data for a nested piezometer monitoring bore site. Pipe 1 screens the Narrabri Formation, Pipe 2 screens the Gunnedah Formation and Pipe 3 screens a mix of lower Gunnedah Formation and fractured rock basalt. (Water levels shown are relative to the measuring point.)
Data: Bureau of Meteorology (Dataset 10)

2.1.5.4.6 Fractured rock aquifer connectivity

Although small-scale groundwater extraction, on the order of approximately 1,000 ML/month between January 2002 and December 2009 (SWS, 2012), occurs from the underlying consolidated rocks surrounding the alluvium in the Namoi river basin (compared to 17,200 ML/month from the alluvium), these rock layers generally make poor aquifers because of their relatively low yields and generally poor quality water. Therefore, there are limited data available by which to characterise them.

Ivkovic (2006) demonstrated widespread connectivity between the shallow and deeper alluvial aquifers, as well as an upward pressure gradient from the underlying fractured rocks in some areas of the Coxs creek and Mooki river basins (see Figure 44 for example). However, the extent of vertical connectivity is unknown.

2.1.5.5 Gaps

There are several data and knowledge gaps identified in this assessment of surface water – groundwater connectivity, including the need for:

- uncertainty analyses on the influence of monitoring bore density adjacent to the stream and the reliability of interpolated water level raster surfaces. A better understanding of the potential errors associated with field measurements and database errors (for example in groundwater elevations and standing water levels) and the implications for surface water and groundwater connectivity mapping would also be useful

- detailed elevation survey data, using lidar for example, that transect the stream–floodplain to enable more accurate analysis of surface water – groundwater connectivity
- monitoring infrastructure designed to collect field data relevant to the assessment of connectivity and water fluxes. The appropriately designed infrastructure would include a number of densely located instrumented riparian piezometer transects co-located with stream gauging stations. The co-location of instrumented nested piezometers and stream gauging stations would allow for the capture of time series data of stream stage height and groundwater levels over a range of hydrological events. These data would facilitate more detailed surface water – groundwater connectivity assessments and would lead to more robust estimates of infiltration rates along streams
- investigations of connection status, direction of flux and infiltration rates at various locations along stream reaches, especially in areas with the greatest resource pressures (Upper Namoi groundwater management zone 8 for example) using various techniques such as those outlined by Brownbill et al. (2011) and CSIRO and SKM (2012a). These techniques include hydrograph separation using environmental tracers and baseflow filtering, using methods such as Lyne and Hollick (1979); longitudinal stream sampling based on tracers and major ion chemistry in combination with detailed flow gauging; hydraulic gradient and flow net analysis; differential flow estimation and water balance investigations; streambed and geomorphological assessments; and integrated numerical modelling
- an assessment of the relationship between streamflow characteristics, climate variability, groundwater extraction, time lags and aquifer–stream connectivity in areas with the greatest resource pressures, such as groundwater management zone 8 of the Mooki river basin and the Quirindi creek basin, where stream reaches have been mapped as disconnected and transition to disconnected in this study, yet were previously mapped as connected. Smaller areas of disconnection and transition to disconnection require further investigation, including the Coxs creek basin (more widespread disconnection), and a region downstream of Carroll (showing both disconnection and transition to disconnection).

Moreover, comprehensively defining the connection between different geological basins and the role of large-scale development on groundwater resources in the Namoi subregion requires improving knowledge of (Welsh et al., 2014):

- the hydraulic connection between the shallow alluvial aquifers and underlying fractured rock aquifers in the deeper geological basins (Surat Basin, Gunnedah Basin). Although potential ‘windows’ of connectivity between these basins and between surface water and groundwater systems have been identified, the rates and processes of groundwater exchange remain unknown
- the controlling mechanisms for vertical leakage (cross-formational flow) for the multiple layers of aquifers and aquitards in the Namoi subregion. Understanding these mechanisms is critical for determining the effect of depressurisation required for CSG development in the subregion

- the hydraulic properties of aquitards and their response to changes in groundwater pressure within adjacent aquifers. Where multiple aquifer and aquitard layers are present, pressure changes caused by groundwater extraction will propagate at various rates and in various directions, depending on the physical and hydraulic properties of the aquifers and aquitards (Smerdon and Ransley, 2012).

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2.1.6 Water management for coal resource developments

Summary

The surface water and groundwater numerical models require data on areas affected by mine operations, depth of mine workings, water extractions and discharge rules to inform the model development and compare with model outputs.

Two futures are considered in a bioregional assessment: the baseline coal resource development (baseline) and the coal resource development pathway (CRDP). The CRDP includes development in the baseline plus additional coal resource development (ACRD). The baseline for the Namoi subregion contains six active coal mines, however groundwater for the Werris Creek Mine is not modelled as it is geologically isolated from the rest of the subregion (see Section 2.1.2 for further detail). There are no coal seam gas (CSG) operations in the baseline for the Namoi subregion. There are ten additional coal resource developments; of these, seven coal projects and one CSG project can be modelled.

The water management systems for the baseline coal mines and additional coal resource developments are discussed below. Only the developments that can be modelled are discussed as there is insufficient water management information available for the other coal mines in the Namoi CRDP.

The two potential futures considered in bioregional assessments (BAs) are:

- baseline coal resource development (baseline): a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012
- coal resource development pathway (CRDP): a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in results between CRDP and baseline is the change that is primarily reported in a BA. This change is due to the additional coal resource development – all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012. Table 13 provides a list of all the coal resource developments in the Namoi subregion, and an indication of how they were categorised for the BA modelling. All developments were included in both the surface water and groundwater modelling unless otherwise stated. Figure 45 shows the location of each development. Further information on the data and rationale used to decide the coal resource development pathway is provided in Section 2.3.4 of companion product 2.3 for the Namoi subregion (Herr et al., 2018).

Table 13 Baseline and coal resource development pathway

Name of coal resource development	Coal mine or coal seam gas (CSG) operation	Included in baseline?	Included in CRDP? (modelled or commentary)
Boggabri Coal Mine	Open-cut coal mine	Yes	Yes – modelled
Narrabri North Mine	Underground coal mine (longwall mining)	Yes	Yes – modelled
Rocglen Mine	Open-cut coal mine	Yes	Yes – modelled
Sunnyside Mine	Open-cut coal mine	Yes	Yes – modelled
Tarrawonga Mine	Open-cut coal mine	Yes	Yes – modelled
Werris Creek Mine	Open-cut coal mine	Yes	Yes – modelled (SW)/commentary (GW)
Boggabri Coal Expansion Project	Open-cut coal mine	No	Yes – modelled
Caroona Coal Project	Underground coal mine (longwall mining)	No	Yes – modelled
Gunnedah Precinct	Open-cut and underground coal mine	No	Yes – commentary
Maules Creek Project	Open-cut coal mine	No	Yes – modelled
Narrabri South Project	Underground coal mine (longwall mining)	No	Yes – modelled
Tarrawonga Coal Expansion Project	Open-cut coal mine	No	Yes – modelled
Vickery Coal Project	Open-cut coal mine	No	Yes – modelled
Vickery South Coal Project (also known as Vickery expansion)	Open-cut coal mine	No	Yes – commentary
Watermark Coal Project	Open-cut coal mine	No	Yes – modelled
Narrabri Gas Project	CSG	No	Yes – modelled

A few elements common to the mine water management systems at all the mines are that unaffected surface water is diverted around the mine site where possible, and affected water in the mine area is utilised for mining and processing purposes. It is not possible to meter groundwater inflows to mines, and consequently inflow volumes must be estimated from surrogate observations or modelling. Additionally, there will be progressive rehabilitation of mined-out areas as mining advances. Thus, the amount of surface water that is disconnected from a catchment due to mining will vary during the life of the mine.

The water management systems for the baseline coal mines and additional coal resource developments (ACRD) (those mines in the CRDP but not in the baseline) are discussed below. The information provided is taken from documentation relating to each development, as indicated. It was outside the scope of the Bioregional Assessment Programme to undertake a critical analysis of the appropriateness of the methods and models used to derive the information presented, nor test the accuracy of the information.

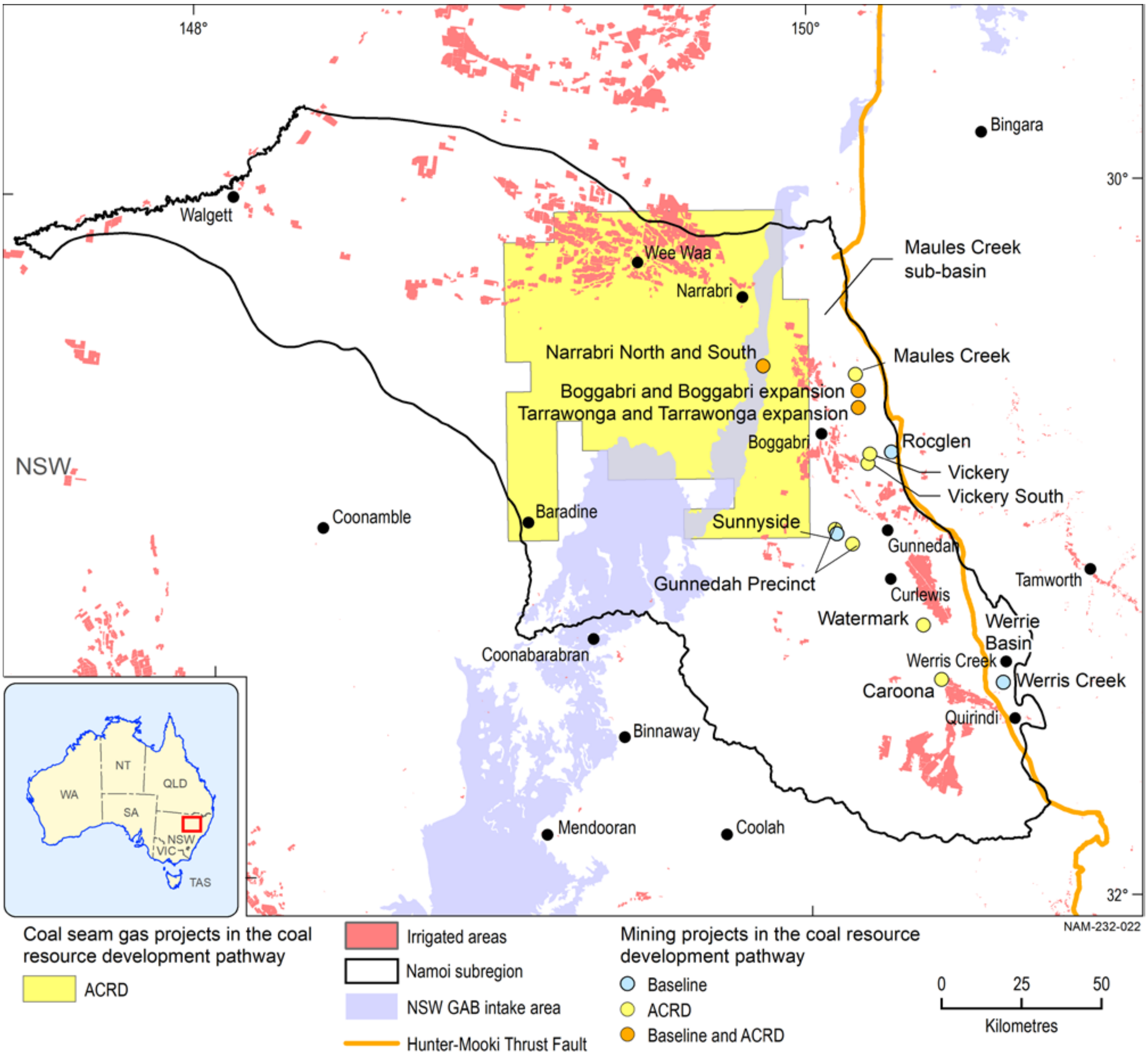

Figure 45 Location of coal and coal seam gas developments in the Namoi subregion

Data: Australian Bureau of Agricultural and Resource Economics and Sciences (Dataset 1), Bioregional Assessment Programme (Dataset 2)

2.1.6.1 Boggabri Coal Mine (baseline) and Boggabri Coal Expansion Project (ACRD)

The Boggabri Coal Mine is an open-cut coal mine targeting the Merriown Coal Member within the Maules Creek Formation (Hansen Bailey, 2010). The mine operations were approved in 1989, for a maximum production rate of 5 Mt/year. Operations commenced in 2006.

In 2012 the NSW Government granted approval for the Boggabri Coal Expansion Project covering an additional area of 658 ha adjacent to the original open-cut mine (NSW Government, 2012). The extension allows the proponent to extract coal at an increased rate of up to 7 Mt/year, up to December 2033.

Water management actions for both the Boggabri Coal Mine and the Boggabri Coal Expansion Project are addressed in the water management plan (Boggabri Coal Pty Ltd, 2014a). Unless otherwise stated, the information in this section has been derived from that document.

2.1.6.1.1 Mine water use

Water balance modelling was undertaken using 103 years of climate data to produce 103 climate simulations, developed by 'stepping through' the historical data (i.e. starting each simulation on a different year of the climate record, and cycling back through the data). A summary of the median (50th percentile) estimated water demands, site inflows and outflows is shown in Table 14, and indicates that the maximum demand will be constant from years 5 to 21 at 1297.9 ML/year.

The water demands for the Boggabri Coal Mine include: construction water; potable water (for drinking and amenities); dust suppression; vehicle washdown; and a coal handling and preparation plant (CHPP).

Table 14 Summary of estimated Boggabri Coal Mine water inflows and outflows representing median (50th percentile) modelled water balance for range of climate realisations modelled

	Water balance elements	Predicted volumes (ML/y)				
		Year 1	Year 2	Year 5	Year 10	Year 21
Inflows: Water management system runoff	Clean water (highwall) dams	0	0	0	0	31
	Dirty water sediment dams	228	237	239	535	471
	Contaminated water dams, mine water dams and pit	301	317	314	295	333
Inflows	Groundwater make	164	182	249	341	406
	Imported water requirement	547	484	557	418	288
	Undisturbed catchment runoff and rehabilitated areas to Nagero Creek	538	537	519	423	587
	Dirty water from sediment dams reused on-site	0	0	173	247	228
Outflows: Demands (mine water or raw water acceptable)	Dust suppression[a]	555	555	555	555	555
	CHPP (predicted to begin operations by year 5)	0	0	724	724	724
	Construction	767	266	0	0	0
Outflows: Demands (raw water only)	Vehicle washdown[b]	8.2	8.2	8.2	8.2	8.2
	Potable water	10.7	10.7	10.7	10.7	10.7
Outflows	**Total demand[c]**	**1340.9**	**839.9**	**1297.9**	**1297.9**	**1297.9**
Evaporation	Clean water (highwall) dams	0	0	0	0	6
	Dirty water sediment dams	35	65	30	52	47
	Contaminated water dams, MWDs and pit	52	66	78	88	96
Site wide release to Nagero Creek (water management system)	Clean water (highwall dam) controlled discharge to creek	0	0	0	0	26
	Dirty water sediment dam overflows to creek	0	21	0	0	0
	Dirty water sediment dam controlled discharge to creek	94	121	15	190	154

[a]This rate is applied as a daily rate of 1.5 ML/day which is only applied for days with rainfall less than 5 mm.
[b]The water use reported for vehicle washdown reflects the volume lost from the system. Total water use for vehicle washdown will be significantly higher than this value, and the volume remaining after losses will be recycled.
[c]Total demand = sum of all outflow volumes
MWD = mine water dam, CHPP = coal handling and preparation plant
Data: Boggabri Coal Pty Ltd (2014b)

2.1.6.1.2 Surface water management

The Boggabri Coal Mine is situated within the catchment of an ephemeral drainage line locally referred to as Nagero Creek, which lies within the Namoi river basin. Clean water runoff from surrounding undisturbed catchments is diverted around the working area into Nagero Creek. If, during the mine life, increased mine footprint means that it is no longer possible to divert clean water into the creek, a highwall dam will be constructed upslope to intercept clean water runoff and provide temporary storage for later discharge to a suitable receiving creek system downstream. Should a diversion drain or highwall dam not be suitable due to advancing topsoil stripping and stockpiling, clean water will be allowed to enter the active mining area and dirty water diversion system through the use of an appropriate licence or harvestable right volume.

Dirty water runoff within the operational mine site will be captured in sediment dams. Runoff from large storm events will overtop the dams and be discharged to Nagero Creek if the water quality is suitable, otherwise it will be pumped to mine water dams for storage and reuse.

Contaminated water (including groundwater inflows) will be stored in contaminated water dams or the mining void, and usually will not be discharged to Nagero Creek. The contaminated water will be reused on-site for dust suppression and coal washing (excluding a raw water component required for coal washing). Should there be a surplus of contaminated water, temporary pit storages will be constructed. A one-off emergency discharge of up to 700 ML of mine water to Nagero Creek was allowed in February 2012 after heavy rainfall for pit dewatering, through a licence variation.

Mine water dams hold water of similar quality to the contaminated water dams; they may also store clean water ‘top-ups’ sourced from imported surface water and groundwater allocations during dry periods when the site is in water deficit.

2.1.6.1.3 Groundwater management

The expected maximum pit depth is to the base of the Merriown Coal Member, however no depth relative to a datum has been reported.

Estimated mean annual seepage rates of groundwater into the mining void were assessed by AGE Pty Ltd (2010) (and reported in Boggabri Coal Pty Ltd (2014b), shown in Table 15). Inflows to the pit are predicted to rise gradually as mining progresses and then stabilise between 365 to 438 ML/year from about year 13, with a peak rate of approximately 457 ML/year. The calculated groundwater inflow over the 2014 reporting period was 224 ML/year (Boggabri Coal Operations Pty Ltd, 2015).

Table 15 Estimated groundwater inflows to mining void at the Boggabri Coal Mine

Year	Mean annual inflow (ML/y)
1	165
2	183
5	250
10	342
21	410

Data: Boggabri Coal Pty Ltd (2014b)

Mining is predicted to result in the reduction in the rate of groundwater flow from the Permian coal seam aquifers to the base of the alluvial aquifer (see Table 3). Modelling indicates that the loss of water from the alluvial aquifer due to the Boggabri Coal Mine reaches a maximum at almost 73 ML/year at the end of mining when the zone of influence and depressurisation of the bedrock has expanded to the maximum extent (AGE Pty Ltd, 2010).

The expected final void depth, after partial backfilling, is 285 mAHD. Once mining operations cease, water levels in the open void will be allowed to rise, resulting in a slow recovery in groundwater levels in the area. This will take approximately 15 to 20 years to reach equilibrium (Hansen Bailey, 2010). Groundwater levels are predicted to stabilise at about 283 mAHD, consistent with pre-mining groundwater levels (Hansen Bailey, 2010).

2.1.6.2 Narrabri North Mine (baseline)

The Narrabri North Mine, Stage 2 Longwall Project site covers an area of approximately 5201 ha. Approval for Stage 1 of the Narrabri Coal Mine was granted on November 2007, permitting the mining and rail transportation of up to 2.5 Mt/year of run-of-mine (ROM) coal for a period of 21 years. Site works commenced in April 2008. An application for Stage 2 was approved in July 2010, allowing for an annual production of up to 8 Mt/year run-of-mine (ROM) coal for 21 years, the approved production rate was increased to 11 Mt/year in 2015.

While both the Hoskissons Coal and Melville Coal Member are present within the mining lease, only the Hoskissons Coal is currently considered to contain coal resources with mining potential (companion product 1.1 for the Namoi subregion (Welsh et al., 2014)). The Hoskissons Coal is 8 to 10 m thick, the depth of cover varies from around 155 to 380 m.

The mine will consist of 20 longwall panels. The first 6 will be approximately 306 m wide and the remaining 14 will increase to 405 m. The mining height will be approximately 4.3 m.

2.1.6.2.1 Mine water use

Water use on-site is primarily for dust suppression, mining operations (e.g. coal handling and preparation plant and longwall) and potable supply. Water collected on-site is retained or reused where possible. Modelled water use requirements for the mine during its operational life are 346 ML in year 2 (peak water demand) and 323 ML in year 18. Water use is relatively uniform from year 3 to year 18, and year 18 has predicted peak groundwater dewatering volume (WRM Water and Environment, 2011).

Early in the mine life it is expected that there will be insufficient runoff from the mine site to meet water demands, and a water licence to extract water from the Namoi River will augment supplies during this period (WRM Water and Environment, 2011). Later in the mine life, after approximately years 3 to 5, groundwater inflows are expected to increase and exceed the mine site water demands resulting in an excess of water.

Water for dust suppression is sourced from on-site water harvesting and mine dewatering. A water treatment plant (WTP) uses reverse osmosis to produce all potable water used on the site. The WTP is supplied from Dam D, which is fed by water pumped from the Namoi River. Water from Dam D can also be filtered for use within the mine to supplement supply when mine dewatering does not produce sufficient water for operations. The water captured in storage dams SD1-SD5 is also transferred to Dam D, where required.

2.1.6.2.2 Surface water management

The Narrabri Coal Mine lies within the Namoi river basin and is drained by the ephemeral Kurrajong Creek and Pine Creek, and their tributaries.

The total storage capacity of the farm dams located within the mine site prior to commencement of mining was estimated at 121 ML, and the existing and proposed sediment dams is expected to be 237 ML. The maximum harvestable right dam capacity for the mine site is approximately 268 ML (WRM Water and Environment, 2009).

Data from a lidar survey of the mine site in March 2015 showed evidence of subsidence caused by extraction of coal from longwall panels 101, 102 and 103. The subsidence impacts, for example creating areas of surface water ponding, are generally consistent with the impacts predicted in WRM Water and Environment (2009), with maximum ground subsidence depths of approximately 2.5 m (WRM Water and Environment, 2015).

A detailed water balance model of the mine was developed to forecast the behavior of the mine water management system under a range of climate conditions (WRM Water and Environment, 2015). The water balance indicated that sufficient capacity was provided by the proposed brine storage ponds to account for the upper estimate of groundwater inflow. Evaporator spray systems on evaporation ponds will be used to reduce the volume of water stored on-site. The water stored in these dams may include mine water pumped out from the underground operations or potentially contaminated runoff from the stockpiling and crushing/sizing area. Water will be drawn from these dams for operational purposes, depending on the water quality requirements of the operations.

The surface water management system includes a water conditioning plant to treat saline groundwater, using reverse osmosis, to a sufficient quality for mine site use, discharge to the Namoi River and potentially for use offsite.

Concentrated brine by-product of the water conditioning plant will be stored and evaporated in lined brine storage ponds on the pit top area without release to the environment. At the completion of the operation, it is predicted that up to 2000 ML of concentrated brine solution will remain and will be re-injected into the underground void (WRM Water and Environment, 2009).

The mine is licensed to discharge water from dams SD2, SD4 and SD5, when water quality meets the limits set in the licence. Modelling of the site gives a predicted percentage of years of uncontrolled discharge of 31.5%, with a median volume of 2 ML/year estimated by the water balance model (URS Australia Pty Ltd, 2013).

An underground pipe to the Namoi River enables extraction of additional water from the Namoi River or discharge of surplus treated water to the river. Off-site releases of treated water from the conditioning plant are expected to commence by about 2019. The median groundwater model output indicates that the release of treated water will peak in 2023 at 283 ML/year for median groundwater inflows. These estimates are lower than earlier predictions (WRM Water and Environment, 2009), as the observed mine water inflows during the mine operations to date have been used to update the groundwater model calibration (WRM Water and Environment, 2015).

2.1.6.2.3 Groundwater management

Groundwater is extracted through the underground mine workings and via the gas drainage wells across the mine site. Table 16 gives the modelled volumes of inflow from the contributing groundwater sources. It is not possible to directly measure the volume of groundwater flowing into the workings, so the volume of produced water has been estimated considering inputs and outputs to the underground system. Estimates of the produced volume of groundwater, for the period December 2011 to May 2015, were compared to predicted volumes in WRM Water and Environment (2015). It was found that produced volumes have been equal to or less than the model predictions since August 2012. Produced volumes are increasing, consistent with the modelled values, and were around 1 ML/day (365 ML/year) in early 2015. Hydrosimulations (2015) modelled the groundwater impacts of the Narrabri North Mine. Figure 46 shows predicted groundwater inflows to the mine.

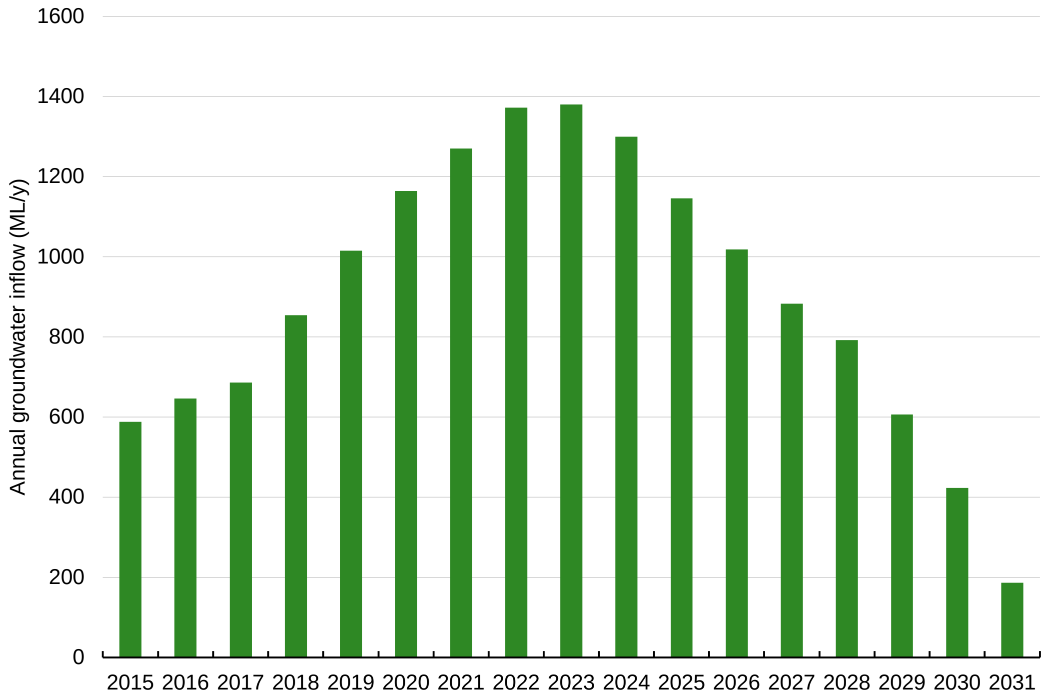

Figure 46 Predicted groundwater inflows for the life of Narrabri North Mine

Data: HydroSimulations (2015)

Table 16 Source of groundwater 'extracted' by Narrabri North Mine

Management zone or groundwater source	Predicted annual inflow volumes (ML/y)
NSW Great Artesian Basin – Southern Recharge Groundwater Source	179
Upper Namoi zone 5 Namoi Valley (Gins Leap To Narrabri) Groundwater Source	110
Gunnedah – Oxley Basin MDB Groundwater Source	1009
Lower Namoi Regulated River Water Source	78
Total	**1376**

Data: Hydrosimulations (2015)

During the longwall mining process fracturing and resultant subsidence occurs above the longwall panels. The predicted height of continuous or connected fracturing varies from around 45 to 200 m below ground level in the shallowest to deepest parts of the mine. During groundwater modelling for the mine for a base case Aquaterra (2009) undertook three uncertainty scenarios using adjusted hydraulic parameters to investigate the effects of fracturing. For the uncertainty scenarios, the modelling shows that if connected fracturing extends into the overlying Garrawilla

Volcanics, a slight increase in the peak inflow rate, to 1423 ML/year, may occur. If vertical permeabilities are increased by a greater amount than anticipated in the subsidence zones above the longwall goafs, inflow rates peaking at up to 1889 ML/year may occur, though this is considered unlikely. If some of the upper fracture zones were to settle and result in lower hydraulic conductivities, then groundwater inflows are estimated to peak around 1168 ML/year.

Modelling of the fracture zone was also undertaken for the later mine modification (Hydrosimulations, 2015). This analysis identified sufficient vertical buffer between the potential maximum fracture zone height and likely depth of surficial cracking to give a low risk that the fracture zone and surficial cracking would intersect.

The impacts of underground mining on river baseflows have been predicted (Aquaterra, 2009). The impacts to baseflows can occur when the drawdown due to the mine extends into the alluvium. The modelling shows the most impacted river reach is the closest section of the Namoi River, to the east of the mine site. Baseflow in this reach is predicted to reduce by a maximum of around 80 ML/year (0.22 ML/day) (years 23–24), which is 2% of the calculated baseflow contribution of this reach (3760 ML/day) (Aquaterra, 2009). Post mining the baseflows are predicted to recover to levels equal to pre-mining following the 100 years of recovery. Hydrosimulations (2015) reported that the proposed mine modification would result in a negligible difference in impact to baseflow.

2.1.6.3 Narrabri South Project (ACRD)

There is currently very little information about the proposed Narrabri South Project underground coal mine available in the public domain. Whitehaven Coal Pty Ltd (2015a) is the sole source of public information on this project, and provided the information included in this section.

The proposed project site is adjacent to the Narrabri North Mine and would also target the Hoskissons Coal. The Narrabri South Project is in the design stage. A concept study was completed in 2009 and a prefeasibility study in 2014.

No environmental impact statement has been prepared to-date. In order to model the proposed mine, the following assumptions have been made:

- The Narrabri South Project will use the same mining method as the Narrabri North Mine, that is, conventional longwall extraction and continuous miner development.
- The infrastructure to support the Narrabri North Mine will be used for the Narrabri South Project.
- The mine will progress at a similar rate to Narrabri North Mine, that is, one longwall panel per year.

2.1.6.4 Rocglen Mine (baseline)

The Rocglen Mine (formerly known as Belmont Coal Project) is an open-cut mine approximately 28 km north of Gunnedah. The mine was approved in 2008 and mining commenced in the same year. The mine is approved to produce up to 1.5 Mt/year of ROM coal using a truck and excavator method. The mine is anticipated to have a production life of between seven and ten years with a potential resource recovery of up to 15 Mt. Coal is extracted from the Upper Glenroc, Lower Glenroc and Belmont coal members within the Maules Creek Formation. The coal is transported to the Whitehaven CHPP for preparation and distribution to customers. In 2011 approval was given to expand operations by increasing the area of the open-cut pit, to maximise resource recovery, although the rate of production did not increase. The footprint of the open-cut will increase by approximately 50 to 164 ha. The information presented in the rest of this section refers to the approved mine extension.

2.1.6.4.1 Site water use and management

Clean water is managed by diversion away from disturbed areas. Dirty water is managed through the capture and storage of runoff water from disturbed areas across the site, and is treated in a series of sediment basins prior to reuse on-site or discharge at a licensed discharge point. Captured water is reused on-site for dust suppression and around crushing and screening operations. A mine water dam holds water to be pumped to and from the open-cut pit. A bore pump dam stores water to be pumped to and from a groundwater bore.

Most water required on-site will be used for dust suppression, including in the crushing and screening process. A nominal amount of potable water and water for ablutions will be trucked in from an external source.

The annual water requirements of the mine were originally estimated to range between 90 and 109 ML/year (GSS Environmental, 2010). A recent update of the mine water management plan (Whitehaven Coal Pty Ltd, 2015b) reported similar levels of observed usage during operations. Water balance modelling shows the predicted rates of water use and discharge from site. Table 17 shows the modelled water balance results for year 5, being the middle year of the estimated mine life, for three climate scenarios.

Table 17 Water balance model results for year 5 at Rocglen Mine

	Description	Dry (ML/y)	Median (ML/y)	Wet (ML/y)
Water source (inputs)	Rainfall-runoff	110	200	290
	Bore use	0[a]	0[a]	0
Water losses and usage (outputs)	Evaporation (from dams)	40	50	60
	Water usage (dust suppression including crushing)	90	90	85
	Discharged (wet weather)	10	50	115
Balance (input-output)	Change in water storage on-site[b]	–30	+10	+30

[a]A wide scatter of bore water use volumes were predicted, the line of best fit was used to give the values in the table; showing a zero supply requirement for the 10th (dry), 50th (median) and 90th (wet) percentile years, however the modelling also showed that there will be occasional years where a supply of up to 35 ML/year may be required (GSS Environmental, 2010).
[b]Change in water storage is calculated from other data and may not sum from values above.
Source: Whitehaven Coal Pty Ltd (2015b)

The water balance modelling has predicted a shortfall in water for below average rainfall years, with an excess in wet years. Shortfalls will be supplemented by clean water generated from runoff in the eastern part of the catchment, and harvested in dams on-site. It is expected that discharge from the site will occur infrequently.

The current environment protection licence permits wet weather discharge from two identified discharge points. The operator interprets the licence to mean that in practice they may also discharge (after effective water treatment) during dry periods to dewater dams (Whitehaven Coal Pty Ltd, 2015b, p. 12).

Historical evidence indicates that short periods of high rainfall have previously resulted in discharges and it is considered likely that there will be two to four discharge events per year (Whitehaven Coal Pty Ltd, 2015b).

2.1.6.4.2 Surface water management

The Rocglen Mine is situated in a small valley between the elevated areas of Vickery State Forest to the west and the Community Conservation Area (zone 2) (Aboriginal Areas) Kelvin to the east. The valley ultimately forms part of the Namoi River floodplain.

The mine site is on the valley floor, with elevations ranging between approximately 280 and 300 mAHD. Prior to mining operations, there were several drainage lines that would have entered the site from the east and drained into the two ephemeral creeks within the mine. Due to the topography of the site, a number of drainage lines have been diverted around the site to keep clean water off-site.

The clean water storage dams that will be used for water supply have a combined capacity of 17 ML, which is well within the maximum harvestable right volume for the project site, of 32 ML.

2.1.6.4.3 Groundwater management

Alluvium associated with the Namoi River and tributaries borders the mining lease to the north and also exists approximately 2 km south and south-west of the mining area.

The geology underlying the alluvium near the mine is structurally disrupted by significant folding and faulting. The Hunter-Mooki Thrust Fault System is a few kilometres east of the mine. Several smaller faults, with near vertical displacements of up to 150 m, surround the mine (Whitehaven Coal Pty Ltd, 2015b). Analysis of groundwater samples from the Maules Creek Formation shows that quality is spatially highly variable.

The expected pit depth is to the base of the Belmont coal member of the Maules Creek Formation. The floor of the Belmont Seam is generally at about 240 to 260 mAHD dropping to about 180 to 200 mAHD on the eastern and western sides of the pit (Douglas Partners, 2010).

Inflows to the open-cut pit are estimated by monitoring the volume of water pumped out of the pit (and adjusting for rainfall inflows) and monitoring bore water levels to estimate groundwater gradients towards the pit. Head gradients combined with estimates of strata permeability are used annually to calculate anticipated groundwater flows toward the pit (Whitehaven Coal Pty Ltd, 2015b).

Connectivity with the Namoi River Alluvium is considered to be limited, however there is some uncertainty regarding the leakage which will occur from the Namoi River Alluvium into the Maules Creek Formation due to the mine. Monitoring bores were installed to provide additional data with which to refine the estimates of leakage rates (Douglas Partners, 2010).

Negligible inflows to the mine pit are predicted from future operations (Douglas Partners, 2010). The exception to this is in the eastern extent of the mine where the seams dip more steeply, and hence the pit will be deeper, and pit inflows are estimated to be about 63 ML/year.

A groundwater model was developed (Douglas Partners, 2010) presenting four possible hydrogeological conceptualisations. Case 1 was modelled as having upper bound permeability; Case 1C with a permeable Western Fault; Case 2 was modelled as having a lower bound permeability; and Case 2C with a permeable Western Fault. Table 18 shows the predicted groundwater inflows to the pit for the different modelled conceptualisations.

Site data suggests that Case 2 flows are more likely than Case 1 flows. The Douglas Partners (2010) modelling report does note uncertainty in site conditions, especially to the south-west of the site.

The mean mine inflows are expected to be on the order of 18.8 to 47 ML/year midway through the project (year 5) and between 40.8 and 125 ML/year at the end of mining (approximately 2020) (Douglas Partners, 2010).

Table 18 Modelled pit inflows at Rocglen Mine

Time	Case 1 – flow components (ML/y) (Case 1C – permeable faulting)			Case 2 – flow components (ML/y) (Case 2C – permeable faulting)		
	Into pit	Storage loss from alluvium	Reduction of flow in alluvium[b]	Into pit	Storage loss from alluvium	Reduction of flow in alluvium[b]
Initial (during first 50 days)[a]	1040 (925)	69 (223)	0.37	604(400)	24 (50)	<0.4
2009	607 (599)	153 (304)	1.5	222 (186)	26 (93)	<0.4
End of northern mining phase	403 (484)	189 (295)	19 (11)	179 (188)	39 (89)	2.2 (0.7)
End of southern mining phase	954 (1234)	440 (705)	70 (68)	386 (545)	99 (274)	13.5 (9)

[a]assumes instant excavation and over estimates initial flow rates
[b]measured at constant head boundaries
Data: Douglas Partners (2010)

Most of the predicted impacts in the alluvium will arise from a loss of storage. However, during later years in the life of the mine the impacts on flows to the alluvium increase slightly, with the greatest impact to the southern alluvium. The northern alluvium is up gradient and less hydraulically connected.

Expected final void depth after partial backfilling will be about 250 mAHD, with the exception of an area of about 38 ha in the southern side of the pit where the surface levels will range from 225 to 250 mAHD (Douglas Partners, 2010, p. 60).

It is expected that groundwater inflow and rainfall recharge into the pit will lead to surface water in the southern part of the pit where the ground elevation is locally lower. Inflow to the pit will be offset by evaporation from the area of surface water, and it is therefore unlikely that groundwater levels will recover to pre-development levels. The final water levels are expected to range between 220 and 245 mAHD, which may take 20 to 50 years to occur. It is expected that local increases in salinity are likely within the final void, but would not impact upon the surrounding groundwater and land.

2.1.6.5 Sunnyside Mine (baseline)

Approval to operate the Sunnyside Mine, an open-cut coal mine, was granted in 2008. This allowed extraction of up to 1 Mt/year ROM coal, with an anticipated mine life of 5 to 6 years. Mining commenced in late 2008, with thermal coal extracted using conventional excavator and truck haulage.

In November 2012 the mine owner suspended all mining operations at the Sunnyside Mine indefinitely, and the mine was placed in care and maintenance. Rehabilitation and environmental management work continued at the site. As the mine was closed in the last quarter of 2012, it will be modelled as part of the baseline.

In November 2015, the development consent on the mine was extended until 2020, to allow extraction to resume if economic conditions improve.

Sunnyside lies in the Mullaley sub-basin of the Gunnedah Basin, targeting the Hoskissons Coal within the Black Jack Group. The Hoskissons Coal subcrops under primarily transported colluvial cover on the eastern flanks of Coocooboonah Creek. The depth of weathering extends approximately 30 m below surface, with the depth to the top of the Hoskissons Coal up to approximately 65 m below surface in the open-cut pit area.

The water management information presented here has been drawn from the *Mining Operations Plan (MOP) Amendment C – October 2015* (Namoi Mining Pty Ltd, 2015), unless otherwise stated.

2.1.6.5.1 Mine water use

Water requirements on the mine site were expected to range between 75 and 100 ML/year (Namoi Mining Pty Ltd, 2008). No coal washing was undertaken, as the coal was transported to the Whitehaven owned Gunnedah CHPP, located off-site.

Ablutions and potable water will be trucked in from off-site. The water requirement for Sunnyside was obtained from a combination of the following sources:

- harvesting clean surface water to a maximum volume of 26.32 ML/year maximum harvestable right volume (Namoi Mining Pty Ltd, 2008)
- capture of dirty water within the site
- extraction of groundwater from one or more bores
- groundwater and surface water retained within the mine void.

Operational water requirements were preferentially sourced from dirty water runoff collected on-site, together with any surface water and groundwater which accumulated in the open-cut and pumped to designated pit dewatering dams. Any shortfall was supplemented by harvested clean water.

The water balance modelling for the mine (Namoi Mining Pty Ltd, 2008) showed that during dry years site water capture (both surface water and groundwater inflow) would be sufficient to meet operational requirements. However, during median and wet years the site water yields exceeded water storage volumes, indicating that discharge of surface water is likely to occur.

2.1.6.5.2 Surface water management

The mine site is located within an ephemeral first order stream catchment which drains north and north-west into the ephemeral Coocooboonah Creek.

Catch banks and drains were constructed to divert potentially sediment-laden waters into sediment basins. The water within those storages will be used for dust suppression and watering rehabilitated areas, if required.

Water from areas where mine plants and equipment and vehicles operate may potentially contain hydrocarbons. These areas were managed by ensuring all water was directed to oil separators and containment systems for subsequent removal.

The base of the depression remaining after rehabilitation of the final void within the open-cut area was expected to be at approximately 305 mAHD, that is, about 40 m below the current land surface, and would cover an area of approximately 18.4 ha.

2.1.6.5.3 Groundwater management

The Sunnyside Mine is located within the exposed Triassic and Permian units on the periphery of the Quaternary alluvial Upper Namoi groundwater management zone 4: Namoi Valley (Keepit Dam to Gins Leap) Groundwater Source.

The alluvium of Coocooboonah Creek to the east, and Native Cat Creek to the north, can extend to at least 50 m thick. Rock Well Creek to the west of the mine site has up to 10 m of alluvium. No registered bores extract groundwater from the alluvium within at least 3 km of the proposed mines (Namoi Mining Pty Ltd, 2015).

Groundwater within the Hoskissons Coal is unconfined where it subcrops beneath the Coocooboonah Creek alluvium, and progressively becomes more confined towards the west (down-dip) of the open-cut.

The coal resource is separated from the underground workings of the Gunnedah Coal Mine No. 5 (part of the abandoned Gunnedah Colliery) by a zone of faulting and intrusive/volcanic rocks (Namoi Mining Pty Ltd, 2015). The Gunnedah Coal Mine No. 5 underground workings are thought to be dry with a minimum volume of 1523 ML of open void space in the workings downgradient of the open-cut (Namoi Mining Pty Ltd, 2015).

The mine operators obtained the bulk of the mine water supply from pit inflows (Namoi Mining Pty Ltd, 2008). Modelled pit inflow rates are in Table 19.

Table 19 Potential pit groundwater inflows for low hydraulic conductivity scenario (without evaporation)

End of mining year	Modelled pit groundwater inflows (ML/y)
1	79
2	102
3	106
4	67
5	64

Data: Geoterra Pty Ltd (2008)

If excess inflow occurs that cannot be used on-site, or stored in the relevant storage dams, it would eventually be directed via a bore into the Gunnedah No 5 Entry underground workings. This water could then be reused as required after the appropriate licence is obtained.

Modelling was also undertaken for five years post mine closure (Geoterra Pty Ltd, 2008). The modelled groundwater level recovery scenario indicates that water levels in the final void would return to approximately 293 mAHD assuming low hydraulic conductivity or up to 302 mAHD for a higher conductivity scenario after the pit has been rehabilitated and excluding the effect of evaporation. It is noted that neither scenario had reached equilibrium during the modelling period.

Based on the short modelling period, the proponent suggests that the combined groundwater inflow and surface water capture in the final void would not generate a pit void lake, as there is insufficient inflow to raise the pit water level above the proposed basal level of 305 mAHD.

2.1.6.6 Tarrawonga Mine (baseline) and Tarrawonga Coal Expansion Project (ACRD)

The Tarrawonga Mine is an open-cut mining operation south of, and adjacent to, the Boggabri Coal Mine. The Tarrawonga Mine commenced operations in 2006, and produces up to approximately 2 Mt/year ROM coal from the Maules Creek Formation using conventional open-cut mining methods. The mine originally had approval to operate until 2017. The Tarrawonga Coal Expansion Project was approved in 2013, allowing for an extension of operations to the east and north and the continued development of the mining operations to facilitate a ROM coal production rate of up to 3 Mt/year until 2030. The information presented here relates to the operations of the Tarrawonga Coal Expansion Project. Unless otherwise stated, the information in this section has been derived from Tarrawonga Coal Pty Ltd (2012).

ROM coal is crushed and screened at an on-site facility and then taken by truck to an off-site coal handling and preparation plant (CHPP).

2.1.6.6.1 Mine water use

The sources of water used at Tarrawonga Coal Expansion Project include the following, in order of priority:

1. groundwater inflows to the open-cut and associated mine dewatering
2. water storages containing runoff from active areas
3. water storages containing runoff from up-catchment areas
4. licensed groundwater extractions.

Water balance modelling of the performance of the mine water management systems was performed using 122 years of historical climate data, to give 122 possible mine life (17 years) 'realisations' (i.e. each model run started on a different year in the 122 year sequence, and the climate record was restarted at year 1, after the end of year 122).

The key water use requirements (demands) and water sources (inflows) in the modelling are summarised in Table 20.

Table 20 Summary of modelled inflows and outflows in Tarrawonga Coal Expansion Project water balance

	Water balance elements	Simulated results (ML/y)		
		25th percentile	Mean	75th percentile
Inflows	Rainfall-runoff	325	402	480
	Groundwater production bore	0	0	0
	Groundwater inflow to mine pit	255[a]	255[a]	255[a]
Outflows	Pond evaporation	118	130	141
	Mine water spill to environment	0	0	0
	Supplied to crusher	8	8	8
	Supplied to truckfill	389	394	399
	Supplied to irrigation	64	125	193

[a]The groundwater inflow rate in the water balance model is not linked to climate, and so does not vary between wet and dry scenarios.
Data: Gilbert and Associates Pty Ltd (2011)

Table 21 shows the volumes that will need to be licensed in the future to account for aquifer interference of the mine void.

Table 21 Predicted licence requirements to address aquifer interference of Tarrawonga Coal Expansion Project

Water source (type)	Predicted mean annual inflow volumes requiring licensing (ML/y)			
	Years 1 to 11	Year 12	Years 13 to 17	Post mining
Gunnedah-Oxley Basin	Mean 209 Max. 252	209	209	167
Upper Namoi zone 4	negligible	198	Mean 142 Max. 169	negligible

Data: Merrick and Alkhatib (2012)

2.1.6.6.2 Surface water management

The mine site is situated on the floodplains of the ephemeral Nagero, Goonbri and Bollol creeks, within the Namoi river basin.

The water management infrastructure comprises a mine water dam and a series of sediment dams and basins and drains used for controlling sediment-laden runoff from the mine area. Drainage works divert ‘clean’ water around the site or away from mine disturbed areas. Runoff from the disturbed areas is collected in sediment basins where suspended sediments are allowed to settle out. Mine water is stored in a mine water dam. Water from these storages is used for dust suppression or coal crushing and screening. During extended wet periods excess water is released from a number of sediment control structures as controlled discharge from licensed discharge points.

The mine plan involves mining through the current alignment of Goonbri Creek. Realignment of a 3 km section of the creek, further to the east, has been approved, and will be undertaken by year 12 of the project. The creek realignment will occur in conjunction with the installation of a low permeability barrier in the alluvium to the east and south-east of the open-cut extent (discussed in the following section), and the construction of flood bunds.

A temporary flood bund is required from year 12 of operations for the western bank of Goonbri Creek, to protect the advancing pit against the risk of inundation. The bund has been designed to protect the open-cut for the peak flow resulting from a 1 in 100 year average recurrence interval rainfall event. The bund will be constructed to a nominal height of 1.5 m above the natural surface level.

A flood protection bund will also be required on the eastern bank of Goonbri Creek to protect the construction works of the Goonbri Creek realignment and the low permeability barrier.

Permanent flood bunds will be constructed on both the eastern and western side of the final void. The permanent flood bunds will generally coincide with the alignment of the low permeability barrier and will be designed to a height to provide protection against the peak modelled flood height from a probable maximum precipitation event. At its maximum the bund would be 6 m high; it will also serve as a noise mitigation measure (Gilbert and Associates Pty Ltd, 2011).

The potential cumulative impacts of the mine on surface water flows as a result of runoff capture are summarised in Table 22 for the Tarrawonga Mine. The table shows that the runoff would be initially reduced. However, runoff would then progressively increase as areas are rehabilitated. The final void and its catchment will remain excised from the Namoi river basin post mining, resulting in a 6% loss of contributing flow from Nagero Creek. The realignment of Goonbri Creek is expected to result in a gain of 2.1% post mining (as parts of the Nagero Creek catchment are diverted to the Bollol/Goonbri creek catchments).

Table 22 Progressive and maximum changes to reductions in the contributing catchment of local creeks and Namoi River as a result of the Tarrawonga Coal Expansion Project

Mine	Percentage reduction in contributing catchment		
	Nagero Creek	Bollol/Goonbri creeks	Namoi River
Tarrawonga Mine prior to extension	2.4%	1.8%	0.01%
Year 2 – extension	6.9%	2.5%	0.02%
Year 4 – extension	6.3%	2.6%	0.02%
Year 6 – extension	4.5%	2.8%	0.02%
Year 12 – extension	2.9%	2.3%	0.01%
Year 16 – extension	3.0%	3.0%	0.02%
Post-mining	6.0%	–2.1%	0.004%

Data: Gilbert and Associates Pty Ltd (2011)

2.1.6.6.3 Groundwater management

A groundwater assessment by Merrick and Alkhatib (2012) evaluated the potential impacts of the Tarrawonga Coal Expansion Project. Mining since 2006 at Tarrawonga Mine and Boggabri Coal Mine provide strong hydrographic evidence of mining effects on the Maules Creek Formation (porous rock) groundwater system with no discernable effect on the alluvial groundwater system. The Tarrawonga Coal Expansion Project involves advancing the open-cut mine pit to excavate a small portion of the alluvial groundwater system.

A low permeability barrier will be constructed in the alluvium to minimise the rate of alluvial groundwater inflows into the open-cut both during operations and post-mining. The low permeability barrier will be constructed using a soil-bentonite mixture. The barrier will be approximately 2 km long and from 2 to 40 m deep. The base of the barrier will extend into the underlying rocks (Maules Creek Formation) by approximately 1 m (Tarrawonga Coal Pty Ltd, 2012).

The expected pit inflows are listed in Table 23. Modelling indicates that these values are likely to be overestimates. The cumulative effects of the nearby Boggabri, Maules Creek and Rocglen coal mines are likely to mean that groundwater levels in the region around all four mines will be lowered more rapidly, however, as the drawdown results from groundwater inflows to four mines, it is likely that total inflows to each mine will be reduced.

Table 23 Predicted pit inflows for the Tarrawonga Coal Expansion Project acting alone

Project year	Pit inflow (ML/y)	Project year	Pit inflow (ML/y)
1	146	10	251.85
2	200.75	11	208.05
3	219	12	405.15
4	229.95	13	332.15
5	219	14	310.25
6	182.5	15	354.05
7	167.9	16	324.85
8	219	17	375.95
9	251.85		

Data: Merrick and Alkhatib (2012)

The model simulations suggest that the potential cumulative mining impacts of the four mines on groundwater discharge to the creeks will be minor, at 36.5 ML/year (Merrick and Alkhatib, 2012, p. A-37).

The expected maximum pit depth is to the base of the Braymont Coal Member through to Negero Coal Member in the Maules Creek Formation.

Up to the end of mining, there would be a continuous loss of water from the aquifer system to the mining void. The Maules Creek Formation would be the source of groundwater inflows until year 12 of the project, from which point onwards the alluvium will be the primary source until the end of mining. After the end of mining the long-term groundwater inflow will be drawn from both porous rock and waste rock sources, with a negligible contribution from the alluvium due to the construction of the low permeability barrier. The final void is expected to be about 250 mAHD, assuming the void is partially backfilled, which is about 25 m lower than current levels in the alluvium. The final void will be at the eastern edge of the open-cut. Water levels are expected to reach equilibrium approximately 130 years post mining. The equilibrium long-term groundwater inflow into the void post mining is expected to be about 110 ML/year. This water will come from the Gunnedah-Oxley Basin, with negligible inflows from the alluvium expected post-mining.

2.1.6.7 Caroona Coal Project (ACRD)

Coal Mines Australia Pty Ltd (a subsidiary of BHP Billiton) was seeking consent to develop the Caroona Coal Project, a proposed underground coal mine. On 11 August 2016 the progression of this project was ceased and the exploration licence was cancelled by the NSW Government. However, as per companion submethodology M04 (as listed in Table 1) for developing a CRDP (Lewis, 2014) once the CRDP is determined, it is not changed for BA purposes, even in cases such as this, where BHP Billiton have discontinued the progression of the project.

The information in this section has been derived from BHP Billiton (2014) unless otherwise stated. The development application includes proposed longwall mining on Doona Ridge and Nicholas Ridge, both of which will target the Hoskissons Coal. Within the Caroona Coal Project underground mining area, the Hoskissons Coal is 8 to 16 m thick and has a depth of cover between 130 and

710 m. Cover depth is shallowest in the north and the east of the mining areas, with depth increasing to the south-west (Nicol et al., 2014).

It is estimated that the Caroona Coal Project will produce up to 260 Mt of ROM coal over the life of the development and up to 10 Mt/year of saleable coal. The mine life is expected to be approximately 30 years. During the operation 67 longwall panels will be constructed either side of the Mooki River alluvial plain.

2.1.6.7.1 Mine water use

At the time of writing, no information was publicly available on the predicted volume of water that will be required to operate the mine site.

2.1.6.7.2 Surface water management

Little information is currently available on the proposed surface water management infrastructure for the proposed mine. A site water balance will be developed for the project and this would inform the development of the water management strategy, which would incorporate the following:

- separation of undisturbed area runoff from disturbed area runoff
- collection and reuse of surface runoff from disturbed areas
- capture of groundwater inflows and reuse
- storage of water on-site
- licensed water extraction to supplement water supply
- consideration of flood impacts on surface infrastructure, and
- treatment and beneficial use or licensed controlled release of excess water.

The project area drains to the Mooki River and Quirindi Creek through a number of ephemeral drainage lines from the ridgelines. The Mooki River flows south between Doona Ridge and Nicholas Ridge. Quirindi Creek flows east to west, with its confluence with the Mooki River in the centre of the exploration area. Runoff from the western side of Doona Ridge flows towards the Yarraman Creek alluvial plain.

Approximately 2103 ha of protocol verified Biophysical Strategic Agricultural Land (NSW Government, 2013) within the project area is predicted to have subsidence impacts. The predicted total maximum subsidence varies between 1.6 and 3.1 m. Typical surface cracking widths vary between 10 to 100 mm depending on depth of cover (BHP Billiton, 2014).

2.1.6.7.3 Groundwater management

BHP Billiton note the following Water Access Licences that are available for the Project:

- WAL 12931 (422 units – Upper Namoi Alluvium – zone 8 groundwater source)
- WAL 36496 (1000 units – Gunnedah-Oxley Basin MDB [Other] groundwater source).

The predicted annual groundwater extraction volumes for the groundwater sources impacted are summarised in Table 24.

Table 24 Predicted volumetric impacts to groundwater sources from Caroona Coal Project

Water sharing plan	Management zone or water source	Predicted interim annual water takes requiring licensing (ML/y)			
		During mine operation		Post-mine operation	
		Mean	Maximum	Mean	Maximum
Upper and Lower Namoi Groundwater Sources 2003	Zones 1, 3, 6, 7, 8 and 10	363	458	167	487
NSW Murray–Darling Basin Fractured Rock Groundwater Sources 2011	Liverpool Ranges Basalt MDB	9	10	4	9
NSW Murray–Darling Basin Porous Rock Groundwater Sources 2011	Gunnedah-Oxley Basin MDB (Spring Ridge)	2	6	6	11
NSW Murray–Darling Basin Porous Rock Groundwater Sources 2011	Gunnedah-Oxley Basin MDB (Other)	1033	2301	88	254

Data: Nicol et al. (2014, p. 120)

The project is estimated to induce a loss of baseflow to the Mooki River of up to 256 ML/year (0.7 ML/day), and potentially contribute to a cumulative impact of 329 ML/year (0.9 ML/day) when the impacts of the Watermark Project are considered (Nicol et al., 2014). The impacts are predicted to occur primarily between Caroona and Breeza. This impact to baseflow represents a significant impact to the low-flow rates in the Mooki River at Breeza (Nicol et al., 2014, p. 98).

2.1.6.8 Maules Creek Project (ACRD)

The Maules Creek Mine is an open-cut coal mine that commenced production in 2015. It is approved to extract up to 13 Mt/year ROM coal over a project life of 20 years. The mine has identified recoverable coal reserves of 381 Mt.

2.1.6.8.1 Mine water use

Water sources for the Maules Creek Mine are:

- Namoi pipeline (flows to raw water dam)
- rainfall and runoff captured in the surface water management system
- groundwater inflow to pit.

The water management plan lists the extraction of groundwater from existing or new bores as a measure that may be implemented if water demand on-site looks like exceeding licensed entitlement.

Water balance modelling has been undertaken over the historical climate record, giving 106 ‘realisations’ of the performance of the water management system. The modelling indicated the requirements for water from external sources and examined on-site storage requirements to prevent unlicensed discharges from site. Table 25 presents the modelled site water balance for Maules Creek Mine for the median runoff inflows for the first five years of the mine life.

Table 25 Annual water balance for realisation with median runoff inflows for Maules Creek Mine

	Water balance elements	Annual water balance (ML/y)				
		Year 1 (2014)	Year 2 (2015)	Year 3 (2016)	Year 4 (2017)	Year 5 (2018)
Water inputs	Direct rainfall + catchment runoff	1674	1235	854	1180	1783
	Raw water (Namoi pipeline)	110	110	361	933	620
	Groundwater inflow	175	226	185	111	36
	Total	1958	1571	1399	2224	2439
Water outputs	Evaporation from dams and ponds	194	248	142	80	107
	Sediment dam overflows (off-site)	100	45	0	0	0
	Highwall dams pumped off-site – site discharge	323	184	97	147	199
	CHPP makeup demand total	357	1001	1186	1601	1577
	Dust suppression demand – total	193	280	312	298	286
	Vehicle wash[a]	91	91	91	91	92
	Total	1259	1849	1828	2216	2261
	Net input	700	–278	–428	7	178

[a]Note that Maules Creek Mine reports total vehicle wash water requirement, whereas some mines only report the vehicle wash losses. The losses are that part of the water requirement that is not recycled through the system.
CHPP = coal handling and preparation plant
Data: Whitehaven Coal Pty Ltd (2014)

River water (accessed via a pipeline from the Namoi River) will be used in conjunction with water from the mine water dam to supply the CHPP and on-site dust suppression. River water will be the sole water source for vehicle washdown.

On average it is likely that annual volumes of approximately 1000 to 1800 ML will be required. The maximum simulated volume required for any year was 2730 ML. The mine holds high security surface water licences for 3000 ML/year. Additional groundwater licensing will be required (Table 26).

Table 26 Predicted groundwater take versus water access licences

Water source	Predicted mean annual water take (ML)	Predicted peak annual water take (ML)	Share component already held (Units)	WAL number
Namoi Groundwater WSP zone 4	17	40.2	38	27385
Namoi Groundwater WSP zone 5	5	14.6	135	12811
Namoi Groundwater WSP zone 11	28	69.4	78	12479
Porous Rock (Gunnedah-Oxley Basin – Other zone)	550	1064	306	29467 (6 units) 29588 (300 units)

WAL = water access licence
Data: Whitehaven Coal Pty Ltd (2014)

2.1.6.8.2 Surface water management

The Maules Creek Mine is on the southern side of Back Creek, an ephemeral tributary of Maules Creek.

Runoff from undisturbed areas on-site, which would naturally drain toward the open-cut pit, is directed to the highwall dams. Surface water will be discharged off-site from highwall dams into Back Creek. There has been a modelled maximum discharge of 88 ML/year, for the median runoff climate scenario (WRM Water and Environment, 2011).

Runoff from disturbed areas on-site is directed to the network of on-site storages and sediment dams. Excess water in most storages on the site, including the pit, is pumped to the mine water dam (MWD), which has a maximum operating volume of 890 ML. When the MWD is at maximum volume all pumping ceases. Water from the raw water dam is not pumped to MWD.

All other water (in the water balance) will be lost to evaporation, or used on-site in either the CHPP or for dust suppression or vehicle washdown.

Pollutant concentration limits have been specified in the environment protection licence (EPL) for discharge from sediment dams. Where pollutant concentrations in sediment dams after a runoff event are less than the limits specified in the EPL, basins may be dewatered to receiving waters (Whitehaven Coal Pty Ltd, 2014).

Should on-site water storages overflow, discharge from the raw water dam and up to five sediment dams will go into Back Creek. The modelled maximum spill is 20 ML/year, for median rainfall scenario. Modelling showed that proposed operating rules meant that the MWD did not spill under any climate scenarios.

2.1.6.8.3 Groundwater management

Groundwater modelling was undertaken to estimate the impacts of the project on local groundwater systems (AGE Pty Ltd, 2011). The modelling found that the simulated rates of groundwater seepage into the mine pit varied throughout the life of the mine. The seepage rate peaked at about 1460 ML/year in year 14. The mean annual groundwater inflow to the pit is 550 ML/year, over the 21 year mine life.

The Maules Creek Mine will impact on the groundwater in the alluvium in three Upper Namoi groundwater management zones: zone 4, zone 5 and zone 11. The modelling indicates that the mine will intercept flow to the alluvial aquifer at a maximum rate of 128 ML/year at the end of mining. The lowest elevation of the pit floor will be reached in year 14, at 82 mAHD.

A final void is proposed that will be approximately 350 ha and up to a maximum depth of 290 m. Based on simulated inflows and outflows, water will not spill from the final void (water level will equilibrate about 100 m below overflow level).

Long-term modelling shows that final void groundwater inflows will be around 584 ML/year, which represents steady state reached in the 1000 year groundwater model.

2.1.6.9 Watermark Coal Project (ACRD)

The Watermark Coal Project was approved by the NSW Government in January 2015 and by the Australian Government in July 2015, but construction has not yet commenced. The approval allows for the extraction of up to 10 Mt/year ROM coal until June 2046, using open-cut mining methods. ROM coal reserves are estimated to be approximately 268 Mt (Hansen Bailey, 2013). The mine will target the Hoskissons Coal and Melville Coal Member (Hansen Bailey, 2013).

Coal extraction will take place from three mining areas. As mining progresses all disturbed areas will be progressively rehabilitated. Tailings and coarse rejects will be co-disposed of in overburden emplacement areas (Hansen Bailey, 2013).

The proposed development includes the construction and operation of a mine access road; administration, workshop and related facilities; a coal handling and preparation plant; and transportation infrastructure. Project activities are planned to take place within a disturbance area of approximately 4084 ha (Shenhua Watermark Coal, 2013).

2.1.6.9.1 Mine water use

Water balance modelling was undertaken and showed that, while most site water requirements will be met by reuse of on-site runoff and groundwater inflows, the average net water deficit will be 21 to 162 ML/year.

Table 27 provides a summary of the water use requirements for the project throughout the mine life.

Where water is required additional to that available from the captured dirty surface water and water intercepted by mining, the project proposes to draw water from adjoining water sources under water access licences already held or to be purchased. It is proposed to use water pumped from the Mooki River or potentially a borefield.

Table 27 Watermark Coal Project predicted water requirements

Mine year	Average water requirement (ML/y)						
	Haul road dust suppression	Stockpile dust suppression	ROM bin dust suppression	CPP net demand	Vehicle washdown[a]	Mean total site demand	Water volume required from external source
2	342	10	15	205	5.5	580	43
5	149	37	55	760	5.5	1010	162
10	189	37	55	760	5.5	1050	128
15	174	36	54	745	5.5	1010	98
21	157	37	55	760	5.5	1010	61
25	393	37	55	760	5.5	1255	68
30	266	7	10	144	5.5	430	21

[a]The volume reported for vehicle washdown represents the losses from the system, which is typically approximately 10% of the total water requirement for vehicle washdown (Hansen Bailey, 2013).
Data: after WRM Water and Environment (2013)

2.1.6.9.2 Surface water management

The mine area is located within the Mooki river basin, a tributary of the Namoi River. Runoff from the site drains to one of three local drainage lines: Watermark Gully or unnamed flow paths to the north; Native Dog Gully to the south; or west to Lake Goran.

The main parts of the water-related infrastructure for the Watermark Coal Project include:

- sediment dams to collect and treat runoff from the operational areas
- dirty water drains to divert sediment-laden runoff to the sediment dams
- clean water drains to divert runoff from the undisturbed catchment around areas disturbed by mining
- a dirty water storage system to store water pumped out of the mining areas and to collect runoff from the CHPP and coal stockpile area. Mine water dams will be the first priority water source for road watering and CHPP water demands
- raw water storage (the main dam) from the water supply pipeline.

If water collected and treated in the sediment dams is not suitable for release to receiving waters it will be pumped back into the water management system. Runoff water will only be released from site if the quality is acceptable and during a rainfall event that exceeds the design capacity of the sediment control dam system (appropriate licences would be obtained for the release of this water).

The water management system has been modelled over the range of historical rainfall conditions and has been shown to have sufficient capacity to contain all mine water on the site without the need for offsite releases.

With the exception of the Western Mining Area (a portion of which will be the final void), it is planned that mining areas will be progressively rehabilitated as mining advances or concludes. The final void is anticipated to cover approximately 100 ha with a maximum depth of approximately

80 m below the natural ground surface. A mine closure plan will be developed within five years of closure (Hansen Bailey, 2013).

2.1.6.9.3 Groundwater management

Groundwater seepage into the proposed mining area is predicted to vary throughout the mine life (Table 28).

Table 28 Predicted Watermark Coal Project groundwater inflows to pit

These are pumpable volumes and so do not include volumes lost to evaporation in the pit, or moisture lost to the mined coal.

Mine year	Estimated mean groundwater inflow rate (ML/y)
2	0
5	14
10	57
15	43
21	175
23	756
25	371
30	132

Data: WRM Water and Environment (2013)

The groundwater seepage from the Permian units into the mining areas averages 180 ML/year over the life of the project. The peak seepage rate to the mining areas is estimated at 756 ML/year in year 23 (AGE Pty Ltd, 2013). The variability in the seepage rate is due to the different geological conditions that will be encountered in different mine areas.

The groundwater model indicates depressurisation in the underlying Permian strata will reduce upward water pressure, and close to the mining areas will induce downward vertical flow from the overlying alluvial aquifers in the underlying Permian units.

The modelling quantifies the effects of this depressurisation as follows:

- a reduction in flow to groundwater management zone 3 – 14 ML over life of mine, average rate 0.5 ML/year
- a reduction in flow to groundwater management zone 7 – 1020.8 ML over life of mine, average rate 34 ML/year
- a reduction in flow to groundwater management zone 8 – 35.5 ML over life of mine. However, over the life of the mine, it is reported that the average result is an increase of flow from the Permian to the alluvium at a rate of 1.1 ML/year.

The proponent argues that, although water from the alluvium and the Mooki River (47.5 ML/year or 0.13 ML/day, in year 24) will flow to the Permian units due to depressurisation resulting from the mine, post mining, when the zone of depressurisation has fully retracted, there will be a net increase in flow to the Mooki River of 7.3 ML/year (0.02 ML/day).

Groundwater levels in the final void are predicted to equilibrate at approximately 303 mAHD, after approximately 2000 years. This level remains below the regional watertable by approximately 1 to 2 m. Consequently the final void will act as a groundwater sink. The water level in the final void is predicted to stabilise well below the crest of the pit, and therefore the pit void is not predicted to spill.

2.1.6.10 Vickery Coal Project (ACRD)

Vickery Coal Project will involve recommencing open-cut mining at the former Vickery Coal Mine. The project was approved in 2014, with a maximum extraction rate of 4.5 Mt/year ROM coal, but mining has not yet commenced, as of August 2016. Mining had previously been undertaken at Vickery from 1986 to 1991 as an underground operation, and then from 1991 to 1998 using open-cut mining methods.

In January 2016 the mine owner submitted an application for the Vickery Extension Project. The extension project would involve an extension to the already approved mine footprint and the development of associated mine infrastructure including an on-site coal handling and preparation plant, road diversions and a rail spur and loop. The area of the proposed extension is approximately 970 ha. The extension would increase the rate of coal extraction to 10 Mt/year, with a 25 year mine life. Due to the timing of the application, the project has not been included in the bioregional assessment for the Namoi subregion. As such no further information on the Vickery Extension Project is presented in this section.

2.1.6.10.1 Mine water use

The average total water demand for the Vickery Coal Project is estimated to be 1179 ML/year (Whitehaven Coal Limited, 2013) of which 493 ML/year on average is to be met by licensed extraction from external water sources. The primary water use would be for dust suppression on internal haul roads and at the coal crushing and screening facility. Water would also be required for washdown of mobile equipment and other minor non-potable uses.

The water for operational uses would be accessed from the following sources, listed in order of priority:

- groundwater inflows to the open-cut and associated dewatering
- water storages containing runoff from active and rehabilitated areas
- water storages containing runoff from up-catchment areas
- licensed groundwater and surface water extractions.

The performance of the water management system has been modelled under a series of climate scenarios. Table 29 presents the range of mine water use predictions for these climate scenarios (Evans and Peck, 2013).

Table 29 Modelled mine water use for Vickery Coal Project

	Description	Total volume (ML) over 30-year mine life (for different climate scenarios)						Annual mean (ML/y)
		Mean	Minimum percentile	10th percentile (low rainfall)	50th percentile (median rainfall)	90th percentile (high rainfall)	Maximum percentile	
Water use	Total water use	35,367	36,488	36,214	35,394	34,557	34,186	1,179
	Licensed extraction (external sources)	14,793	17,900	16,400	14,750	12,910	11,500	493
Runoff draining to	Open cut	16,834	15,033	15,629	16,597	18,635	19,241	561
	MIA	3,973	3,718	3,806	3,961	4,164	4,417	132
	Western emplacement	7,008	5,742	6,183	6,834	8,035	9,047	234
	Eastern emplacement	615	344	415	602	819	1,228	21
	Rehabilitated catchments	3,485	2,118	2,779	3,434	4,264	5,293	116
Transferred to mine water dam from	Open cut	17,104	15,184	15,827	16,821	19,105	9,611	570
	MIA	3,971	3,718	3,804	3,961	4,160	4,417	132
	Western emplacement	2,904	2,492	2,654	2,895	3,166	3,373	97
	Eastern emplacement	110	56	81	106	146	176	4
	Rehabilitated catchments	1,522	1,168	1,353	1,543	1,673	1,787	51

MIA = mine infrastructure area
Data: Evans and Peck (2013)

Whitehaven holds a number of Water Access Licences (WALs) for extraction from the Lower Namoi Regulated River water source and the Upper Namoi – zone 4 groundwater sources to meet mine water needs. A total of 1482 ML/year is licensed for extraction, of which 1302 ML is from surface water sources and 180 ML/year from groundwater sources.

Under the NSW Aquifer Interference Policy, licences are required to account for any loss of flow to aquifers resulting from the Project. Resource Strategies Pty Ltd (2013b) indicated the predicted licence requirements for the two groundwater sources predicted to be impacted (Table 30).

Table 30 Predicted licensing requirements to address groundwater interference resulting from the Vickery Coal Project

Management zone or groundwater source	Predicted groundwater inflow volume requiring licensing (ML/y)			
	During project		Post-mining	
	Mean	Maximum	Mean	Maximum
Upper Namoi zone 4 – Namoi Valley (Keepit Dam to Gins Leap) Groundwater Source	44	78	88	98
Gunnedah-Oxley Basin – Namoi Management Zone	430	700	NA	430

NA = not available
Data: after Resource Strategies Pty Ltd (2013b)

2.1.6.10.2 Surface water management

The Vickery Coal Project area is drained via unnamed ephemeral drainage lines that rise in the Vickery State Forest and drain in a westerly direction to join Driggle Draggle Creek which, in turn, drains into Barbers Lagoon, an anabranch of the Namoi River. Additionally, a small section of the Vickery Coal Project area drains in a southerly direction to join Stratford Creek, a minor tributary of the Namoi River.

The proposed mine water management system has been designed to segregate mine water, overburden runoff and ‘clean’ runoff from outside the mine. Temporary and permanent up-catchment diversion dams, bunds, and drains would be constructed over the life of the Vickery Coal Project to divert runoff from undisturbed areas around the open-cut and disturbed areas of the site. The maximum harvestable right volume for the mine is 392 ML (Evans and Peck, 2013).

At the point where most of the site drains into Driggle Draggle Creek mean annual runoff would be expected to decrease as a result of the mine footprint covering about 14.5 km^2 of the catchment. At the completion of mining, the Vickery Coal Project would result in a 4.3% reduction in surface area to the catchment of Driggle Draggle Creek and a 0.01% reduction in the Namoi river basin.

Runoff from disturbed areas of the mine will be drained to a series of sediment basins. From the basins the water would either be used for operational needs on-site or discharged to the environment. Discharges would only occur when the water was at a suitable quality (total suspended solids (TSS) typically 50 milligrams per litre).

The mine water management system has been designed to provide sufficient capacity to store, treat and discharge runoff as required, even in extended periods of above average rainfall. However, in the event that the main mine water storages are near or at capacity, any excess mine water would be retained in the open-cut while runoff collected in the sediment basins would be managed so as to only discharge water of appropriate sediment concentration (Resource Strategies Pty Ltd, 2013a).

Modelling of the operation of the mine water management system for a range of climate scenarios indicates that there is likely to be little requirement to store water within the open-cut for an extended length of time, unless extremely high rainfall occurs during the later stages of mine life. If such a climate sequence occurred, up to 1000 ML of water may be required to be stored within the open-cut for a period of up to two years. This would be achieved by partitioning off sections of the open-cut, as required (Resource Strategies Pty Ltd, 2013a).

2.1.6.10.3 Groundwater management

The Vickery coal resource is hosted by the Maules Creek Formation, within the Maules Creek sub-basin of the lower Permian Bellata Group which is within the porous rock groundwater systems of the Gunnedah Basin. The coal resource is wholly located within the Gunnedah-Oxley Basin Murray–Darling Basin (MDB) Groundwater Source.

The Vickery Coal Project area is effectively encircled by alluvium, including that associated with the Namoi River (to the south, up to approximately 140 m thick) and Driggle Draggle Creek and Stratford Creek surface water drainages (to the north, between 40 to 70 m thick) (Merrick and Alkhatib, 2013). These alluvial sediments are part of the Upper Namoi groundwater management zone 4, Namoi Valley (Keepit Dam to Gins Leap) Groundwater Source.

The mine is located between the Boggabri Thrust fault (approximately 5 km to the west) and the Hunter-Mooki Thrust Fault system (to the east of the mine site). The mine site is intersected by a number of named faults.

Groundwater modelling was used to predict pit inflows to the mine throughout the project life (Merrick and Alkhatib, 2013). The inflow is expected to vary between 110 and 620.5 ML/year during the mine life. Table 31 provides the predicted pit inflows for each year of the mine life (Merrick and Alkhatib, 2013).

It was determined that groundwater contributed baseflow only in: the reach of the Namoi River examined in the model (4 km reach of the Namoi River to the immediate west of the project area); Barbers Lagoon; and the upgradient reach of Driggle Draggle Creek. No change in baseflow is predicted for the latter two reaches, however there is a predicted reduction in baseflow to the 4 km reach of the Namoi River to the immediate west of the Vickery Coal Project area. Baseflow to this reach is expected to decrease by about 5.5 ML/year (0.015 ML/day) from commencement of the project. The analysis of surface water – groundwater interaction presented in Section 2.1.5 found that this reach is generally considered connected, losing. However, that analysis was undertaken at a regional scale, whereas the modelling undertaken for the Vickery Coal Mine was at a local scale.

The equilibrium long-term groundwater inflow to the final mine voids is expected to be about 292 ML/year for the northern void and 219 ML/year for the southern void. Merrick and Alkhatib (2013) estimate that the northern void would reach an average water level of 168.8 mAHD and the southern void would reach an average water level of 146.7 mAHD, approximately 100 years after mining ceases (under current climate scenarios). The equilibrium water levels would be about 90 to 100 m lower than current groundwater levels at the northern void, and about 105 to 115 m lower at the southern void. Both voids would act as permanent groundwater sinks.

Table 31 Predicted pit inflows for the Vickery Coal Mine

Project year	Pit inflow (ML/y)	Project year	Pit inflow (ML/y)
1	0	16	482
2	146	17	460
3	135	18	573
4	197	19	558
5	230	20	515
6	245	21	558
7	248	22	631
8	237	23	653
9	241	24	646
10	241	25	661
11	274	26	646
12	288	27	650
13	292	28	697
14	318	29	664
15	456	30	365

Data: Merrick and Alkhatib (2013)

2.1.6.11 Narrabri Gas Project (ACRD)

The Narrabri Gas Project is currently in the preliminary stages of environmental approval. Santos Ltd has submitted a preliminary environmental assessment (PEA) to the NSW Department of Planning and Infrastructure (GHD, 2014), which proposes to develop the CSG reserves in the Narrabri area. The project has also been referred for assessment under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), and will require Commonwealth approval. There is relatively limited information available in the public domain relating to the project, as the environmental impact statement and supporting studies are currently being prepared. It is noted that the Narrabri Gas Project Environmental Impact Statement was released in early 2017 and will contain updated information about the proposed water management strategy for the project. However, these details were not available to the Assessment team at the time of writing and consequently are not reflected in this section.

The targeted coal seams for the project are primarily in the Maules Creek Formation (GHD, 2014). The proposal is to develop a gas field with up to 850 production and appraisal wells, as well as an integrated gas and water gathering system. The proposed gas field would include:

- a central water management and treatment facility, located outside the Pilliga Forest, to store and treat co-produced water for reuse
- a central gas processing unit at the water treatment facility, to treat and compress the natural gas to Australian pipeline requirements

- a small gas processing unit and water pumping station to transfer the gas and water extracted from the coal seams to the central processing facility
- supporting infrastructure including the upgrade of the Narrabri Operations Centre, workers' accommodation, power generation and distribution networks (GHD, 2014).

The Narrabri Gas Project area covers about 98,000 ha including several state forests and private land. It excludes the conservation area and nature reserves of the Pilliga woodlands. The proposed field operations will take up approximately 900 ha mostly in the Pilliga Forest. The Narrabri Gas Project could produce 200 TJ (terajoules) of natural gas per day, which would be transported via a new pipeline connection running south from Narrabri (GHD, 2014).

For the Narrabri Gas Project, estimated peak water production is approximately 2920 ML/year, which is forecast to stabilise at around 1460 ML/year approximately 10 years after production commences (Santos, 2012). The produced water and brine is intended to be first stored in ponds and then treated – typically by desalination using reverse osmosis or through amendment by altering the chemical balance of the water. The selection of the treatment process will depend on the original water quality and the intended use of the treated water (Santos, 2012).

Santos currently has no plans to use hydraulic fracture stimulation on future wells drilled as part of the Narrabri Gas Project, as geological data indicates that hydraulic fracturing would not increase gas flows in the coal seams (Ecological, 2014).

2.1.6.12 Mine footprints

To quantify the hydrological changes of mine developments, the location and spatial extent of the mine footprint over time is needed. Footprint polygons are used in the modelling to identify which cells in the models need to be modified to reflect impacts of mine development in the baseline and coal resource development pathway (CRDP).

2.1.6.12.1 Extraction of mine footprints from environmental impact statements and other sources

The main source of mine footprint is the respective environmental impact statements (EIS) for each mine. Figures depicting proposed mine plans for different years were used as the basis for determining how the mining footprint propagates over the mining period. Each figure was digitised and georeferenced using one of three methods:

- The preferred method was to use maps or plans with coordinates already on them.
- If there were no coordinates, then three point locations were matched with points on Google Earth and the latitude and longitude from Google Earth were used to georeference the image.
- If there were not three clearly identifiable point locations in the image, then supplementary points were found by matching contour information to the Shuttle Radar Topography Mission Smoothed Digital Elevation Model (SRTM DEM-S) grid (Geoscience Australia, Dataset 3).

The runoff contributing areas were determined as a time series over the life of the mine. Since the contributing area was not provided for all years, the footprint areas were calculated through linear interpolation. Any area upslope of a water storage or dirty or contaminated water area that was not diverted around the mine was included in the surface water mine footprint area. The surface water footprints were exported as shapefiles (.shp) for modelling.

2.1.6.12.2 NSW Department of Trade and Investment historical data (2000 to 2012)

For Boggabri and Tarrawonga baseline mines for which EIS were not available, the NSW Department of Trade and Investment's (DTI) historical mine footprint data were used.

2.1.6.12.3 Google Earth imagery

On-ground evidence of mines with planned 2015 or earlier start years was verified using Google Earth imagery. The Google Earth images were also used to verify the extent of the surface water mine footprint obtained from the DTI data. For Tarrawonga the baseline mine footprint data from DTI only covered the mine pit area, therefore adjustments were made on the footprint area based on Google Earth imagery. The image was also used to decide the start year of the Tarrawonga expansion as 2015.

Table 32 lists the assumptions made in generating the time series of footprint areas. It also includes the assumptions made for representing hydrological changes due to mines.

Table 32 Assumptions made in surface water modelling for representing hydrological changes of mines and generation of time series data

Characteristic	Assumption for modelling	Basis for assumption
Start date for baseline mines	As specified in development consent that was current at December 2012	The Assessment team does not have the information to model impacts of all historical mines. For modelling, the Assessment team use the timelines of the operation that were current at the date selected for defining baseline coal resource developments.
Start date for additional coal resource development	• as specified in development consent or • as indicated by a mining company representative, if different from development consent or • assumed 2018 if not commenced and uncertain commencement date	Start dates have been determined from current mine reports or mine company contacts; mining activities may not always commence on intended schedule due to delays in the approval process, or to market related reasons. A start date was estimated for mines that were approved to start at a time but had since not started.
End date for baseline mines	As originally specified in development consent or revised (includes a change in end date from an approved modification that does not involve an expansion of mining area). Does not include extensions in time to accommodate expansion of mining areas that commenced after December 2012, which are included in the CRDP as additional coal resource development.	End dates have been determined from current mine reports or mine company contacts.
End date for additional coal resource development	End date obtained from development consent	End dates have been determined from current mine reports or mine company contacts. For mines that were approved to start at a time but had since not started, the end dates were estimated by adding the proposed mine life to the estimated start date.

Characteristic	Assumption for modelling	Basis for assumption
Time series of footprints	Mine footprints expand and contract over time based on individual mining operational plans	Rehabilitation is typically undertaken progressively. As new areas of the mine excavation are commenced, the depleted pit and other mine-affected areas are rehabilitated.
Post-mining longwall footprints	Sustained at maximum footprint to 2102	Subsidence is permanent.
Post-mining open-cut footprints	• use information available in the EIS • in absence of relevant information, sustained at maximum footprint for 10 years • scaled back to final void area (if known) or to 0.16 times of maximum footprint area for a further 10 years	Absence of any other information on this for some of the mines. Anecdotal evidence from environmental officers at Glencore in the companion Hunter subregion suggested 5–10 years for return to undisturbed conditions.
Final void areas	• use information from EIS • if final voids not known, then use 0.16 of maximum footprint area	In the companion Hunter subregion, for mines for which data were available, final void area was compared to the maximum footprint area. The median of the ratio of final void area to the maximum footprint area was 16%, with a range of 4% to 32%.
Longwall mine	Assume a permanent 5% reduction in surface water runoff from the affected area	Subsidence is not modelled, but is inevitable where longwall mining occurs. Impacts on surface runoff can vary from very little to more than 50% interception, although given that efforts would be undertaken to rehabilitate mine area as close to the pre-mining condition as possible, the latter is unlikely. Therefore the impact is likely to be smaller, so we conservatively assume a 5% reduction in runoff here. The Assessment team does not have any basis for varying this by mine location, longwall panel depth or other factors.
Open-cut and longwall mine site facilities	Treat the same as mining disturbed areas	Assume that site facilities are not abandoned immediately when mining ceases, allowing for rehabilitation of site. Rehabilitation is assumed to return disturbed areas to pre-disturbance conditions over 10 years, following completion of rehabilitation.

CRDP = coal resource development pathway; EIS = environmental impact statement

2.1.6.12.4 Mine footprints time series

A number of assumptions need to be made in the surface water modelling to represent the hydrological impacts of mining developments on water-dependent assets. These assumptions are consistent with the policy and legislative framework governing the operation of mines (Table 32). This section discusses the approach for defining surface water footprint time series and characterising their hydrological responses pre- and post-development. The time series data are used in surface water modelling to estimate impacts of the additional coal resource development mines on hydrological response variables. The hydrological impacts are reported in companion product 2.6.1 for the Namoi subregion (Aryal et al., 2018).

It is important, therefore, to determine the areas where surface runoff will be intercepted. This area is termed the surface water footprint of the mine, and it can differ from the groundwater footprint. For the purposes of bioregional assessments, surface water footprint covers the entire area disturbed by coal mine operations, including pits, road, spoil dumps, water storages and infrastructure. It may also include otherwise undisturbed parts of the landscape from which natural runoff is retained in reservoirs within mining complex. The footprint does not include established rehabilitated areas from which surface runoff can enter the stream network. Nor does it include catchment areas upstream of drainage channels that divert water around a mine site and do not retain it.

For an underground mine, surface subsidence associated with the collapse of the longwall panels is expected to lead to increased ponding on the surface. This increased ponding is likely to result in a decrease in natural flow to the streams. As discussed in Table 32, a 5% reduction in runoff in areas covered by the underground mine footprint is conservatively (i.e. impact is likely to be smaller) assumed, which factors in regulatory requirements on mining companies to minimise the impacts from mine subsidence through such steps as appropriate longwall orientation and drainage management.

Mine footprint areas change over the lifetime of a mine's operations. As new parts of the lease are opened up for active use, the footprint increases. As mined parts of the lease are rehabilitated and their runoff returned to natural drainage, the footprint decreases although not necessarily to pre-mining condition. As well as the area of any final voids, the final mine footprint may also include the area covered by any infrastructure (e.g. dams, levee banks, roads) that is intended to remain on the site after final rehabilitation.

Time series of mine footprints for baseline and CRDP mines were compiled from spatial data supplied by mining companies and the NSW Department of Trade and Investment, or extracted by the Assessment team from environmental impact statements and related documents, Landsat TM and Google Earth imagery.

Figure 47 to Figure 57 show temporal variations of mine footprint areas for Namoi coal resource development. Two of the projects have footprints shown for both the baseline and CRDP (Boggabri Coal Mine – Figure 47, and Tarrawonga Mine – Figure 54). Figures for the other projects show mine footprints either under baseline or CRDP.

Boggabri Coal Mine started operating in 2006. The surface water footprint of the Boggabri Coal Mine and Boggabri Coal Expansion Project spans two surface water modelling catchments.

Figure 47 shows the growth of mine footprint areas for both the baseline and CRDP from 2006 to the end of assessment year 2102. The baseline footprint reaches a maximum area of 5.5 km^2 in 2012, while the total CRDP footprint reaches its maximum area of 18.6 km^2 in 2033.

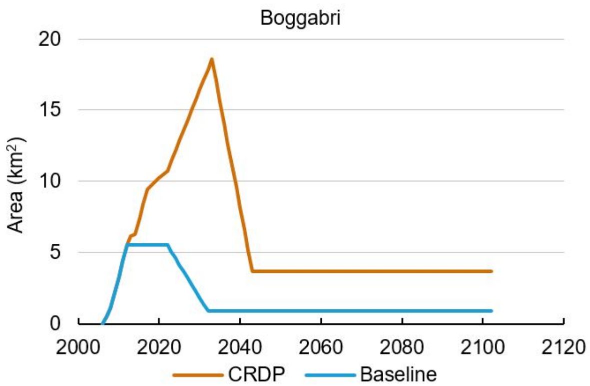

Figure 47 Temporal variation of footprint area for the Boggabri Coal Mine under the baseline and CRDP

CRDP = coal resource development pathway
Data: Bioregional Assessment Programme (Dataset 4)

The Maules Creek Mine started in 2015 and is identified as a mine under CRDP for the Namoi subregion. The surface water footprint of the mine directly affects one surface water modelling catchment. The first-year mine footprint area is 4.8 km^2. The planned maximum footprint area is 18.5 km^2 in 2019 (Figure 48).

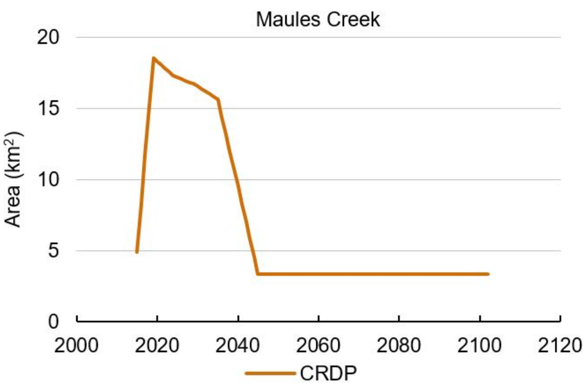

Figure 48 Temporal variation of the footprint area for the Maules Creek Project under the CRDP

CRDP = coal resource development pathway
Data: Bioregional Assessment Programme (Dataset 4)

The Watermark Coal Project has mines identified under CRDP for the Namoi subregion. The project occupies within four surface water modelling catchments and is planned to commence in 2018 (Figure 49). The mine has 6.0 km^2 of total footprint area in the first year and a maximum total footprint of 20.6 km^2 in 2038.

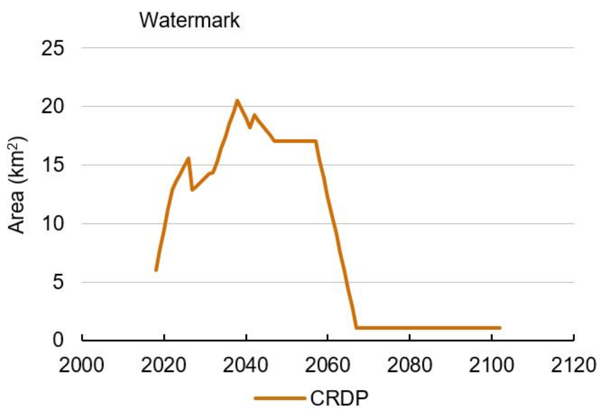

Figure 49 Temporal variation of the footprint area for the Watermark Coal Project under the CRDP

CRDP = coal resource development pathway
Data: Bioregional Assessment Programme (Dataset 4)

Vickery Coal Project is under CRDP with an assumed 2018 start date. The surface water footprint for the Vickery Coal Project spans two surface water modelling catchments with a net mine footprint area of 9.4 km^2 in the first year, reaching a maximum of 24.5 km^2 in 2034 (Figure 50).

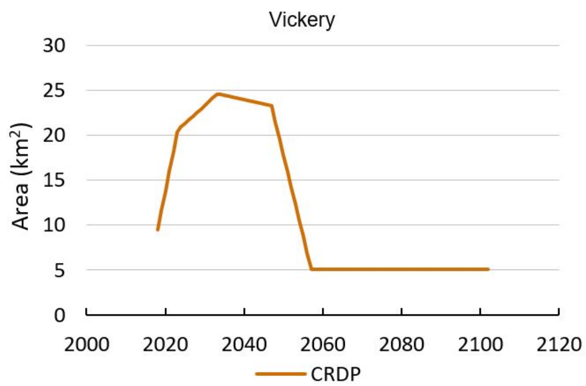

Figure 50 Temporal variation of the footprint area for the Vickery Coal Project under the CRDP

CRDP = coal resource development pathway
Data: Bioregional Assessment Programme (Dataset 4)

Sunnyside Mine is a baseline mine which started in 2008 and was completed in 2012. The surface water footprint of the mine directly affects one surface water modelling catchment. The mine footprint area starts with an area of 0.9 km^2 in 2008 with a peak footprint area of 1.3 km^2 in 2012 (Figure 51).

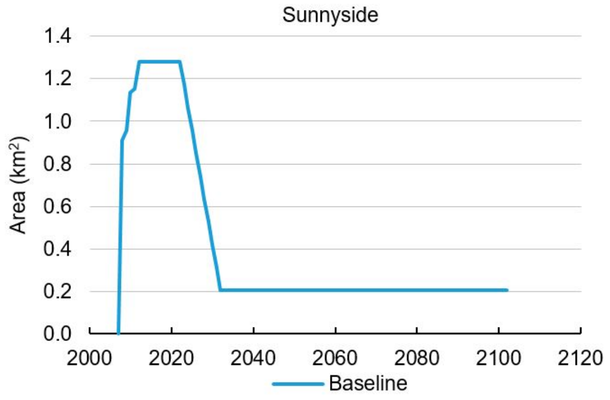

Figure 51 Temporal variation of the footprint area for the Sunnyside Mine under the baseline

Data: Bioregional Assessment Programme (Dataset 4)

Werris Creek Mine started in 2004 and is included in the baseline. The surface water footprint of the mine directly affects two surface water modelling catchments. It has a mine footprint area of 4.0 km^2 in 2005 increasing to 6.7 km^2 in 2020 (Figure 52).

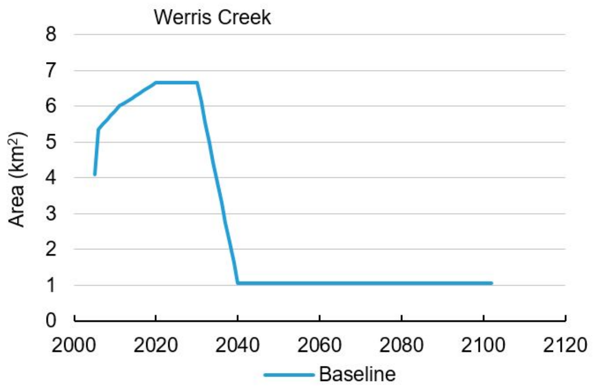

Figure 52 Temporal variation of the footprint area for the Werris Creek Mine under the baseline

Data: Bioregional Assessment Programme (Dataset 4)

Rocglen Mine started in 2009 with a net mine footprint of 2.9 km^2. The maximum mine footprint of 3.4 km^2 in 2013 continues until the end of mining in 2018. Due to extensive mine rehabilitation work the footprint decreases to 1.6 km^2 in the last year and gradually to zero over the following ten years (Figure 53).

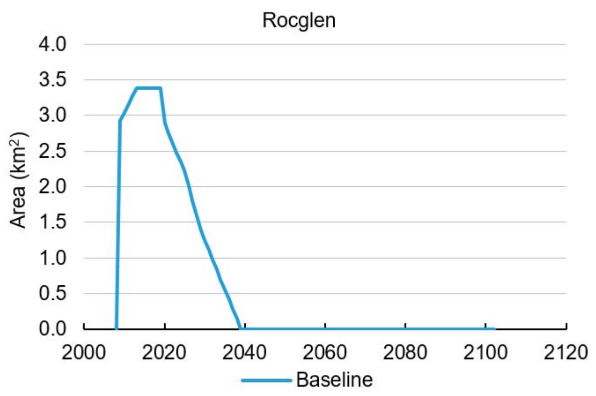

Figure 53 Temporal variation of the footprint area for the Rocglen Mine under the baseline

Data: Bioregional Assessment Programme (Dataset 4)

Footprints of the Tarrawonga Mine and Tarrawonga Coal Expansion Project directly affect two surface water modelling catchments. Figure 54 shows the growth of mine footprint areas for both the baseline and CRDP. The baseline mine starts in 2006 with its footprint reaching a maximum of 5.0 km^2 in 2014. The total CRDP footprint reaches its maximum of 7.2 km^2 in 2016 (Figure 54).

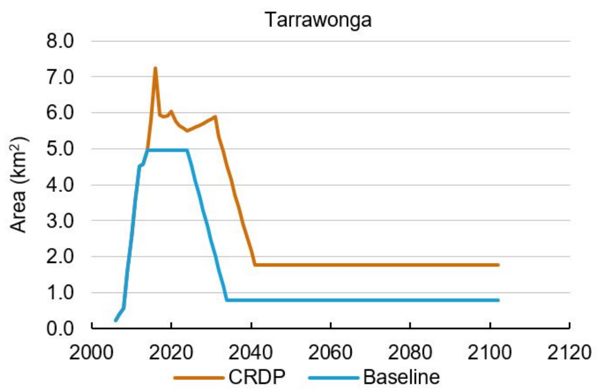

Figure 54 Temporal variation of the footprint area for the Tarrawonga Mine under the baseline and CRDP

CRDP = coal resource development pathway
Data: Bioregional Assessment Programme (Dataset 4)

Caroona Coal Project is a longwall underground mine under CRDP with an assumed 2020 start date. The footprint of the project lies within one surface water modelling catchment. The planned area of underground excavation in the first year is 0.73 km^2, increasing to 78 km^2 in 2049 (Figure 55).

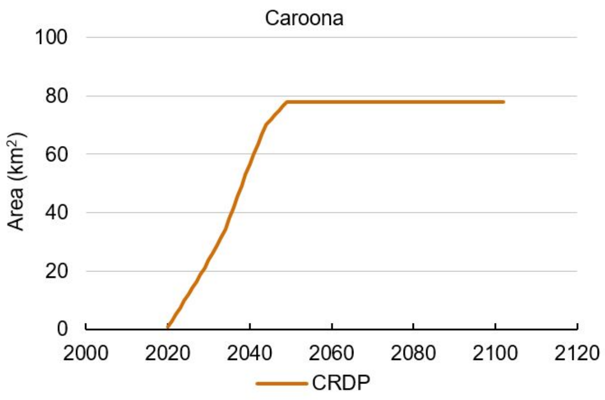

Figure 55 Temporal variation of the underground footprint area for the Caroona Coal Project under the CRDP

CRDP = coal resource development pathway
Data: Bioregional Assessment Programme (Dataset 4)

Narrabri South Project is a longwall underground mine under CRDP with a 2030 start date. The footprint of the mine directly affects one surface water modelling catchment. The planned area of underground excavation in the first year is 0.4 km^2 increasing to 24.2 km^2 in 2054 (Figure 56).

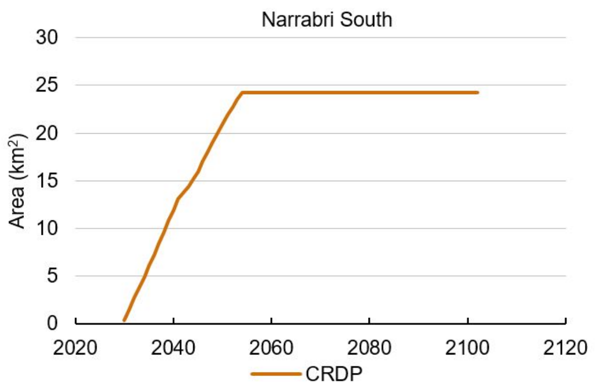

Figure 56 Temporal variation of the underground footprint area for the Narrabri South Project under the CRDP

CRDP = coal resource development pathway
Data: Bioregional Assessment Programme (Dataset 4)

Narrabri North Mine, a longwall underground mine under baseline, commenced in 2010. The planned area of underground excavation in the first year is 0.7 km^2 and is 30.1 km^2 in 2035. The total footprint due to surface mine facilities is 5.8 km^2 (Figure 57). The mine directly affects two surface water modelling catchments.

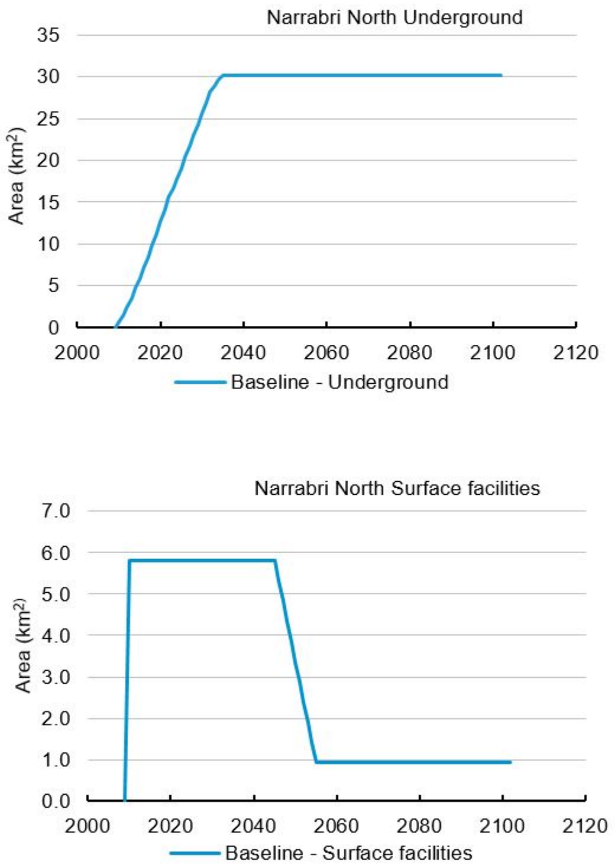

Figure 57 Temporal variation of the underground and surface footprint area for the Narrabri North Mine under the baseline

Note the y-axis limits are different in the bottom two plots.
Data: Bioregional Assessment Programme (Dataset 4)

Table 33 summarises the areas of changed surface water hydrology for three key points in the footprint time series for each open-cut mine: end of 2012 prior to commencement of any additional coal resource development mines in the CRDP; the maximum disturbed area represented in the model; and the final disturbed area following full rehabilitation. Open-cut mines and site facilities (whether they be for open-cut or underground operations) are included in the areas given, as they have the same hydrological effect in the surface water model.

Table 33 Key characteristics of data used to represent mine impacts in the surface water model for the Namoi subregion

Mine or mine complex	Open-cut, underground or surface	In baseline?	In CRDP?	2012 area disturbed by open-cut pits, site facilities (km^2)	Maximum area disturbed by open-cut pits, site facilities (km^2)	Final area disturbed by open-cut pits, site facilities (km^2)	Maximum area disturbed above longwall panels (km^2)	Name of post-2012 mine expansion project
Boggabri	OC	Y	N	5.5	5.5	0.9	na	na
	OC	N	Y	5.5	18.6	3.7	na	Boggabri Coal Expansion Project
Tarrawonga	OC	Y	N	4.5	4.97	0.8	na	na
	OC	N	Y	4.5	8.07	1.8	na	Tarrawonga Coal Expansion Project
Maules Creek	OC	N	Y	na	18.5	3.4	na	na
Watermark	OC	N	Y	na	20.5	1.1	na	na
Vickery	OC	N	Y	na	24.5	5.0	na	na
Sunnyside	OC	Y	N	1.3	1.3	0.2	na	na
Werris Creek	OC	Y	N	6.1	6.67	1.1	na	na
Rocglen	OC	Y	N	3.3	3.40	0.0	na	na
Caroona	UG	N	Y	na	na	na	78.0	na
Narrabri South	UG	N	Y	na	na	na	24.2	na
Narrabri North	Surface	Y	N	5.8	5.80	na	na	na
Narrabri North	UG	Y	N	2.5	na	0.92	30.1	na

na = not applicable, OC = open-cut, UG = underground

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Glossary

The register of terms and definitions used in the Bioregional Assessment Programme is available online at http://environment.data.gov.au/def/ba/glossary (note that terms and definitions are respectively listed under the 'Name' and 'Description' columns in this register). This register is a list of terms, which are the preferred descriptors for concepts. Other properties are included for each term, including licence information, source of definition and date of approval. Semantic relationships (such as hierarchical relationships) are formalised for some terms, as well as linkages to other terms in related vocabularies.

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with a coal seam gas (CSG) operation or coal mine. For example, activities during the production life-cycle stage in a CSG operation include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into components, which are grouped into life-cycle stages.

additional coal resource development: all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012

annual flow: the volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

aquifer: rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit quantities of water to bores and springs

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.

artesian aquifer: an aquifer that has enough natural pressure to allow water in a bore to rise to the ground surface

assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. The assessment extent is created by revising the preliminary assessment extent on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

asset: an entity that has value to the community and, for bioregional assessment purposes, is associated with a subregion or bioregion. Technically, an asset is a store of value and may be managed and/or used to maintain and/or produce further value. Each asset will have many values associated with it and they can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

baseflow: the portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system

baseflow index: the ratio of baseflow to total streamflow over a long period of time (years) baseline coal resource development: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012

basement: the crust below the rocks of interest. In hydrogeology it means non-prospective rocks below accessible groundwater. Commonly refers to igneous and metamorphic rocks which are unconformably overlain by sedimentary beds or cover material, and sometimes used to indicate 'bedrock' (i.e. underlying or encasing palaeovalley sediments).

bioregion: a geographic land area within which coal seam gas (CSG) and/or coal mining developments are taking place, or could take place, and for which bioregional assessments (BAs) are conducted

bioregional assessment: a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion, with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and coal mining development on water resources. The central purpose of bioregional assessments is to analyse the impacts and risks associated with changes to water-dependent assets that arise in response to current and future pathways of coal seam gas and coal mining development.

bore: a narrow, artificially constructed hole or cavity used to intercept, collect or store water from an aquifer, or to passively observe or collect groundwater information. Also known as a borehole or piezometer.

causal pathway: for the purposes of bioregional assessments, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets

Clarence-Moreton bioregion: The Clarence-Moreton bioregion is located in north-east NSW and south-east Queensland and adjoins the Northern Inland Catchments bioregion. Along with the towns of Casino, Lismore and Grafton, it contains the outskirts of the Queensland cities of Brisbane, Ipswich, Logan and Toowoomba. The bioregion contains large river systems (including the Clarence, Richmond and Logan-Albert rivers) and extensive wetlands, some of which are nationally important. Many of these wetlands are home to water-dependent plants and animals that are listed as rare or threatened under Queensland and Commonwealth legislation. The bioregion contains numerous national parks and forest reserves and includes sites of international importance for bird conservation. A large area of the bioregion is used for dryland farming and plantations and as grazing land for livestock. Irrigated agriculture takes up a comparatively small area. Groundwater is extracted for various uses but most commonly for livestock and agricultural purposes. The largest water reservoir in this bioregion is Lake Wivenhoe on the Brisbane River, which supplies Brisbane and its surrounds. The NSW part of the bioregion has smaller dams located in the upper Richmond river basin.

coal resource development pathway: a future that includes all coal mines and coal seam gas (CSG) fields that are in the baseline as well as those that are expected to begin commercial production after December 2012 component: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a coal seam gas (CSG) operation or coal mine. For example, components during the development life-cycle stage of a coal mine include developing the mine infrastructure, the open pit, surface facilities and underground facilities. Components are grouped into life-cycle stages.

conceptual model: abstraction or simplification of reality

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

connectivity: a descriptive measure of the interaction between water bodies (groundwater and/or surface water)

consequence: synonym of impact

context: the circumstances that form the setting for an event, statement or idea

cumulative impact: for the purposes of bioregional assessments, the total change in water resources and water-dependent assets resulting from coal seam gas and coal mining developments when all past, present and reasonably foreseeable actions that are likely to impact on water resources are considered

dataset: a collection of data in files, in databases or delivered by services that comprise a related set of information. Datasets may be spatial (e.g. a shape file or geodatabase or a Web Feature Service) or aspatial (e.g. an Access database, a list of people or a model configuration file).

depressurisation: in the context of coal seam gas operations, depressurisation is the process whereby the hydrostatic (water) pressure within a coal seam is reduced (through pumping) such that natural gas desorbs from within the coal matrix, enabling the gas (and associated water) to flow to surface

derived dataset: a dataset that has been created by the Bioregional Assessment Programme

dewatering: the process of controlling groundwater flow within and around mining operations that occur below the watertable. In such operations, mine dewatering plans are important to provide more efficient work conditions, improve stability and safety, and enhance economic viability of operations. There are various dewatering methods, such as direct pumping of water from within a mine, installation of dewatering wells around the mine perimeter, and pit slope drains.

derived dataset: a dataset that has been created by the Bioregional Assessment Programme

discharge: water that moves from a groundwater body to the ground surface or surface water body (e.g. a river or lake)

diversion: see extraction

drawdown: a lowering of the groundwater level (caused, for example, by pumping). In the bioregional assessment (BA) context this is reported as the difference in groundwater level between two potential futures considered in BAs: baseline coal resource development (baseline) and the coal resource development pathway (CRDP). The difference in drawdown between CRDP and baseline is due to the additional coal resource development (ACRD). Drawdown under the baseline is relative to drawdown with no coal resource development; likewise, drawdown under the CRDP is relative to drawdown with no coal resource development.

ecosystem: a dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit. Note: ecosystems include those that are human-influenced such as rural and urban ecosystems.

ecosystem function: the biological, geochemical and physical processes and components that take place or occur within an ecosystem. It refers to the structural components of an ecosystem (e.g. vegetation, water, soil, atmosphere and biota) and how they interact with each other, within ecosystems and across ecosystems.

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), change in the quantity and/or quality of surface water or groundwater. An effect is a specific type of an impact (any change resulting from prior events).

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels

formation: rock layers that have common physical characteristics (lithology) deposited during a specific period of geological time

Geofabric: a nationally consistent series of interrelated spatial datasets defining hierarchically-nested river basins, stream segments, hydrological networks and associated cartography

geological formation: stratigraphic unit with distinct rock types, which is able to mapped at surface or in the subsurface, and which formed at a specific period of geological time

goaf: That part of a mine from which the coal has been partially or wholly removed; the waste left in old workings.

groundwater: water occurring naturally below ground level (whether stored in or flowing through aquifers or within low-permeability aquitards), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.

groundwater recharge: replenishment of groundwater by natural infiltration of surface water (precipitation, runoff), or artificially via infiltration lakes or injection

groundwater system: see water system

Gwydir subregion: The Gwydir subregion includes parts of the northern Murray–Darling Basin in northern New South Wales and southern Queensland. The main rivers draining the subregion are the Gwydir and Macintyre-Barwon rivers. The subregion extends westward from the lower slopes of the New England Tablelands onto the low-lying riverine plains of the Barwon-Darling river system. Moree is the largest town in the subregion. Most of the land in the subregion is used for grazing and cropping. Groundwater is heavily used for irrigation of summer crops such as cotton. The subregion contains seasonal, semi-permanent and permanent wetlands and lagoons. This includes the Gwydir Wetlands, which is an internationally recognised and protected wetland. The subregion is home to a number of endangered water-dependent ecological communities, animals and plants which are protected under Commonwealth and New South Wales legislation.

Hunter subregion: Along the coast, the Hunter subregion extends north from the northern edge of Broken Bay on the New South Wales Central Coast to just north of Newcastle. The subregion is bordered in the west and north–west by the Great Dividing Range and in the north by the towns of Scone and Muswellbrook. The Hunter River is the major river in the subregion, rising in the Barrington Tops and Liverpool Ranges and draining south-west to Lake Glenbawn before heading east where it enters the Tasman Sea at Newcastle. The subregion also includes smaller catchments along the central coast, including the Macquarie and Tuggerah lakes catchments.

hydrogeology: the study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of interactions between water and rock

hydrological response variable: a hydrological characteristic of the system that potentially changes due to coal resource development (for example, drawdown or the annual flow volume)

impact: a change resulting from prior events, at any stage in a chain of events or a causal pathway. An impact might be equivalent to an effect (change in the quality and/or quantity of surface water or groundwater), or it might be a change resulting from those effects (for example, ecological changes that result from hydrological changes).

impact mode: the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events.

Impact Modes and Effects Analysis: a systematic hazard identification and prioritisation technique based on Failure Modes and Effects Analysis

inflow: surface water runoff and deep drainage to groundwater (groundwater recharge) and transfers into the water system (both surface water and groundwater) for a defined area

life-cycle stage: one of five stages of operations in coal resource development considered as part of the Impact Modes and Effects Analysis (IMEA). For coal seam gas (CSG) operations these are exploration and appraisal, construction, production, work-over and decommissioning. For coal mines these are exploration and appraisal, development, production, closure and rehabilitation. Each life-cycle stage is further divided into components, which are further divided into activities.

likelihood: probability that something might happen

material: pertinent or relevant

model node: a point in the landscape where hydrological changes (and their uncertainty) are assessed. Hydrological changes at points other than model nodes are obtained by interpolation.

Namoi subregion: The Namoi subregion is located within the Murray–Darling Basin in central New South Wales. The subregion lies within the Namoi river basin, which includes the Namoi, Peel and Manilla rivers. However, the subregion being assessed is smaller than the Namoi river basin because the eastern part of the river basin does not overlie a coal-bearing geological basin. The largest towns in the subregion are Gunnedah, Narrabri and Walgett. The main surface water resource of the Namoi subregion is the Namoi River. There are three large dams that supply water to the subregion, of which Keepit Dam is the main water storage. More than half of the water released from Keepit Dam and river inflow may be extracted for use for agriculture, towns and households. Of this, the great majority is used for agricultural irrigation. The landscape has been considerably altered since European settlement for agriculture. Significant volumes of groundwater are also used for agriculture (cropping). Across the subregion there are a number of water-dependent ecological communities, and plant and animal species that are listed as threatened under either Commonwealth or New South Wales legislation. The subregion also contains Lake Goran, a wetland of national importance, and sites of international importance for bird conservation.

Northern Inland Catchments bioregion: The Northern Inland Catchments bioregion is located west of the Great Dividing Range in eastern Australia and includes parts of the northern Murray–Darling Basin in northern New South Wales and southern Queensland. The Northern Inland Catchments bioregion adjoins the Clarence-Moreton bioregion in the north-east, and the Northern Sydney Basin bioregion in the south. The bioregion was selected for assessment because of the likely coal seam gas and coal mining development and the potential for water dependent impacts on the environment and other water-using industries such as agriculture. The Northern Inland Catchments bioregion includes four subregions: the Maranoa-Balonne-Condamine, Gwydir, Namoi and Central West subregions. The subregion boundaries follow river basin boundaries, but only include areas that have the types of rocks known to contain coal and coal seam gas. Some water resources outside the Northern Inland Catchments bioregion that may potentially be impacted as a result of coal and coal seam gas development in the Northern Inland Catchments bioregion will also be considered in the assessment.

percentile: a specific type of quantile where the range of a distribution or set of runs is divided into 100 contiguous intervals, each with probability 0.01. An individual percentile may be used to indicate the value below which a given percentage or proportion of observations in a group of observations fall. For example, the 95th percentile is the value below which 95% of the observations may be found.

permeability: the measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the ground.

porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass preliminary assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. The PAE is estimated at the beginning of a bioregional assessment, and is updated to the 'assessment extent' on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

recharge: see groundwater recharge

riparian: An area or zone within or along the banks of a stream or adjacent to a watercourse or wetland; relating to a riverbank and its environment, particularly to the vegetation.

risk: the effect of uncertainty on objectives

runoff: rainfall that does not infiltrate the ground or evaporate to the atmosphere. This water flows down a slope and enters surface water systems.

run-of-mine coal: refers to coal extracted from a mining operation and delivered to a coal handling and preparation plant (CHPP), prior to any further processing stages that may be required. The ROM coal is essentially the raw material from the mine that feeds the CHPP and, in addition to coal, may also include minor non-coal rocks and minerals.

saturated zone: the part of the ground in which all the voids in the rocks or soil are filled with water. The watertable is the top of the saturated zone in an unconfined aquifer.

source dataset: a pre-existing dataset sourced from outside the Bioregional Assessment Programme (including from Programme partner organisations) or a dataset created by the Programme based on analyses conducted by the Programme for use in the bioregional assessments (BAs)

spring: a naturally occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool of water. Typically, it represents the point at which the watertable intersects ground level.

stratigraphy: stratified (layered) rocks

subcrop: 1 - A subsurface outcrop, e.g. where a formation intersects a subsurface plane such as an unconformity. 2 - In mining, any near-surface development of a rock or orebody, usually beneath superficial material.

subregion: an identified area wholly contained within a bioregion that enables convenient presentation of outputs of a bioregional assessment (BA)

subsidence: localised lowering of the land surface. It occurs when underground voids or cavities collapse, or when soil or geological formations (including coal seams, sandstone and other sedimentary strata) compact due to reduction in moisture content and pressure within the ground.

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs sustainable yield: the level of water extraction from a particular system that, if exceeded, would compromise the productive base of the water resource and important environmental assets or ecosystem functions

tmax: year of maximum change

uncertainty: the state, even partial, of deficiency of information related to understanding or knowledge of an event, its consequence, or likelihood. For the purposes of bioregional assessments, uncertainty includes: the variation caused by natural fluctuations or heterogeneity; the incomplete knowledge or understanding of the system under consideration; and the simplification or abstraction of the system in the conceptual and numerical models.

unsaturated zone: the zone in soils and rocks occurring above the watertable, where there is some air within the pore spaces

water allocation: the specific volume of water allocated to water access entitlements in a given season, defined according to rules established in the relevant water plan

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development

water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

water use: the volume of water diverted from a stream, extracted from groundwater, or transferred to another area for use. It is not representative of 'on-farm' or 'town' use; rather it represents the volume taken from the environment.

watertable: the upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.

well: typically a narrow diameter hole drilled into the earth for the purposes of exploring, evaluating or recovering various natural resources, such as hydrocarbons (oil and gas) or water. As part of the drilling and construction process the well can be encased by materials such as steel and cement, or it may be uncased. Wells are sometimes known as a ‘wellbore’.

2.2 Statistical analysis and interpolation

Originally the statistical analysis and interpolation was intended to be reported independently of the observations analysis. Instead it has been combined with the observations analysis as product 2.1-2.2 to improve readability. For statistical analysis and interpolation see Section 2.1 of this product.

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