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 Gloucester subregion

Product 2.1-2.2 for the Gloucester subregion from the Northern Sydney Basin 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 Office of Water Science, within 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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Authorship is listed in relative order of contribution.

Cover photograph

View of the Gloucester valley NSW with the Barrington River and associated riparian vegetation in the foreground and the township Gloucester in the distance looking south from the Kia Ora Lookout, 2013

Credit: Heinz Buettikofer, CSIRO

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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
- Independent reviewers: Warwick McDonald (CSIRO).

Currency of scientific results

The modelling results contained in this product were completed in July 2015 using the best available data, models and approaches available at that time. The product content was completed in November 2016.

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 will be 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, will undertake 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.

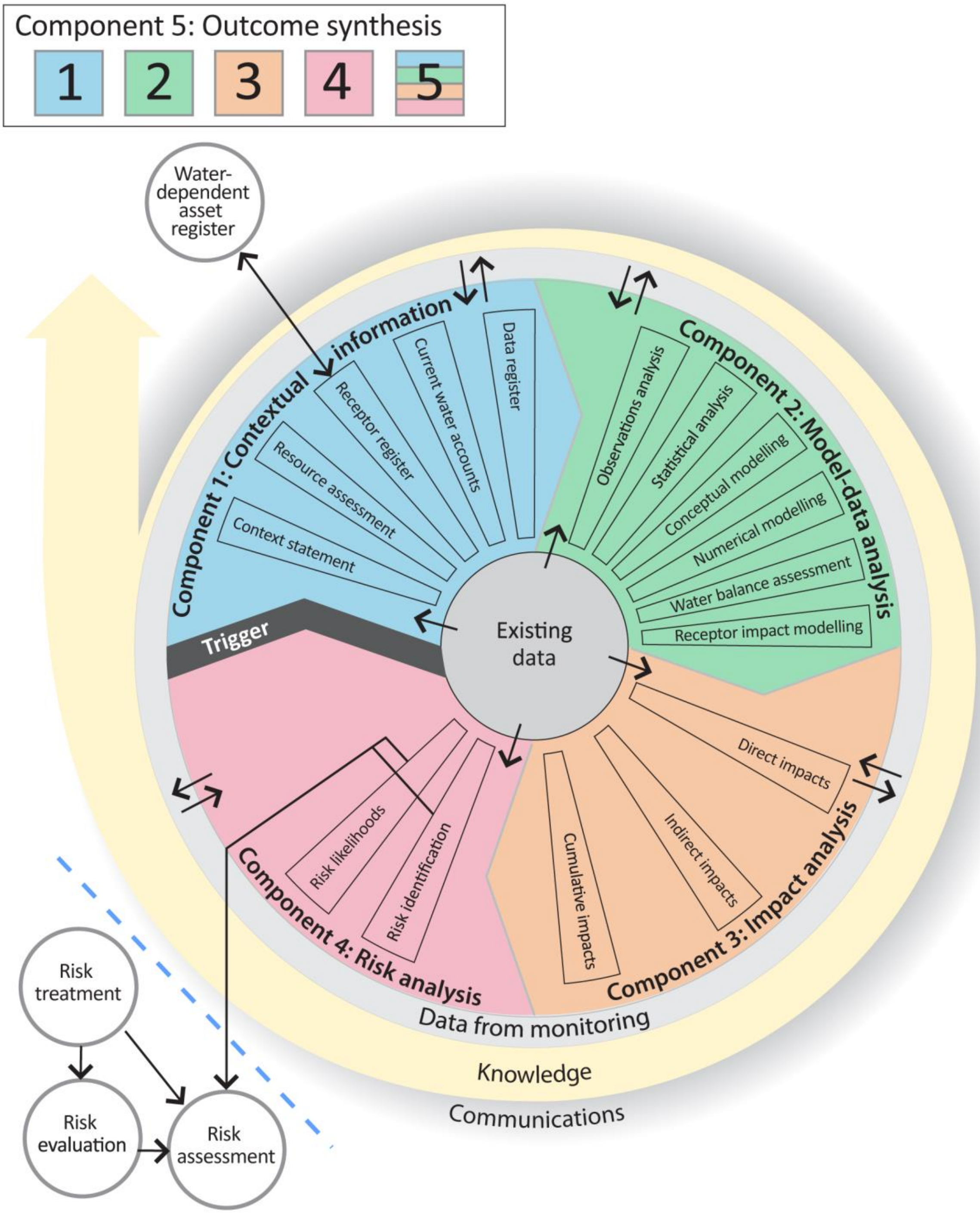


Figure 1 Schematic diagram of the bioregional assessment methodology

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) to, in the first instance, 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 – in this case an explanation will be supplied in the technical products of that BA. Ultimately the Programme anticipates publishing a consolidated 'operational BA methodology' with fully worked examples based on the experience and lessons learned through applying the methods to 13 bioregions and subregions.

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.

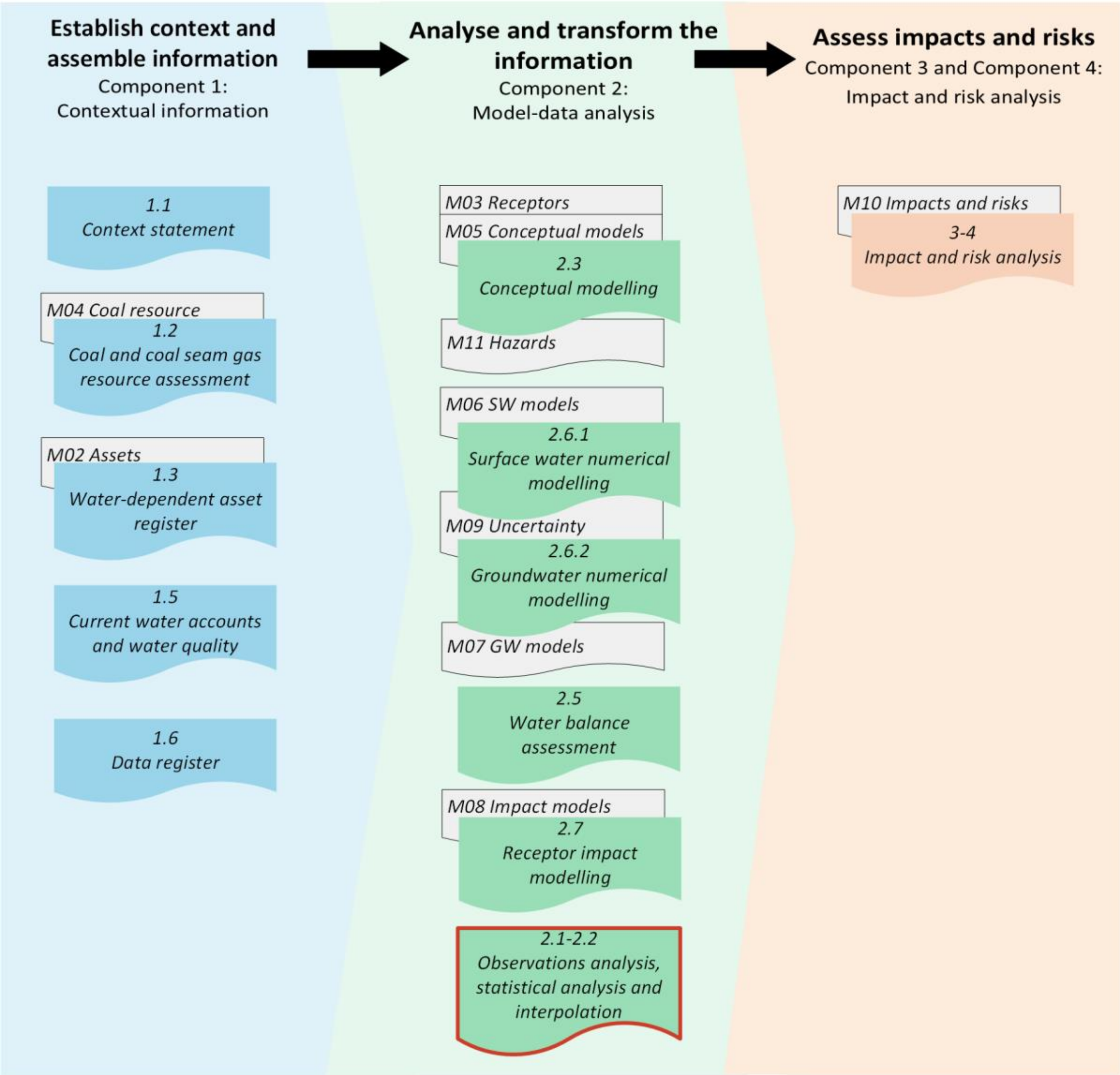


Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Gloucester subregion

For each subregion in the Northern Sydney Basin 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 products 2.6.1 (surface water modelling) and 2.6.2 (groundwater 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 Gloucester 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 Gloucester 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 Gloucester subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Gloucester 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 Sydney Basin 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

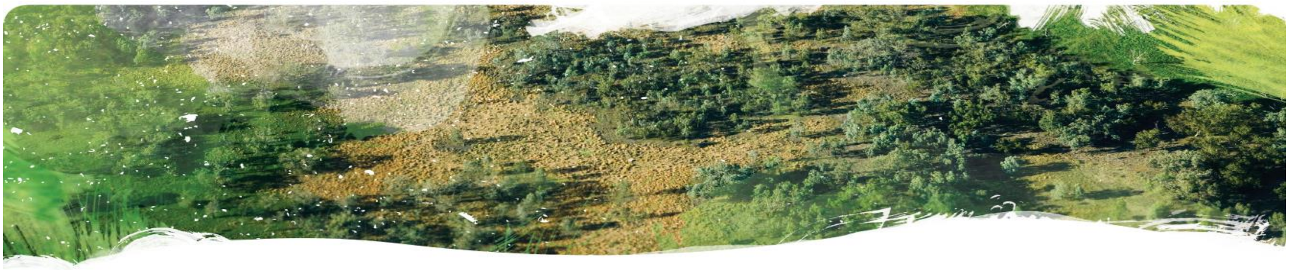
The following notes are relevant only for this technical product.

- 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 17, Figure 18, Figure 19, Figure 20, Figure 21, Figure 22 and Figure 23. 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 Sydney Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Contact bioregionalassessments@bom.gov.au to access metadata (including copyright, attribution and licensing information) for all datasets cited or used to make figures in this product. At a later date, this information, as well as all unencumbered datasets, will be published online.
- 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 created date. Where a created date is not available, the publication date or last updated 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 23 February 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 23 February 2018, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.



2.1 Observations analysis for the Gloucester subregion

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

The statistical analysis and interpolation aims to develop a quantitative understanding of the Gloucester 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 covers data characteristics, including accuracy, for all datasets used in the Geography section of the companion product 1.1 for the Gloucester subregion (McVicar et al., 2014).

For physical geography brief assessments are provided from the relevant literature for the: (i) digital elevation model (DEM) data, (ii) surface watercourses and basin/catchment boundary data, (iii) physiographic classes, (iv) soil classes, (v) pre-European vegetation, (vi) current vegetation, (vii) land cover dynamics and (viii) vegetation height.

For human geography concise descriptions are provided of the: (i) population density and (ii) land use management.

For retrospective climate analysis brief descriptions are provided for: (i) precipitation (P), (ii) maximum and minimum air temperature (Tmax and Tmin, respectively), (iii) vapour pressure (VP), (iv) net radiation (Rn), (v) wind speed and (vi) potential evapotranspiration (PET).

For prospective climate analysis some commentary, a brief outline of the approach used, and the utility of the approach are provided. Finally, subregion-specific characterisation of errors of the input climate data for the long-term (from January 1980 to December 2009) monthly relative error values were calculated. This was performed as the root mean squared error (RMSE) grid divided by the mean grid for each P, Tmax and Tmin, in turn. The final relative error was expressed as a percentage. For P a relative error of 46% is calculated, due, in part to P being a highly spatially variable process (it has low spatial autocorrelation) especially in areas such as those proximal to the Gloucester subregion that have high amounts of relative relief. Additionally, in the relative error grid the influence of spatial density of meteorological stations is clearly seen. For Tmax the relative error is approximately 2% and for Tmin the relative error is 6%. Air temperature variation is more spatially homogenous than precipitation variation, hence the relative errors are lower. Maximum air temperatures, which are not influenced by cold air drainage like minimum temperatures are, are modelled with greater accuracy.

All geographic data specific to the bioregional assessment (BA) of the Gloucester subregion were obtained from state or national datasets. No statistical analyses or interpolations were undertaken within the Assessment to generate any of these datasets. Spatial datasets were clipped to the Gloucester subregion boundary such that subregion characteristics could be identified and simple statistics calculated (e.g. areas, maximum and minimum elevations). Details of the source data and/or methods are provided in Section 2.1.1.1 about observed data.

Spatial analyses specific to the Gloucester subregion were undertaken on some of the meteorological datasets to characterise the errors for water balance modelling. These methods are presented in Section 2.1.1.2 about statistical analysis and interpolation.

2.1.1.1 Observed data

2.1.1.1.1 Physical geography

Digital elevation model

The digital elevation model (DEM) was obtained from the 3 arc-second (~90 m resolution grid cell) Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007). Dual radar antennae acquired interferometric synthetic aperture radar (InSAR), using phase difference measurements derived from the two radar images to measure topography (originally acquired onboard the NASA Space Shuttle Endeavour during its mission between 11 and 22 February 2000, when it measured the Earth's surface elevation between 60° N and 56° S latitudes). The positional accuracy (often represented as X and Y) of the SRTM data are in the order of 10 m, as reported by Smith and Sandwell (2003, Section 4.3) and Rodriguez et al. (2006, p. 257). For Australia, these data were processed according to Gallant et al. (2011) and the elevational accuracy (often represented as Z) of the SRTM DEM compared to 1198 permanent survey mark (PSM) data points had a mean error of –0.539 m. The absolute accuracy of the DEM was 14.54 m at the 95th percentile with a root mean square error (RMSE) of 7.029 m in open, flat terrain. Ninety-nine percent of points are within a height difference of less than 29.97 m (Gallant et al., 2011, p. 63–64).

Surface watercourses

Surface watercourses were defined using the GeoData Topo 250K Series 3 Topographic Data – 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, as appropriate, used to describe the surface hydrology of the Gloucester 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). The Geofabric registers the topology between important hydrological features such as rivers, water bodies, aquifers and monitoring points, and information about surface water basins and catchments.

Physiographic classes

The physiographic classes were obtained from the Australian Soil Resource Information System (ASRIS) (Pain et al., 2011). The following description is derived from this reference. These classes are based on a visual interpretation of landforms as expressed on the SRTM DEM. Apart from its descriptive role, a map of physiographic regions provides a regional system of reference for geomorphological and related physical geographical accounts. Through the groupings of physiographic regional characteristics at different levels, the action of underlying controls (for instance geology or climate) may be made apparent. These data have an Australia-wide coverage.

Soil classes

Soils classes used the Australian Soil Classification (ASC) system which is a product from ASRIS (2011). National soil data was provided by the Australian Collaborative Land Evaluation Program (ACLEP), endorsed through the National Committee on Soil and Terrain (NCST) (ACLEP, 2014). These data have an Australia-wide coverage and are underpinned by a collation of the best available nationally consistent soils data and information. Usually these data are the most dominant soil in a polygon, not the only soil in a polygon.

Pre-European vegetation

Pre-European (1788) vegetation data was sourced from Carnahan (1976) and Australian Survey and Land Information Group (AUSLIG, 1990). The following description is derived from these references. A reconstruction of natural vegetation of Australia is shown as it probably would have been in the 1780s. Generally, the minimum mapping unit is 30,000 ha, but in some cases smaller areas of significant vegetation, such as rainforest, are also mapped. Attribute information includes growth form of the tallest and lower stratum, foliage cover of the tallest stratum and the dominant floristic type. These data are provided at a map scale of 1:5 million and have an Australia-wide coverage.

Current vegetation

Current major vegetation types were obtained from the National Vegetation Information System (NVIS), a comprehensive data system that provides information about the extent and distribution of vegetation types in Australian landscapes published by SEWPaC (2012). The following description is derived from this reference. This dataset (v4.1) contains the latest summary information (November 2012) about Australia's present (extant) native vegetation, which has been classified into major vegetation groups (MVGs) and major vegetation subgroups (MVSs). Many state and territory vegetation mapping agencies supplied new information to the NVIS v4.1 from 2009 to 2011, however for NSW, NVIS data was only partially updated from 2001 to 2009, with extensive areas of 1997 data remaining from earlier versions. NVIS v4.1 identifies 85 MVSs summarising the type and distribution of Australia's native vegetation. The classification contains an emphasis on the structural and floristic composition of the dominant stratum (as with MVGs), but with additional types identified according to typical shrub or ground layers occurring with a dominant tree or shrub stratum. In a mapping sense, the subgroups reflect the dominant vegetation occurring in a map unit from a mix of several vegetation types. Less-dominant vegetation groups which are also present in the map unit are not shown. It is in Albers equal area projection with a 100 m resolution (1 ha) grid size.

Current land cover

Land cover was derived from MODIS (or Moderate Resolution Imaging Spectroradiometer) satellite imagery. Specifically the Normalised Difference Vegetation Index (NDVI) (a simple graphical indicator that can be used to analyse remote sensing measurements) is rescaled to percent green vegetation cover and this is temporally filtered into the persistent and recurrent components (Donohue et al., 2009a). The MODIS NDVI imagery has a spatial resolution of 250 m, has global coverage, and is available monthly from February 2000 onwards, with the persistent-recurrent processing being performed Australia-wide. The accuracy of this is likely to be in the order of 5 to 10% (Donohue, 2014, pers. comm.).

Current vegetation height

Vegetation height was measured using a satellite based light detection and ranging system (lidar) between 20 May 2005 to 23 June 2005 using the Geoscience Laser Altimeter System (GLAS) aboard ICESat (Ice, Cloud and Land Elevation Satellite). Using a regression tree approach to model canopy height, 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.

2.1.1.1.2 Human geography

For human geography the main datasets used are: (i) population density and (ii) land use management. A brief outline of each follows.

Population density

Human population information for the Gloucester subregion was derived from the 2011 Australian Census (ABS, 2011). An estimate of 5000 people living in the subregion was determined by intersecting the subregion boundary with the 2011 Australian Census 'mesh blocks boundaries' and population counts. The accuracy of this is likely to be in the order of 1 to 2%. This is as the Gloucester subregion boundary does not exactly match the 2011 Australian Census mesh blocks so intersection was needed away from the dense population centres of Gloucester and Stroud to provide this estimate. This estimate is as accurate as can be performed.

Land use management

Catchment Scale Land Use Management (CLUM) compiled November 2012 (data ranges from 1997 to 2009, scale ranges from 1:25,000 to 1:250,000) was obtained from the Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES, 2012). The most current catchment scale land use dataset for Australia has been compiled using nationally agreed land use mapping principles and procedures of the Australian Land Use and Management (ALUM) Classification version 7. The land use datasets were collected as part of state and territory mapping programs and the Australian Collaborative Land Use and Management Program (ACLUMP). The updated dataset is a combined 50 m raster for Australia, with edge-matching errors corrected for NSW (for which there was no new data provided compared to the previous version).

2.1.1.1.3 Climate (retrospective)

For retrospective climate analysis the following variables were analysed: (i) precipitation (P), (ii) maximum and minimum air temperature (Tmax and Tmin, respectively), (iii) vapour pressure (VP), (iv) net radiation (Rn), (v) wind speed, and (vi) potential evapotranspiration (PET). All these variables are national Australia-wide grids with a 0.05 degree (or ~5 km) grid cell resolution at a daily time step. They come from various sources and have different start dates. They are briefly dealt with in turn in the following paragraphs.

Precipitation

Daily and monthly P grids are available from 1900 onwards and were generated by the Bureau of Meteorology (Jones et al., 2009) by using optimal geostatistical techniques, taking elevation into account, to interpolate daily and monthly station P totals measured at isolated stations. Daily time-step data are used as input to surface water modelling (see companion product 2.6.1 for the Gloucester subregion (Zhang et al., 2018)), with groundwater models using monthly input data (see companion product 2.6.2 for the Gloucester subregion (Peeters et al., 2018)). Given that precipitation is the most spatially discontinuous meteorological process, it is the on-ground observation network that has the high spatial density of observations (Jones et al., 2009, Figure 2). Jones et al. (2009) fully cross-validated the estimates for the seven years from 2001 to 2007 by randomly deleting 5% of the stations in the network, performing an analysis using the remaining 95% of station observations and then calculating the analysis errors for the omitted stations. 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 2001 to 2007, 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).

Air temperature

Daily Tmax and Tmin grids are available from 1900 onwards and were generated by the Bureau of Meteorology (Jones et al., 2009) by using optimal geostatistics techniques, taking elevation into account (the environmental lapse rate), to interpolate daily extremes of air temperature measured at isolated stations. 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 (calculated as RMSE/mean).

Vapour pressure

Daily VP data, also generated by the Bureau of Meteorology (Jones et al., 2009), are available from 1950 onwards and are recorded at two times of the day, 9 am and 3 pm, both local times. The same optimal geostatistics techniques (as used for P, Tmax and Tmin above) were used to spatially interpolate VP measurements made at the isolated stations. Between 2001 and 2007, the mean daily VP Australia-wide was 13.7 hPa at 9 am and 13.1 hPa at 3 pm, with RMSE statistics of 1.8 and 2.5 hPa, respectively (Jones et al., 2009, Table 4b). These represent relative errors of 13 and 19%, respectively (calculated as RMSE/mean). Between 2001 and 2007, the mean monthly VP Australia-wide was 13.7 hPa at 9 am and 13.1 hPa at 3 pm, with RMSE statistics of 1.1 and 1.7 hPa, respectively (Jones et al., 2009, Table 4a). These represent relative errors of 8 and 13%, respectively (calculated as RMSE/mean).

Net radiation

Daily Rn is generated by CSIRO Land and Water using a combination of gridded meteorological data and satellite data (Donohue et al., 2010). This is available from 1982 onwards, due to use of satellite based albedo (the colour of the land surface, defining how much sunlight is reflected) in the outgoing shortwave radiation calculations. The incoming shortwave and longwave components have been validated and at a monthly time step have RMSE values of 18 and 9 W/m^2 (Donohue et al., 2009b, Figure 5b and Figure 5d, respectively). The outgoing shortwave and longwave components utilise time series remotely sensed imagery, and thus capture the true dynamics of the land surface (as opposed to other methods that use long-term climatologies).

Wind speed

Daily mean wind speed is also generated by CSIRO Land and Water (McVicar et al., 2008) from 1975 onwards using daily wind-run observations made at the Bureau of Meteorology network of anemometers. These are quality controlled and then used as input to a tri-variate thin-plate spline as a function of longitude, latitude and distance inland from the coast (McVicar et al., 2008). Importantly, these grids capture the 'stilling' process (declining wind speeds) that has been observed at many terrestrial locations across the globe which is partly responsible for reducing rates of evaporative demand (Donohue et al., 2010; McVicar et al., 2012a). The RMSE of monthly wind speed is 0.32 m/s (Donohue et al., 2009b, Figure 2e).

Potential evapotranspiration

PET, a measure of the 'drying power' of the atmosphere, is calculated using the fully physically based Penman formulation and hence uses all of the previously mentioned meteorological variables. It is calculated per Donohue et al. (2010) and is available from 1982 onwards. Being a 'potential' means that direct validation of PET is not possible, however, when assessing trends of this physically based PET formulation with other PET forms, Donohue et al. (2010) showed that the Penman formulation was most optimally able to respond in a complementary manner to monthly P trends (Donohue et al., 2010, Table 4).

In summary, all the data sources mentioned in this section provide the best gridded estimates of retrospective climate data available for the Gloucester subregion.

2.1.1.1.4 Climate (prospective)

For prospective climate analysis, Post et al. (2012) assessed changes in P and PET using output from 15 GCMs (global climate models) and reported changes for large basins such as the Manning River and Karuah River. Specifically they used GCMs from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007, hereafter referred to as IPCC AR4) and used the IPCC A1B global warming scenario output to transform historical daily climate records to provide future daily climate projections of P and PET that can be used in a rainfall-runoff model. Compared to the global mean temperature in 1990, this scenario indicates a global temperature that is 1 °C higher in 2030 and 2 °C higher in 2070. This scenario is based upon: (i) very rapid economic growth, (ii) with global populations peaking mid-century and declining thereafter, and (iii) the rapid introduction of new and more efficient technologies with a balance across all energy sources (IPCC, 2007).

2.1.1.2 Statistical analysis and interpolation

All geographic data specific to the Gloucester subregion were obtained from state or national datasets. This means no statistical analysis or interpolation was performed to generate any of the geographic datasets. However, to characterise errors of the input climate data used for the water balance modelling (reported in companion product 2.5 for the Gloucester subregion (Herron et al., 2018)), some subregion-specific spatial analysis was performed. This is outlined in the following sections.

In addition to the work documented in Section 2.1.1.2.1 there is a separate 'climate sensitivity' activity underway to determine how sensitive the hydrological models in the Gloucester subregion are to climate inputs. Currently, only one future climate is input to the prospective hydrological modelling conducted in the Gloucester subregion. Obviously it is not known what the future climate in the Gloucester subregion will be out to ~2100, yet the output from GCMs can be used to generate 100 or 1000 stochastic/ensemble future climate sequences reflecting variability over different time scales based on characteristics of observed instrumental records that can be used as input to the prospective hydrological modelling conducted in the Gloucester subregion. Doing this will allow the relative impacts of the most likely future coal development and a range of possible future climates to be compared.

2.1.1.2.1 Retrospective climate error analysis

In addition to generating daily and monthly grids of meteorological variables (P, Tmax and Tmin), the Bureau of Meteorology (Jones et al., 2009) also generates 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 being a function of the interpolation algorithm, density of isolated station observations and degree of spatial-autocorrelation of the process(es) driving the spatial variance captured in the data being interpolated.

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 mean values for the same variables for the same time period. Relative error, expressed as a percent, was calculated by dividing monthly RMSE mean grid by the monthly mean grids (i.e. RMSE grid/mean grid for each meteorological variable).

Precipitation error analysis

The spatially-averaged long-term monthly mean P for the Gloucester subregion is 87 mm/month, and the associated P RMSE subregion mean is 40 mm/month, see Figure 3a and Figure 3b, respectively. This results in a relative error of 46% in the input P grids (Figure 3c). The relative high error is due, in part, to P being a highly spatially variable process (it has low spatial autocorrelation) especially in areas such as those proximal to the Gloucester subregion that have high amounts of relative relief. Additionally, in the relative error grid the influence of spatial density of meteorological stations is clearly seen. In the north-east of the Karuah river basin (near the location of Myall Lakes National Park) and in the north-western portion of the Manning river basin (proximal to the Barrington Tops National Park) the higher relative P errors are found due to the low density of observations in these regions.

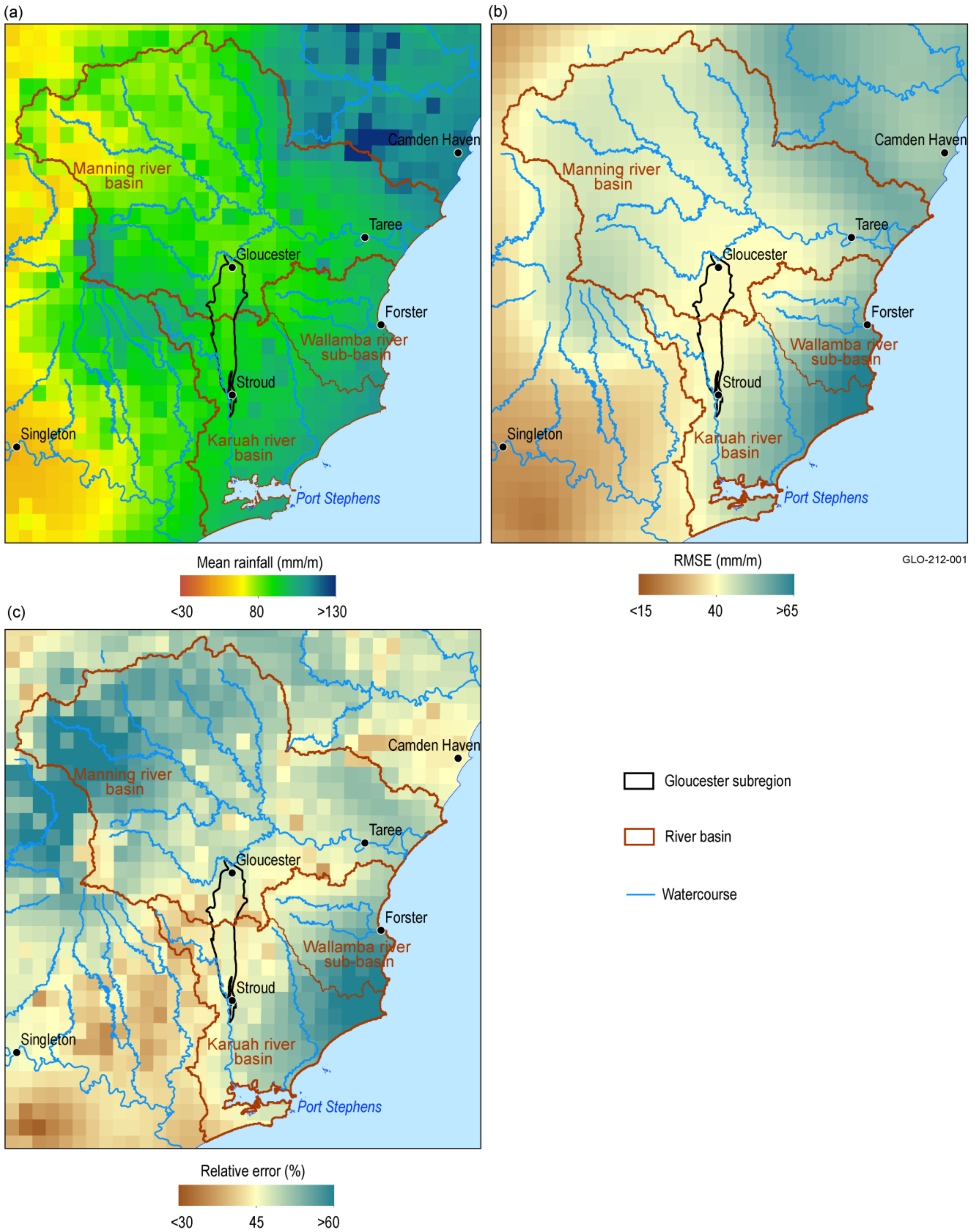


Figure 3 Spatial variation of precipitation from 1980 to 2009

(a) monthly mean precipitation, (b) monthly mean root mean square error (RMSE) precipitation and (c) monthly mean precipitation relative error for the Gloucester subregion and proximal surface water basins.
Data: CSIRO Land and Water (Dataset 1)

Air temperature error analysis

For air temperatures, a meteorological field that has higher spatial autocorrelation than P, regional distribution is governed by topography and distance from the ocean. The Tmax spatially-averaged long-term monthly mean is 22.8 °C for the Gloucester subregion (Figure 4a). The associated RMSE is approximately 0.47 °C (Figure 4b), which leads to a relative error of approximately 2% for Tmax (Figure 4c). For Tmin in the Gloucester subregion, there are similar spatial patterns, with the spatially-averaged long-term monthly mean being 11.4 °C (Figure 5a) and the associated RMSE being approximately 0.67 °C (Figure 5b), which leads to a relative error of 6% for Tmin (Figure 5c).

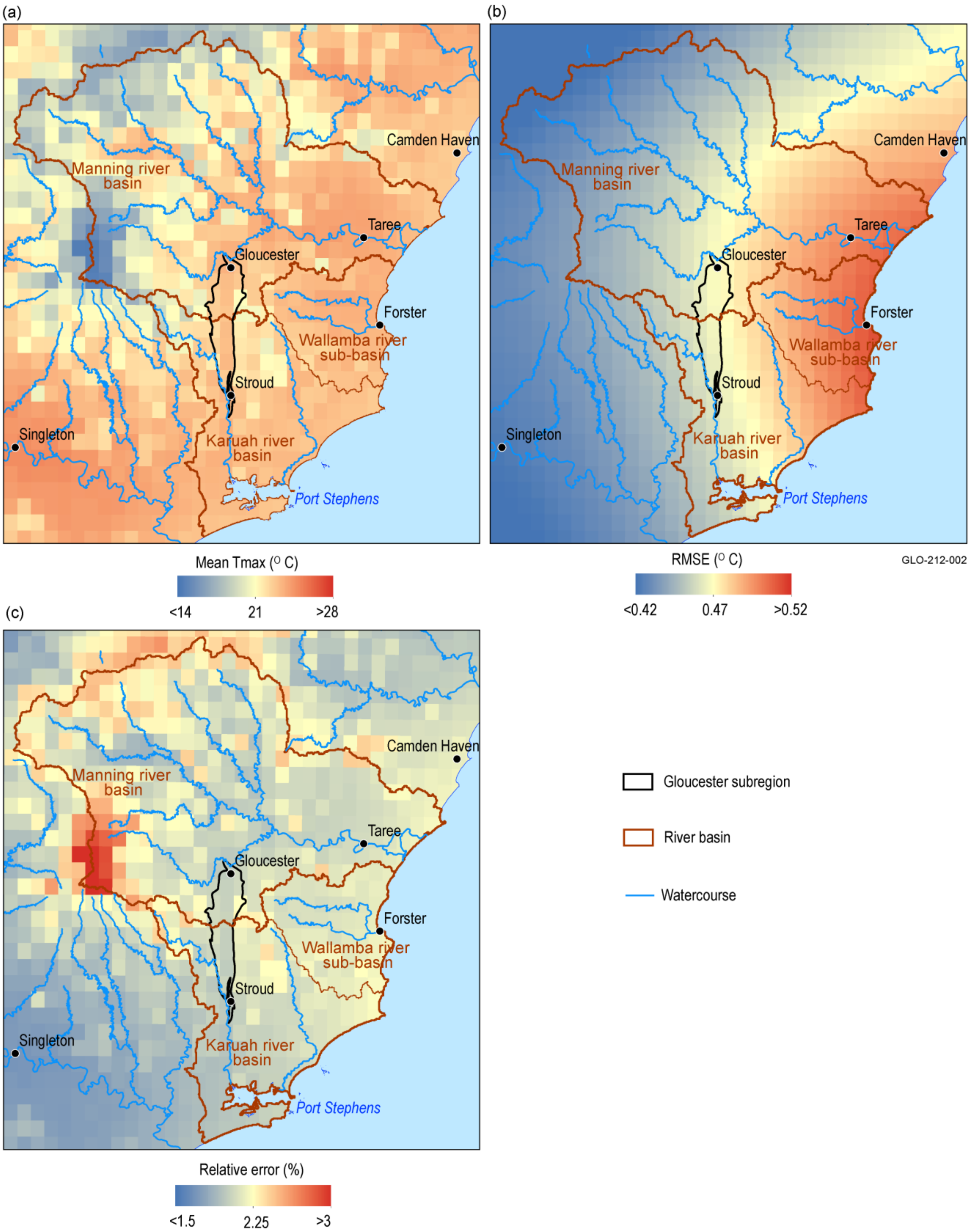


Figure 4 Spatial variation of maximum air temperature (Tmax) from 1980 to 2009

(a) monthly mean Tmax, (b) monthly mean root mean square error (RMSE) Tmax and (c) monthly mean Tmax relative error for the Gloucester subregion and proximal surface water basins.
Data: CSIRO Land and Water (Dataset 1)

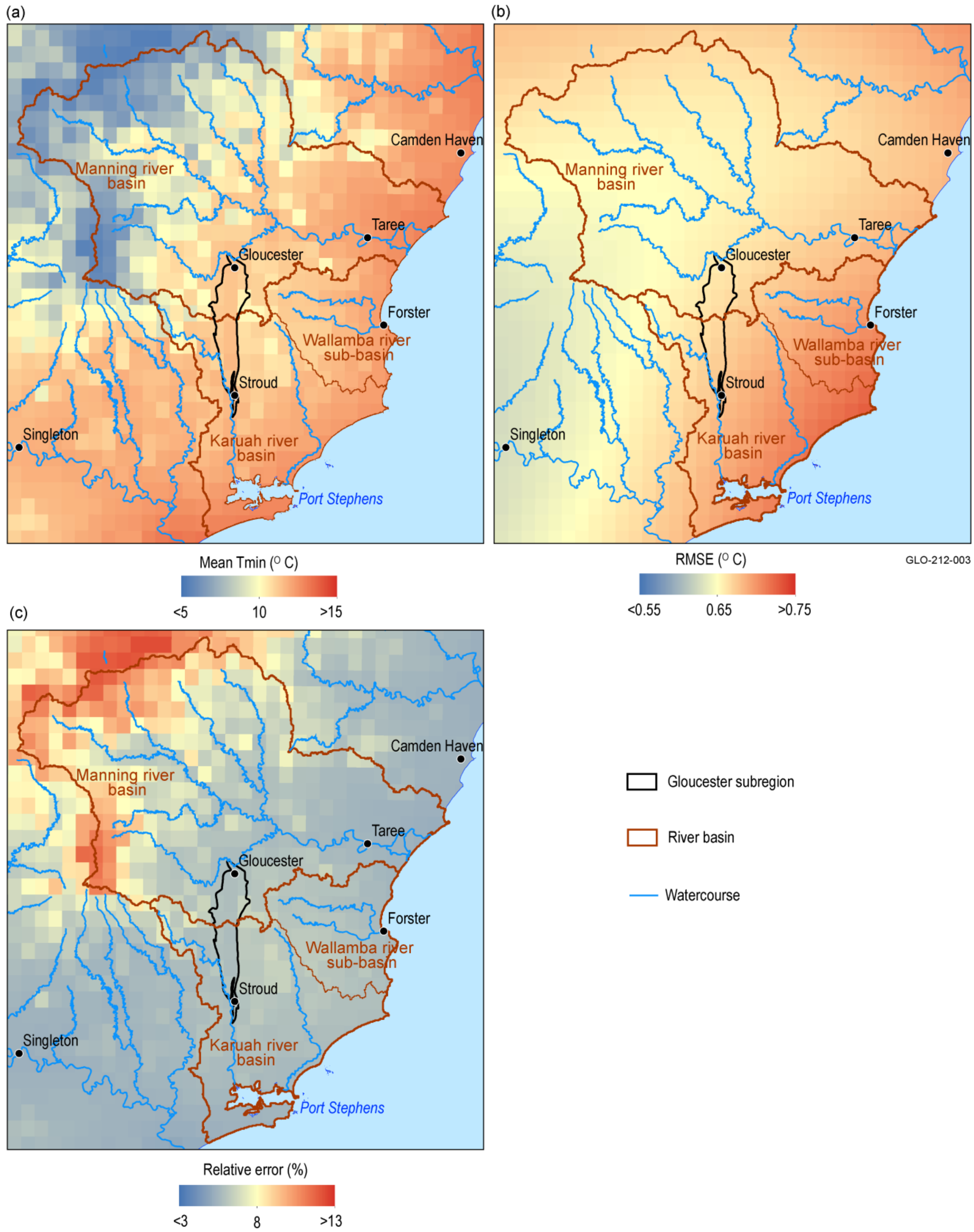


Figure 5 Spatial variation of minimum air temperature (Tmin) from 1980 to 2009

(a) monthly mean Tmin, (b) monthly mean root mean square error (RMSE) Tmin and (c) monthly mean Tmin relative error for the Gloucester subregion and proximal surface water basins.
Data: CSIRO Land and Water (Dataset 1)

2.1.1.3 Gaps

2.1.1.3.1 Increasing density of meteorological observations

The characterisation of input data errors in Section 2.1.1.2 suggests that having a denser network of official Bureau of Meteorology stations recording precipitation is essential for improved water-related modelling in the Gloucester subregion. With the number of stations observing daily P declining across all of Australia – from approximately 7500 in the 1970s to approximately 6500 in the late 2000s (Jones et al., 2009, Figure 1a) – there has been an associated decrease in the level of predictability of P (Jones et al., 2009, Figure 9). The observational network needs to be located to better capture the influence of local relative relief in the Gloucester subregion and surrounds. For example, locating stations to the east of the subregion, the direction from which the prevailing sea breezes bring moisture laden air which often becomes precipitation due to orographic processes, will allow better observation of this process. The importance of small changes in elevation on precipitation rates should not be underestimated. For example, for a flat area of Norway in the 1950s (with approximately 50 m elevation difference) more than 200 rain gauges were installed in an area of about 30 km^2 and it was found that precipitation rates on the small hills could be double those on the adjacent lower areas (Bergeron, 1960; Roe, 2005).

2.1.1.3.2 Recent observed declining wind speeds

Future climate projections produced by GCMs are uncertain (Lim and Roderick, 2009; Sun et al., 2011) and use of historically repeated PET values (calculated using the physically-based Penman's formulation of PET) means that the impact of declining rates of observed wind speed which are offsetting increasing air temperature enhancement of PET (Donohue et al., 2010; McVicar et al., 2012a; McVicar et al., 2012b) are not included in the resultant calculations. In 'equitant' areas like the Gloucester subregion, where actual evapotranspiration is at times water-limited and at other times energy-limited through the year (McVicar et al., 2012b), estimates of both P and PET are important for future projections.

2.1.1.3.3 Impacts of increasing CO_2 concentrations on future streamflow

Finally, the impact of rising atmospheric concentrations of CO_2 on vegetation water use, which likely means increasing streamflow generation in energy-limited areas (Betts et al., 2007; McVicar et al., 2010) and decreasing streamflow generation in water-limited areas (McVicar et al., 2010; Ukkola et al., 2015), needs to be incorporated for long-term hydrological modelling. In energy-limited areas the impact of vegetation water use efficiency (WUE; essentially a measure of CO_2 assimilation per a measure of H_2O transpiration) is altered by atmospheric concentrations of CO_2 and this directly increases streamflow generation (Betts et al., 2007; McVicar et al., 2010); this is a positive feedback. In water-limited areas, CO_2 driven vegetation enhancement (Donohue et al., 2013) is likely to offset the WUE changes, and likely result in greater vegetation water-use and indirectly reduce streamflow generation (McVicar et al., 2010; Ukkola et al., 2015); this is a negative feedback. An increase of 1 ppm of CO_2 roughly equates to an increase of 1 mm of H_2O available to vegetation (even though there has been no change in P; Farquhar, 1997); over the long-term this may have profound implications on catchment water balances, and the feedbacks with vegetation. For example, if modelling out to 2100 with a current atmospheric CO_2 concentration of approximately 400 ppm (which is increasing at about 2 ppm per year so by 2100 atmospheric CO_2 will be about 600 ppm) this 50% increase on its current value will not be accounted for. The atmospheric CO_2 increase is already having long-term impacts on vegetation dynamics (Donohue et al., 2013) and catchment water balances (Betts et al., 2007; McVicar et al., 2010; Ukkola et al., 2015).

References

ABARES (2012) Catchment scale land use mapping for Australia. Update November 2012 (CLUM Update 11/12) dataset. Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Canberra.

ABS (2011) Australian Statistical Geography Standard (ASGS) Volume 1 – Main Structure and Greater Capital City Statistical Areas (cat no. 1270.0.55.001) and 2074.0 – Census of Population and Housing: Mesh Block Counts, 2011. Australian Bureau of Statistics, Canberra.

ACLEP (2014) ACLEP website. Australian Collaborative Land Evaluation Program, Department of Agriculture, Fisheries and Forestry. Viewed 3 June 2014, http://www.clw.csiro.au/aclep.

ASRIS (2011) ASRIS – Australian Soil Resource Information System. Australian soil classification dominant soil order (250 m raster). Canberra. Viewed 5 June 2014, http://www.asris.csiro.au/downloads/NSG/.

AUSLIG (1990) Atlas of Australian resources, Vol. 6, Vegetation. Department of Administrative Services, Commonwealth Government Printer, Canberra.

Bergeron T (1960) Preliminary results of Project Pluvius. Commission of Land Erosion General Assembly. International Association of Scientific Hydrology, 226–237.

Betts R, Boucher O, Collins M, Cox P, Falloon P, Gedney N, Hemming D, Huntingford C, Jones C, Sexton D and Webb M (2007) Projected increase in continental runoff due to plant responses to increasing carbon dioxide. Nature 448(7157), 1037–U1035. DOI: 10.1038/nature06045.

Bureau of Meteorology (2012) Australian Hydrological Geospatial Fabric (Geofabric) Version 2.1. Viewed 5 June 2014, http://www.bom.gov.au/water/geofabric.

Carnahan J (1976) Natural vegetation map 1:6,000,000 and commentary. In: Plumb TW (ed.) Atlas of Australian resources. Second Series. Department of Natural Resources, Canberra.

Donohue RJ, McVicar TR and Roderick ML (2009a) Climate-related trends in Australian vegetation cover as inferred from satellite observations, 1981–2006. Global Change Biology 15(4), 1025–1039. DOI: 10.1111/j.1365-2486.2008.01746.x.

Donohue RJ, McVicar TR and Roderick ML (2009b) Generating Australian potential evaporation data suitable for assessing the dynamics in evaporative demand within a changing climate. CSIRO: Water for a Healthy Country Flagship, Canberra.

Donohue RJ, McVicar TR and Roderick ML (2010) Assessing the ability of potential evaporation formulations to capture the dynamics in evaporative demand within a changing climate. Journal of Hydrology 386(1–4), 186–197. DOI: doi:10.1016/j.jhydrol.2010.03.020.

Donohue R, Roderick M, McVicar T and Farquhar G (2013) Impact of CO_2 fertilization on maximum foliage cover across the globe's warm, arid environments. Geophysical Research Letters 40(12), 3031–3035. DOI: 10.1002/grl.50563.

Farquhar GD (1997) Carbon dioxide and vegetation. Science, 278(5342), 1411–1411.

Farr T, Rosen P, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L, Seal D, Shaffer S, Shimada J, Umland J, Werner M, Oskin M, Burbank D and Alsdorf D (2007) The shuttle radar topography mission. Reviews of Geophysics 45(2). DOI: 10.1029/2005RG000183.

Gallant J, Dowling T, Read A, Wilson N, Tickle P and Inskeep C (2011) 1 second SRTM-derived digital elevation models user guide. Geoscience Australia, Canberra. Viewed 31 January 2014, http://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=72759.

Geoscience Australia (2006) GeoData Topo 250K, Series 3 topographic data. Canberra, ACT, Australia. Viewed 6 June 2014, http://www.ga.gov.au/oracle/agsocat/geocat_brief.php?catno=64164.

Herron NF, Crosbie RS, Viney NR, Peeters LJM and Zhang YQ (2018) Water balance assessment for the Gloucester subregion. Product 2.5 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/NSB/GLO/2.5.

IPCC (2007) Climate change 2007: The physical science basis. Contribution of Working Group I to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change [Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jones DA, Wang W and Fawcett R (2009) High-quality spatial climate data-sets for Australia. Australian Meteorological and Oceanographic Journal 58(4), 233–248.

Lim W and Roderick M (2009) An atlas of the global water cycle: Based on the IPCC AR4 models. ANU E Press, Canberra.

McVicar TR, Donohue RJ, O'Grady AP and Li LT (2010) The effects of climatic changes on plant physiological and catchment ecohydrological processes in the high-rainfall catchments of the Murray-Darling Basin: A Scoping Study. A report commissioned by the Murray-Darling Basin Authority. CSIRO Water for a Healthy Country Flagship, Australia. Viewed 28 May 2014, http://www.clw.csiro.au/publications/waterforahealthycountry/2010/wfhc-climatic-changes-high-rainfall-mdb.pdf.

McVicar T, Langhi L, Barron O, Rachakonda PK, Zhang Y, Dawes W, Holland K, Macfarlane C and Raisbeck-Brown N (2014) Context statement for the Gloucester subregion. Product 1.1 from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 18 June 2015, http://data.bioregionalassessments.gov.au/product/NSB/GLO/1.1.

McVicar TR, Roderick ML, Donohue RJ and Van Niel TG (2012b) Less bluster ahead? Ecohydrological implications of global trends of terrestrial near-surface wind speeds. Ecohydrology 5(4), 381–388.

McVicar TR, Roderick ML, Donohue RJ, Li LT, Van Niel TG, Thomas A, Grieser J, Jhajharia D, Himri Y, Mahowald NM, Mescherskaya AV, Kruger AC, Rehman S and Dinpashoh Y (2012a) Global review and synthesis of trends in observed terrestrial near-surface wind speeds: implications for evaporation. Journal of Hydrology 416/417, 182–205. DOI: 10.1016/j.jhydrol.2011.10.024.

McVicar TR, Van Niel TG, Li LT, Roderick ML, Rayner DP, Ricciardulli L and Donohue RJ (2008) Wind speed climatology and trends for Australia, 1975–2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. Geophysical Research Letters 35, L20403. DOI: 10.1029/2008GL035627.

Pain C, Gregory L, Wilson P and McKenzie NJ (2011) The physiographic regions of Australia – Explanatory notes. Australian Collaborative Land Evaluation Program and National Committee on Soil and Terrain, Canberra.

Peeters LJM, Dawes WR, Rachakonda PR, Pagendam DE, Singh RM, Pickett TW, Frery E, Marvanek SP and McVicar TR (2018) Groundwater numerical modelling for the Gloucester subregion. Product 2.6.2 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/NSB/GLO/2.6.2.

Post D, Chiew F, Teng J, Wang B and Marvanek S (2012) Projected changes in climate and runoff for south-eastern Australia under 1 °C and 2 °C of global warming. A SEACI Phase 2 special report. Canberra. Viewed 6 June 2014, http://www.seaci.org/publications/documents/SEACI-2Reports/SEACI2_Projections_Report.pdf.

Rodriguez E, Morris C and Belz J (2006) A global assessment of the SRTM performance. Photogrammetric Engineering and Remote Sensing 72(3), 249–260.

Roe G (2005) Orographic precipitation. Annual Review of Earth and Planetary Sciences 33, 645–671. DOI: 10.1146/annurev.earth.33.092203.122541.

SEWPaC (2012) Australia – Present major vegetation subgroups, NVIS Version 4.1 (Albers 100 m analysis product). Australian Government Department of Sustainability Environment Water Population and Communities, Canberra.

Simard M, Pinto N, Fisher JB and Baccini A (2011) Mapping forest canopy height globally with spaceborne lidar. Journal of Geophysical Research 116(G04021), DOI: 10.1029/2011JG001708.

Smith B and Sandwell D (2003) Accuracy and resolution of shuttle radar topography mission data. Geophysical Research Letters 30(9). DOI: 10.1029/2002GL016643.

Sun FB, Roderick ML, Lim WH and Farquhar GD (2011) Hydroclimatic projections for the Murray-Darling Basin based on an ensemble derived from Intergovernmental Panel on Climate Change AR4 climate models. Water Resources Research 47, 14. DOI: 10.1029/2010wr009829.

Ukkola AM, Prentice IC, Keenan TF, van Dijk AIJM, Viney NR, Myneni RB and Bi J (2015) Reduced streamflow in water-stressed climates consistent with CO_2 effects on vegetation. Nature Climate Change. DOI: 10.1038/nclimate2831.

Zhang YQ, Viney NR, Peeters LJM, Wang B, Yang A, Li LT, McVicar TR, Marvanek SP, Rachakonda PK, Shi XG, Pagendam DE and Singh RM (2018) Surface water numerical modelling for the Gloucester subregion. Product 2.6.1 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/NSB/GLO/2.6.1.

Datasets

Dataset 1 CSIRO Land and Water (2015) BILO Climate Relative Error Grids V01. Bioregional Assessment Source Dataset. Viewed 12 October 2015, http://data.bioregionalassessments.gov.au/dataset/c0c139f5-3648-4e0f-9acf-a884b7cc859b.

2.1.2 Geology

Summary

A review of available surface and subsurface datasets in the coal-bearing geological Gloucester Basin was conducted to build a first-order regional geological model. As a modelled representation, it is based on available data inputs at the time it was built and is one possible representation among many.

The Gloucester basin geological model represents an interpretation of the underground geometries and lithologies. The interpretation is based on wells, outcrop and geophysical data and accounts for the uncertainties and resolution inherent in these data. The well data helps to define the limits between the different geological units as well as the lithology. The uncertainty in these data increases as the distance from the wells increases. Geophysical data (mostly seismic reflection data) were used to extrapolate the data calibrated at the wells and to define a basin-scale fault population.

As the density of both wells and geophysical data is low in the geological Gloucester Basin, isopach maps (i.e. stratigraphic thickness maps) were used to define the basin-scale architecture of the sequences. Each isopach map was calibrated against well picks at the formation scale and constrained by trends observed within each interval. Defining a reference horizon and stacking of the successive isopach maps resulted in an initial non-faulted and non-eroded geological model. Major fault trends were added to allow for major misfits between the non-faulted geomodel and the formation tops at wells.

A fault population was established for the Gloucester subregion based on data from the Stratford CSG Prospect area, where AGL Energy Limited (AGL) proposes to extract coal seam gas (CGS), and published data for other sedimentary coal basins in Australia, New Zealand and the United Kingdom.

The Gloucester subregion geological model can be updated and refined with additional or new datasets and can be populated with hydraulic properties derived from stratigraphic facies.

The geology of the Gloucester subregion is summarised in companion product 1.1, the context statement for Gloucester subregion (McVicar et al., 2014). This summary was based on review of existing literature.

The construction of the Gloucester three-dimensional geological model was based on the understanding gained from this review as well as analyses of available deep well and geophysical datasets. Details of these datasets are provided in Section 2.1.2.1 about observed data.

The methods used to generate derivative datasets and their use in producing the three-dimensional geological model are described in Section 2.1.2.2 about statistical analysis and interpolation.

2.1.2.1 Observed data

Two types of observed data were used to develop and build a geological model: a deep wells dataset (NSW Trade and Investment, Dataset 1) and geophysical datasets (Bioregional Assessment Programme, Dataset 2; AGL, Dataset 3; Geoscience Australia, Dataset 4). The deep wells dataset consists of stratigraphic and lithological data extracted from well completion reports (see listing of well completion reports within the list of references following Section 2.1.2.3). The geophysical dataset comprises the digital elevation model (DEM) and published interpretation of seismic reflection data. The 1:100,000 scale Dungog geological map (Roberts et al., 1991) has also been used as a guide to determine the geological limits and the major structural trends in the subregion (see Section 1.1.3 in companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)). The cross-sections associated with the geological maps are interpretative and thus not used in this model as we are producing a new interpretation of the hard datasets.

2.1.2.1.1 Deep wells dataset

The deep wells data (NSW Trade and Investment, Dataset 1) provide information about the rock types, stratigraphic units and geological structure of the Gloucester subregion from geophysical logs, core and cutting analyses and test data. In order to make the geological model in the timeframe of the project, a set of wells crossing all the geological layers with homogenous interpretation have been selected among the petroleum wells accessible in the public domain. Groundwater boreholes usually do not reach deep structures and are not used in this modelling step.

A first series of stratigraphic wells, named PGSD or Stratford 1 to 9, were drilled by Pacific Power in the Gloucester Gas Project from 1993 to 2001. From 2005 to 2008, Lucas Energy Pty Ltd. and Molopo Australia Ltd (until 2007) continued the exploration in the Gloucester Gas Project (wells APW01, LMG01 to 03, Stratford 4, 5A, 8, 9). They extended exploration in Petroleum Exploration Licence (PEL) 285 bloc: toward north of the Gloucester Gas Project (LMGW01, Waukivory 1), south of the Gloucester Gas Project (wells LMGC01, Craven 1 and 3a), the western part of the Gloucester subregion (Faulkland 1 and 3) and the southern limit of the Gloucester subregion (Weismantel 1 to 3). In 2008, AGL obtained the PEL 285 exploration licence, increased the depth of Stratford 7, drilled a new well in the prospect (Stratford 10), and extended the exploration zone toward the north (Waukivory 3 and 4) and in the Craven/Ward River central zone (Ward River 1 to 5, Craven 6).

Twenty-four recent deep wells (drilled in the last ten years and deeper than 650 m), with coherent, informative data (especially the geophysical logs) and the best spatial coverage were selected from publicly available reports (see Section 2.1.3.1.3). Data collection for the Gloucester subregion geological model was completed in November 2013. Table 3 shows a list of selected wells.

Table 3 List of selected wells for the Gloucester subregion geological model

Well name	Abbreviation	Date	Company	Latitude (GDA 94)	Longitude (GDA 94)	Total depth (m MD KB[a])
Craven 1	C1	2008	Lucas Energy Pty Ltd Molopo Australia Ltd	–32°08'13.204"	151°54'58.579"	959
Craven 3a	C3a	2008	Lucas Energy Pty Ltd Molopo Australia Ltd	–32°08'49.792"	151°53'53.632"	883
Faulkland 1a	F1a	2008	Lucas Energy Pty Ltd	–32°03'13.88054"	151°33'17.01438"	1374
Faulkland 3	F3	2008	Lucas Energy Pty Ltd	–32°01'51.55903"	151°33'54.44711"	1004
Gloucester 2	G2	2009	AGL Energy Ltd	–32°00'04.086"	151°57'31.711"	974
LMGC 01	LMGC01	2007	Lucas Energy Pty Ltd Molopo Australia Ltd	–32°09’11.4”	151°56’10.7”	937
Stratford 10	S10	2008	AGL Energy Ltd	–32°05'15.279''	151°57'16.259''	1157
Stratford 4	S4	2007	Lucas Energy Pty Ltd Molopo Australia Ltd	–32°05’14.34”	151°58’15.75”	846
Stratford 5a	S5a	2008	Lucas Energy Pty Ltd Molopo Australia Ltd	–32°05’21.33”	151°58’26.16”	668
Stratford 7	S7	2008	AGL Energy Ltd	–32°05'41.823"	151°59'07.0383"	925
Stratford 8	S8	2008	Lucas Energy Pty Ltd	–32°05’44.27”	151°07’49.29”	773
Stratford 9	S9	2008	Lucas Energy Pty Ltd	–32.05155°	151.57461°	993
Ward River 1	WR1	2010	AGL Energy Ltd	–32°10'42.937"	151°56'18.283"	961
Ward River 3	WR3	2010	AGL Energy Ltd	–32°11'39.001"	151°56'41.144"	900
Ward River 4a	WR4a	2010	AGL Energy Ltd	–32°13'51.415"	151°57'7.41691"	766
Ward River 5	WR5	2011	AGL Energy Ltd	–32°09'46.105"	151°57'36.379"	844
Waukivory 1	Wauki1	2008	Lucas Energy Pty Ltd Molopo Australia Ltd	–32°03'31.750"	151°58'06.229"	798
Waukivory 3	Wauki3	2009	AGL Energy Ltd	–32°01'20.339''	151°58'35.281''	818
Waukivory 4	Wauki4	2009	AGL Energy Ltd	–32°03'15.69''	151°59'23.69''	763
Weismantel 1	W1	2008	Lucas Energy Pty Ltd Molopo Australia Ltd	–32°14'41.194"	151°55'35.384"	703
Weismantel 2	W2	2008	Lucas Energy Pty Ltd	–32°16’10.124”	151°56’22.094”	668
Weismantel 3	W3	2008	Lucas Energy Pty Ltd Molopo Australia Ltd	–32.152831°	151.555179°	797

[a]The depths are measured depth (MD) relative to the kelly bushing reference height (KB). The coordinates are expressed in the coordinate system used in the well completion reports. The well abbreviations shown here are used to identify well locations in maps used later in this section.
Source: see the listing of well completion reports within the list of references following Section 2.1.2.3.

Well distribution varies within the Gloucester geological basin (inset (a) of Figure 6). The highest concentration is near the Gloucester Gas Project, with almost one-third of the wells concentrated within 7 km^2, whereas the major part of the subregion is much less explored. The depths of these wells vary between 667.72 m MD (well Stratford 5A) and 1374.27 m measured depth (MD) relative to the kelly bushing (KB) (well Faulkland 1A). A kelly drive refers to a type of well drilling device on an oil or gas drilling rig. The kelly is the polygonal tubing and the kelly bushing is the mechanical device that turns the kelly when rotated by the rotary table. Together they are referred to as a kelly drive.

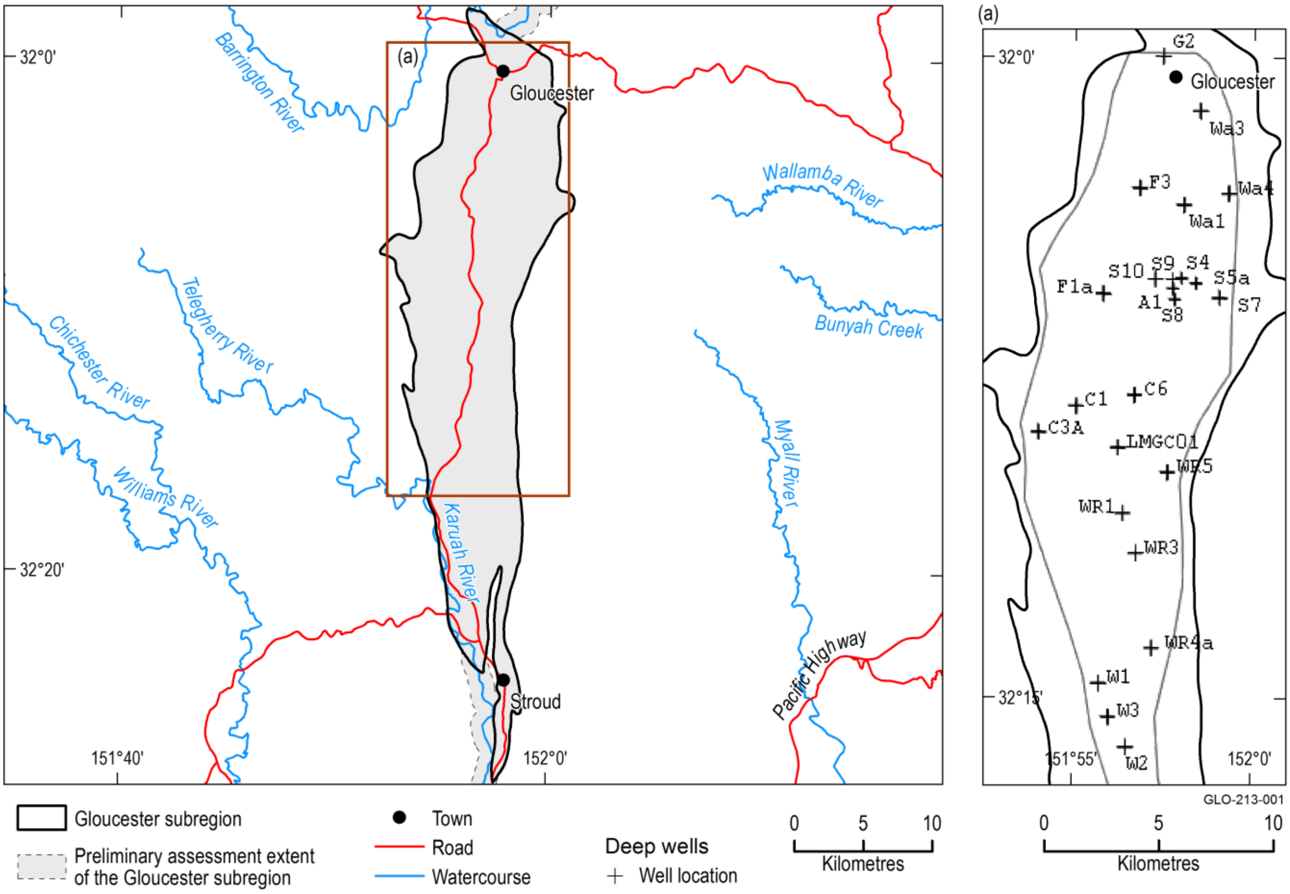


Figure 6 Deep well selection spatial distribution in the Gloucester subregion

See Table 3 for well name abbreviations.

No major lithological variations were recognised from one formation to another. Most of the formations were deposited in a fluvial to deltaic environment and the main rock types are sandstone, siltstone, mudstone and coal. Consequently, the highest level of facies variation is in a horizontal direction within each formation. The correlation of coal seams between wells remains ambiguous given the high probability of discontinuity/pinch out of seams or lateral splitting. Over-correlation of seams could likely lead to local over-interpretation of faults (Section 2.1.2.2.4), however, based on the available data, it is difficult to estimate the amount of stratigraphic induced error (i.e. coal splitting) and the number and location of real faults.

2.1.2.1.2 Geophysical dataset

The surface topography has been extracted from a DEM model described in Section 2.1.1 Geography of this product (Bioregional Assessment Programme, Dataset 2; Geoscience Australia, Dataset 4).

A review was conducted on Grieves and Saunders' (2003) interpretation of three-dimensional seismic reflection data in the Gloucester Gas Project (AGL, Dataset 3). The interpretation consisted of reprocessed seismic data (acquired by Esso Australia's Coal Exploration division in 1979 to 1983) with new borehole seam correlations (nine deep wells drilled by Pacific Power in 1993 to 1999). Grieves and Saunders (2003) highlighted a high degree of uncertainty in both structural mapping and the location and orientation of the mapped faults. This uncertainty is due to the sparse and incomplete seismic coverage and difficulties with the seismic interpretation. The interpretation by Grieves and Saunders (2003) was used to define a fault size population and constrain the structural interpretation of the Gloucester subregion (Section 2.1.3.2.4).

2.1.2.2 Statistical analysis and interpolation

Observed datasets (Section 2.1.2.1) were processed to form derived datasets. These datasets were analysed and interpolated to develop a three-dimensional geological model at the basin scale. The three-dimensional geocellular model was built using RMS Roxar software. This package is commercial software developed by Emerson and used in the oil and gas industry. For more details, please refer to the RMS Roxar website (Emerson, 2016).

2.1.2.2.1 Workflow

A step by step workflow was designed to define the subsurface structural and stratigraphic architecture of the Gloucester Basin and support scientific reasoning through the data processing. It is based on classical 3D approaches (Ross et al., 2004) and adapted in order to produce a simple regional model from datasets that are poorly constrained. The aim of this workflow is to avoid inducing a structural complexity that is highly uncertain in the grid geometry (Wellmann et al., 2010).

This workflow comprised:

1. selection and processing of observed data to form derived datasets and implementing model numerical database including:
    a. determining formation tops and lithological datasets derived from the deep wells dataset
    b. mapping the DEM data extracted from the geophysical dataset
2. three-dimensional non-faulted and non-eroded geological modelling:
    a. selecting a reference horizon and creating a horizon depth map
    b. determining the thickness of the formations (isopach) and extrapolating isopach maps
    c. building a non-faulted and non-eroded geological model
    d. extracting depth structure maps from the geological model

3. fault analysis:
   a. identifying major fault trends displacement and the spatial distribution
   b. defining faults statistical population – based on seismic data and comparison with fault populations from others coal-bearing basins
   c. building a faulted and eroded geological model.

2.1.2.2.2 Data processing

Even if the data density is higher than in other subregions studied in the frame of the Bioregional Assessment Programme, the spatial distribution and density of the geological data in the Gloucester geological basin can be defined as poor: for instance, there is no large scale and good quality 3D seismic data and the wells are concentrated mainly in the Gloucester Gas Project area. For more details please refer to the companion product 1.1, the context statement for Gloucester subregion (McVicar et al., 2014).

Stratigraphic and structural information provided by the deep well dataset were processed to form the wells derived dataset. Well completion reports from the 24 selected deep wells (see the listing of well completion reports within the list of references following Section 2.1.2.3.) were analysed to determine each formation top depth (Table 4). The markers of the formation top depths in the wells are called 'well picks'. The error in the formation top positions is a function of the well stratigraphic interpretation (see Section 2.1.2.1.1).

Table 4 Depth to top of geological formations from deep wells in the Gloucester subregion

Well name	Formation top	Pick depth (m TVDss[a])	Well name	Formation top	Pick depth (m TVDss[a])
APW 01	Jilleon	275.81	Stratford 9	Jilleon	326.89
APW 01	Wenham	514.19	Stratford 9	Wenham	574.91
APW 01	Dog Trap Creek	649.74	Stratford 9	Speldon	605.69
Craven 1	Jilleon	462.1	Stratford 9	Dog Trap Creek	670.95
Craven 1	Wenham	756.48	Stratford 9	Waukivory	793.94
Craven 3a	Jilleon	173.52	Stratford 10	Jilleon	337.27
Craven 3a	Wenham	391.52	Stratford 10	Wenham	548.45
Craven 3a	Dog Trap Creek	491.8	Stratford 10	Dog Trap Creek	591.57
Craven 3a	Waukivory	579.13	Stratford 10	Waukivory	753.98
Craven 6	Jilleon	231.07	Weismantel 1	Waukivory	–99.9
Craven 6	Wenham	565.31	Weismantel 1	Alum M. Volcanics[b]	589.6
Craven 6	Dog Trap Creek	614.94	Weismantel 2	Mammy Johnsons	–74.24
Craven 6	Waukivory	693.37	Weismantel 2	Alum M. Volcanics[b]	485.46
Faulkland 1a	Jilleon	684.93	Weismantel 3	Waukivory	–91.45
Faulkland 1a	Wenham	917.46	Weismantel 3	Alum M. Volcanics[b]	542.43
Faulkland 1a	Dog Trap Creek	989.56	Waukivory 1	Jilleon	307.06
Faulkland 3	Jilleon	293.408	Waukivory 1	Wenham	657.3

Well name	Formation top	Pick depth (m TVDss[a])	Well name	Formation top	Pick depth (m TVDss[a])
Faulkland 3	Wenham	487.918	Waukivory 1	Speldon	661.9
Faulkland 3	Dog Trap Creek	550.558	Waukivory 1	Dog Trap Creek	679.8
Faulkland 3	Waukivory	670.118	Waukivory 3	Jilleon	38.46
Gloucester 2	Waukivory	–106.75	Waukivory 3	Wenham	157.46
LMGC 01	Wenham	526	Waukivory 3	Dog Trap Creek	192.46
LMGC 01	Speldon	545	Waukivory 3	Waukivory	322.46
Stratford 4	Jilleon	179.17	Waukivory 4	Mammy Johnsons	–142.26
Stratford 4	Wenham	392.08	Waukivory 4	Durallie Road	70.14
Stratford 4	Speldon	407.17	Waukivory 4	Alum M. Volcanics[b]	281.74
Stratford 4	Dog Trap Creek	440	Wards River 1	Jilleon	75.77
Stratford 4	Waukivory	583.2	Wards River 1	Wenham	435.77
Stratford 5a	Jilleon	–129.77	Wards River 1	Dog Trap Creek	555.77
Stratford 5a	Wenham	181.82	Wards River 1	Waukivory	595.77
Stratford 5a	Speldon	189.29	Wards River 3	Jilleon	–101.81
Stratford 5a	Dog Trap Creek	241.51	Wards River 3	Wenham	225.48
Stratford 5a	Waukivory	339.89	Wards River 3	Speldon	297.56
Stratford 7	Waukivory	–165.03	Wards River 3	Dog Trap Creek	338.49
Stratford 7	Mammy Johnsons	–15.03	Wards River 3	Waukivory	488.19
Stratford 7	Durallie Road	209.97	Wards River 4a	Waukivory	–106.18
Stratford 7	Alum M. Volcanics	398.97	Wards River 4a	Mammy Johnsons	268.82
Stratford 8	Jilleon	185.421	Wards River 4a	Durallie Road	531.82
Stratford 8	Wenham	382.881	Wards River 5	Waukivory	–152.62
Stratford 8	Speldon	389.981	Wards River 5	Mammy Johnsons	229.38
Stratford 8	Dogtrap	445.771	Wards River 5	Durallie Road	466.38
Stratford 8	Waukivory	554.831	Wards River 5	Alum M. Volcanics[b]	592.38

[a]TVDss = total vertical depth subsea reported to the Australian Height Datum
[b]Alum Mountain Volcanics
Source: see the listing of well completion reports within the list of references following Section 2.1.2.3.

Eight regional stratigraphic units, selected by the definition of the formation top depths were modelled for the Gloucester subregion (Figure 7):

- Alum Mountain Volcanics
- Durallie Road Formation
- Mammy Johnsons Formation
- Waukivory Creek Formation
- Dog Trap Creek Formation
- Speldon Formation
- Wenham Formation
- Jilleon Formation.

The Wards River Conglomerate was not included as it is a time-transgressive formation representing a stratigraphic boundary rather than a timeline. In the west, the Wards River Conglomerate represents the equivalent of the upper Waukivory Formation to the lower Leloma Formation. In the east, the Ward River Conglomerate thins and is intercalated between the Wenham and the Jilleon formations.

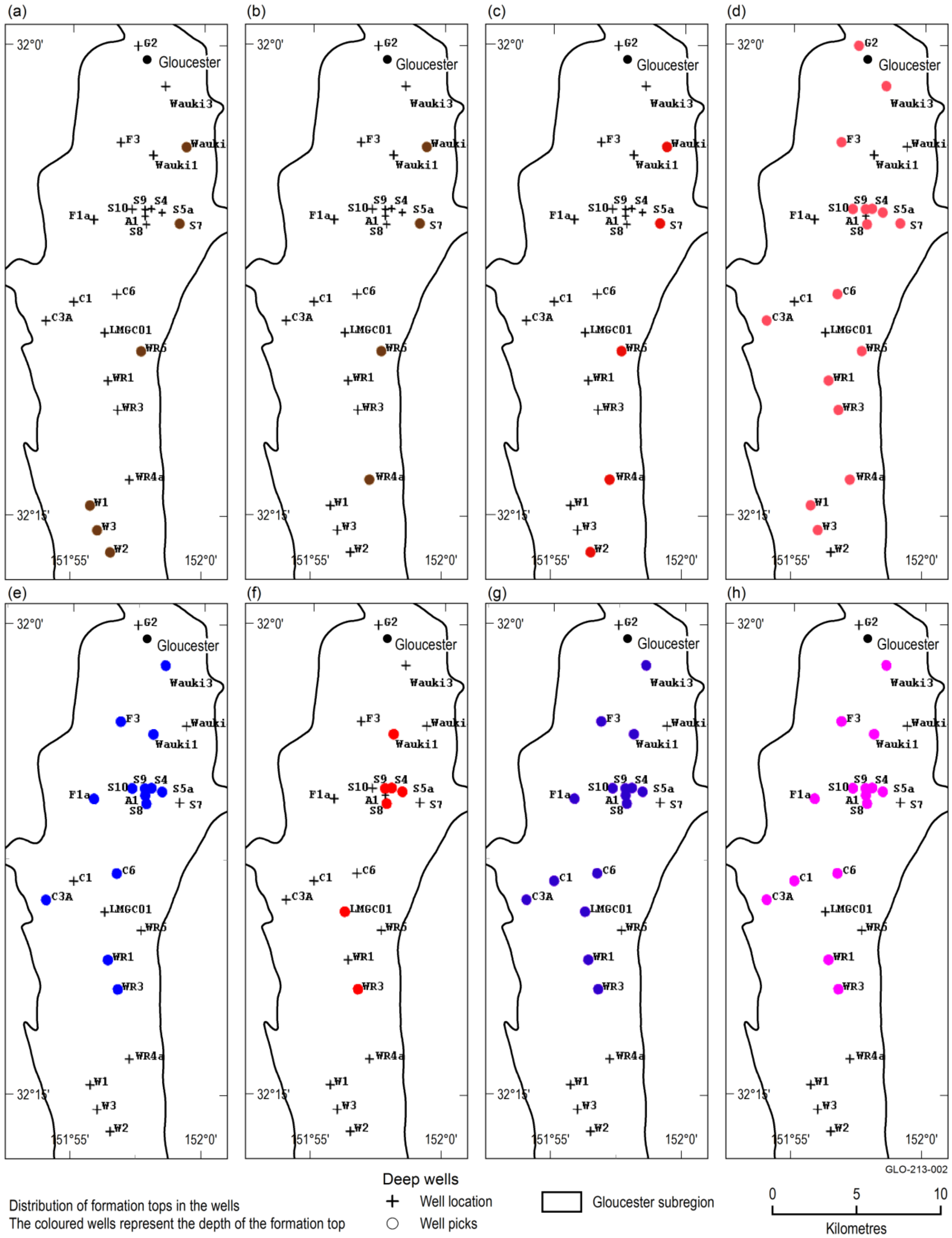


Figure 7 Distribution of formation tops in the wells derived dataset (24 wells) for the Gloucester subregion, running from bottom to top

The coloured wells are those that contain a formation top: (a) Alum Mountain Volcanics, (b) Durallie Road Formation, (c) Mammy Johnsons Formation, (d) Waukivory Creek Formation, (e) Dog Trap Creek Formation, (f) Speldon Formation, (g) Wenham Formation and (h) Jilleon Formation.
The different formations are figured in different colours.
'Well picks' are the markers of the formation top depths in the wells.
See Table 3 for well acronyms and Table 4 for more details about the well picks.

The 1 second STRM data from the DEM (see Section 2.1.2.1.2) were extrapolated with a local B-spline algorithm to produce a topographic surface for the geological modelling domain (Figure 8). The local B-spline algorithm calculates the amplitude of a family of bell-shaped functions (B-splines) using a local heuristic approach. The sum of these functions defines a function in (x, y) that approaches the input data.

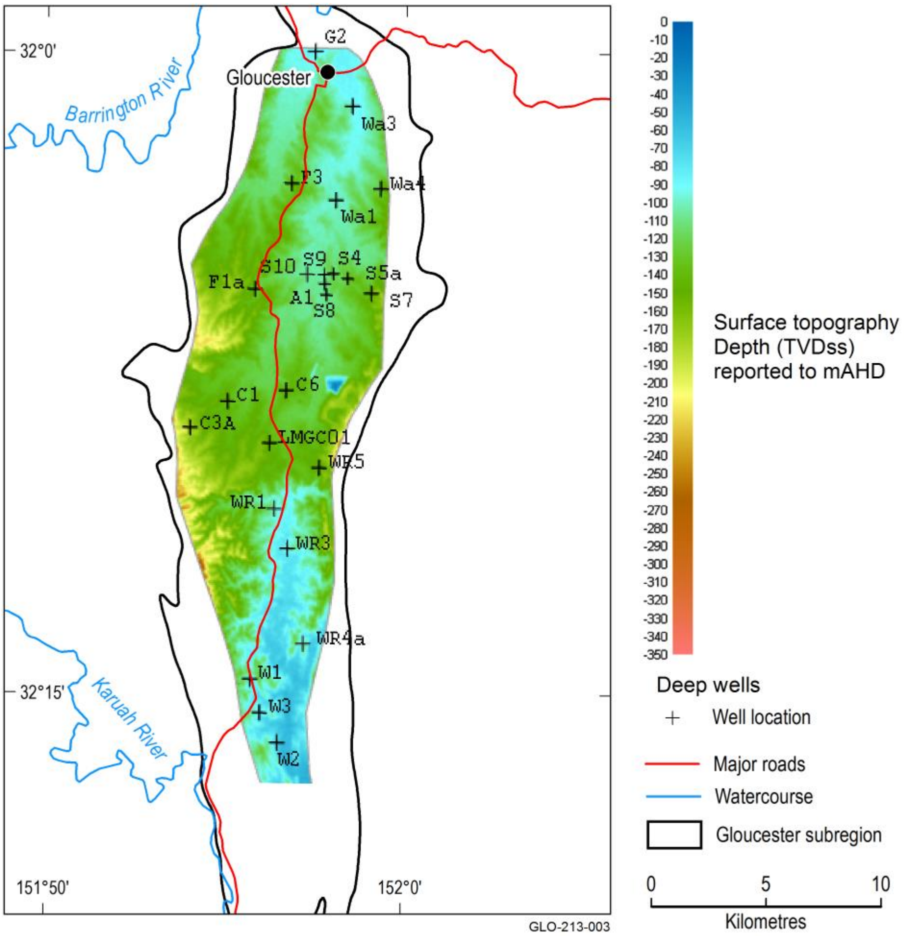


Figure 8 Surface topography map above the coal-bearing geological Gloucester Basin area modelled in three dimensions

TVDss = total vertical depth subsea reported to the Australian Height Datum; negative values represent elevation above sea level
See Table 3 for well acronyms.
Data: NSW Trade and Investment (Dataset 1); Bioregional Assessment Programme (Dataset 2); Geoscience Australia (Dataset 4)

2.1.2.2.3 Three-dimensional non-faulted and non-eroded geological model

The three-dimensional non-faulted and non-eroded geological model building is an intermediary step in the modelling process. Intermediary non-faulted and non-eroded isopach maps are built on the base of the well data extrapolation and then intermediary non-faulted and non-eroded depth maps are computed on the base of a reference horizon, that is, the top of the Wenham Formation. This process is explained in the modelling workflow, Section 2.1.2.2.1. The intermediary maps of thickness (isopach maps) and depth are not to be taken as real geological results. They just represent a step in the modelling and the trends observed, and do not necessarily correspond to current geological formation depth or thickness variations.

The top of the Wenham Formation was selected as the reference horizon as it represents the shallowest formation top with the highest number of well picks (16 wells) (Figure 7).

Isopach data were determined directly from the twenty-four selected wells. Seven isopach maps were extrapolated (Figure 9):

- Top Alum Mountain Volcanics to top Durallie Road Formation (isopach map (a))
- Top Durallie Road Formation to top Mammy Johnsons Formation (isopach map (b))
- Top Mammy Johnsons Formation to top Waukivory Creek Formation (isopach map (c))
- Top Waukivory Creek Formation to top Dog Trap Creek Formation (isopach map (d))
- Top Dog Trap Creek Formation to top Speldon Formation (isopach map (e))
- Top Speldon Formation to top Wenham Formation (isopach map (f))
- Top Wenham Formation to top Jilleon Formation (isopach map (g)).

For isopach maps (a), (b), (c) and (g), general thickness trends were determined from the formation thickness data deduced from the well picks (isochore data) showed on Figure 9. For isopach maps (d), (e) and (f), no trend was adequately defined for the Gloucester subregion and a general thickness was used.

The resulting isopach maps are nondeterministic and the uncertainty increases as the isochore data concentration decreases. Note that these isopachs correspond to an intermediary step in the modelling and do not represent the final isopachs observed in the geological Gloucester basin. For their determinations only the well data and unfaulted models are considered, virtually eroding them toward the edges of the basin by the creation of the ‘faulted final model’.

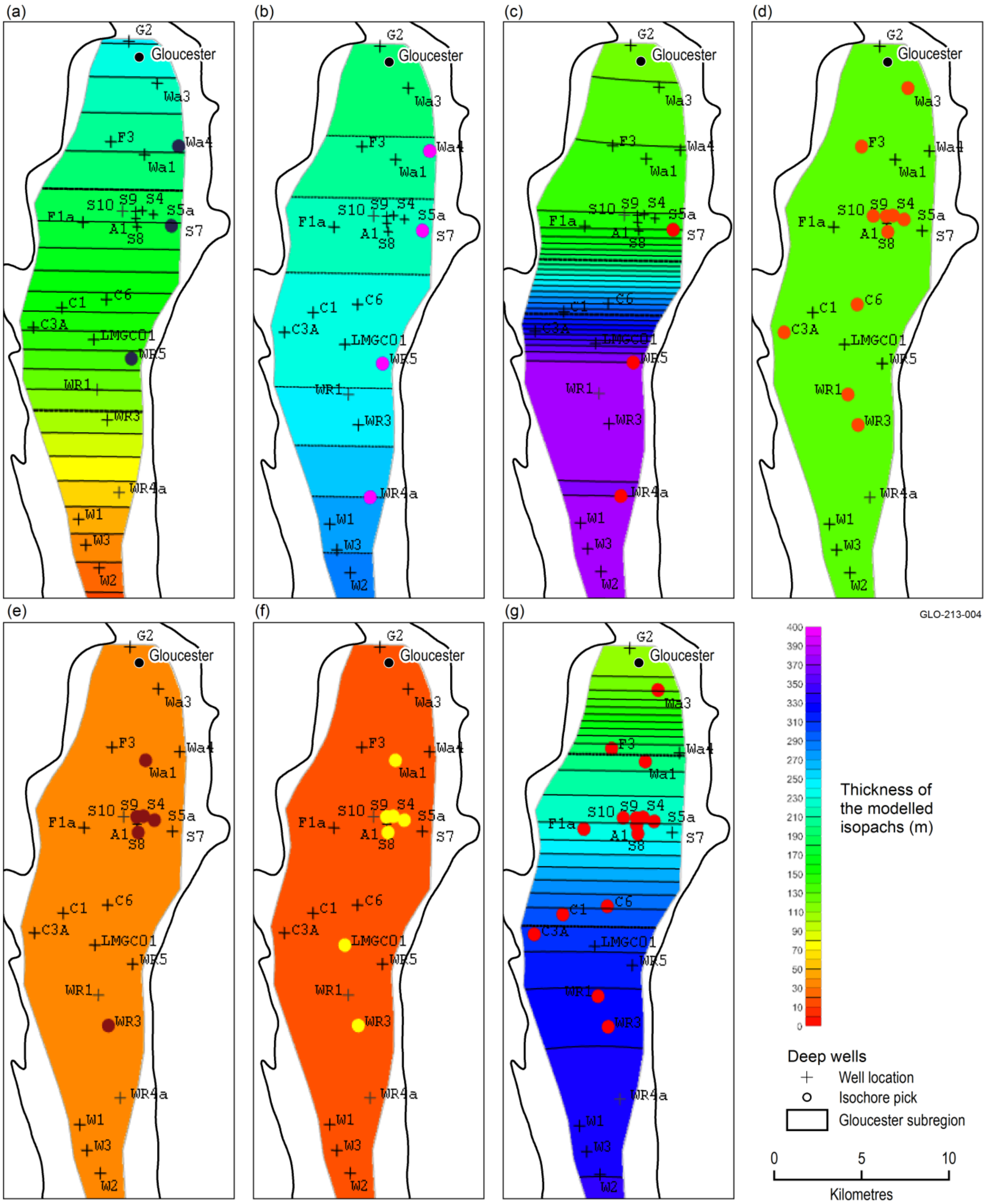


Figure 9 Isopach maps containing distribution of formation thicknesses in the wells derived dataset (24 wells) for the coal-bearing geological Gloucester Basin area modelled in three dimensions

(a) Top Alum Mountain Volcanics to top Durallie Road Formation, (b) Top Durallie Road Formation to top Mammy Johnsons Formation, (c) Top Mammy Johnsons Formation to top Waukivory Creek Formation, (d) Top Waukivory Creek Formation to top Dog Trap Creek Formation, (e) Top Dog Trap Creek Formation to top Speldon Formation, (f) Top Speldon Formation to top Wenham Formation and (g) Top Wenham Formation to top Jilleon Formation.
See Table 3 for well acronyms.
Data: NSW Trade and Investment (Dataset 1)

The horizon depth map (Figure 10) was created using a radial basis algorithm with a 50 m lateral step (x and y). This algorithm provides a good approximation of scattered data by forming linear combinations of radial functions centred at each data point. Please refer to the RMS Roxar website (Emerson, 2016) for more details.

The resulting horizon depth map is nondeterministic with uncertainty increasing as data concentration decreases.

The structural map of the top of the Wenham Formation and the isopach maps (Figure 9) were used to build a non-faulted and non-eroded geological model. This model has a horizontal resolution of 200 by 200 m (x, y), with 50 vertical layers for a total of 501,000 cells. The depth ranges between +818 mAHD and –1830 mAHD.

Figure 10 shows depth structure maps of the non-faulted and non-eroded formation tops extracted from the geological model.

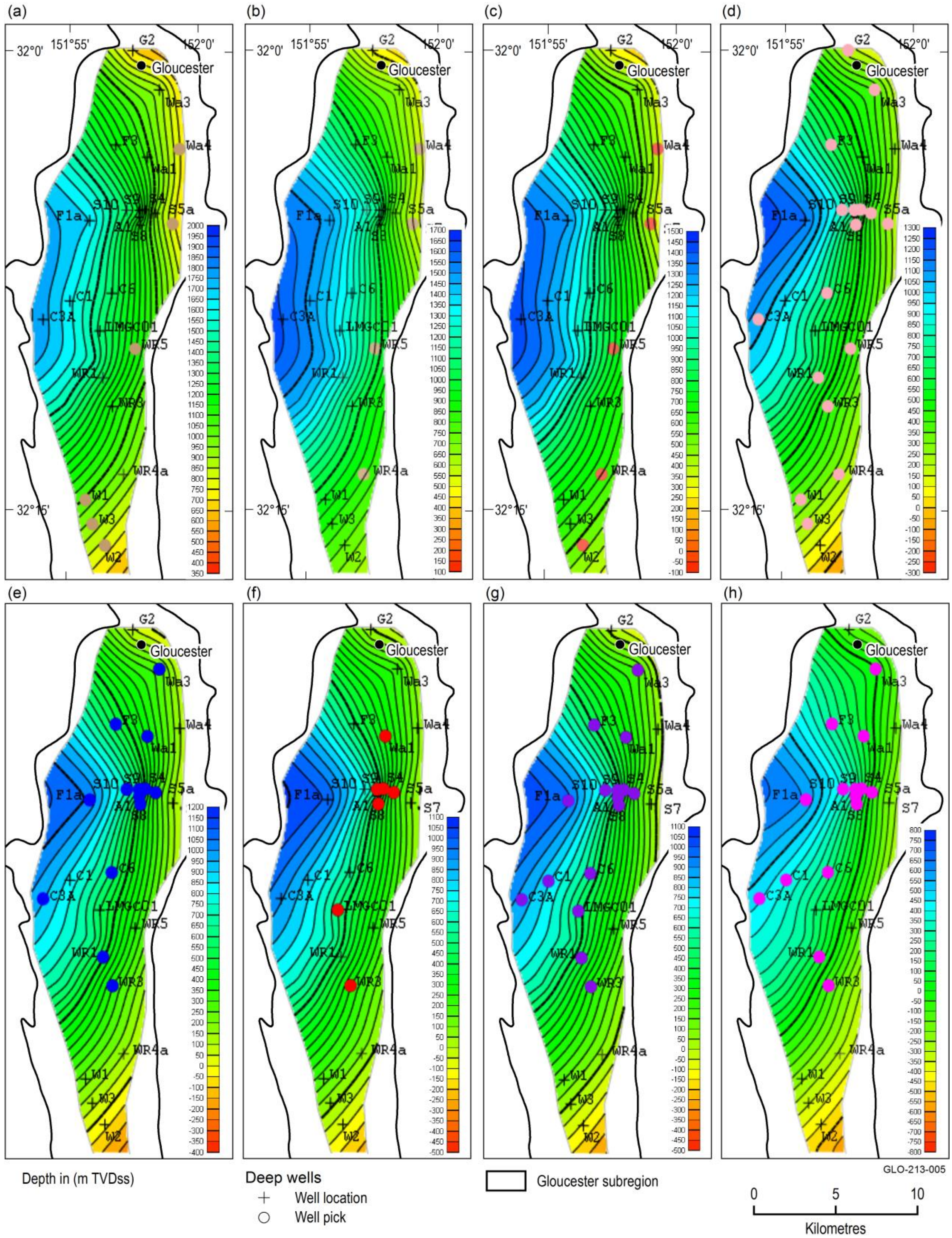


Figure 10 Depth structure maps of non-faulted and non-eroded horizons extracted from the coal-bearing geological Gloucester Basin area modelled in three dimensions

(a) Alum Mountain Volcanics, (b) Durallie Road Formation, (c) Mammy Johnsons Formation, (d) Waukivory Creek Formation, (e) Dog Trap Creek Formation, (f) Speldon Formation, (g) Wenham Formation and (h) Jilleon Formation.
'Well picks' are the markers of the formation top depths in the wells.
TVDss = total vertical depth subsea reported to the Australian Height Datum; negative values represent elevation above sea level; different colour scales are used for each map
See Table 3 for well acronyms.
Data: NSW Trade and Investment (Dataset 1)

2.1.2.2.4 Fault analysis

Major fault trends and displacements were incorporated in the model to obtain a faulted geological model. These fault trends were estimated from the observation of the geological map (location of the edges of the basin) and included to accommodate visible misfits (greater than 100 m) between the extracted non-faulted and non-eroded horizons (Figure 10) and the formation tops at wells (Figure 7).

This model was then eroded using the present-day surface topography. The final eroded and faulted model (Figure 11) has a horizontal resolution of 200 by 200 m (x, y), with 50 vertical layers for a total of 501,000 cells. The depth ranges between +665 mAHD and –1755 mAHD.

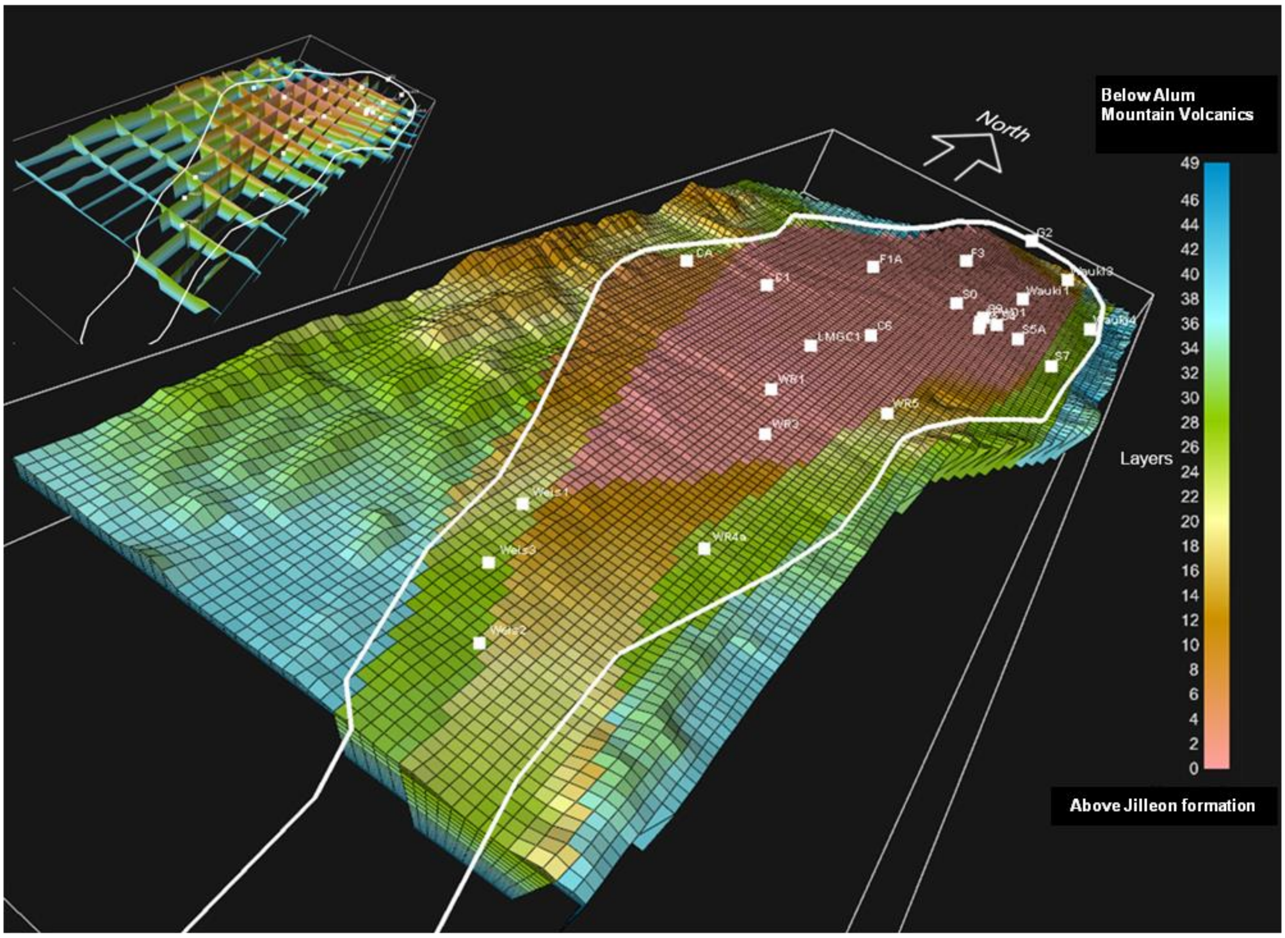


Figure 11 Three-dimensional perspective view of the eroded and faulted geological model for the Gloucester subregion – diagram in the top left-hand corner shows vertical sections within the model

Figure 12 shows the formation tops extracted from the eroded and faulted geological model. The main fault trends affect the stratigraphic pile and are localised along the western and eastern flanks of the Gloucester subregion. The trends located within the subregion accommodate a normal displacement which varies between 200 and 500 m. The other fault trends, which fit the geological limit of the subregion, accommodate normal displacements up to 1000 m.

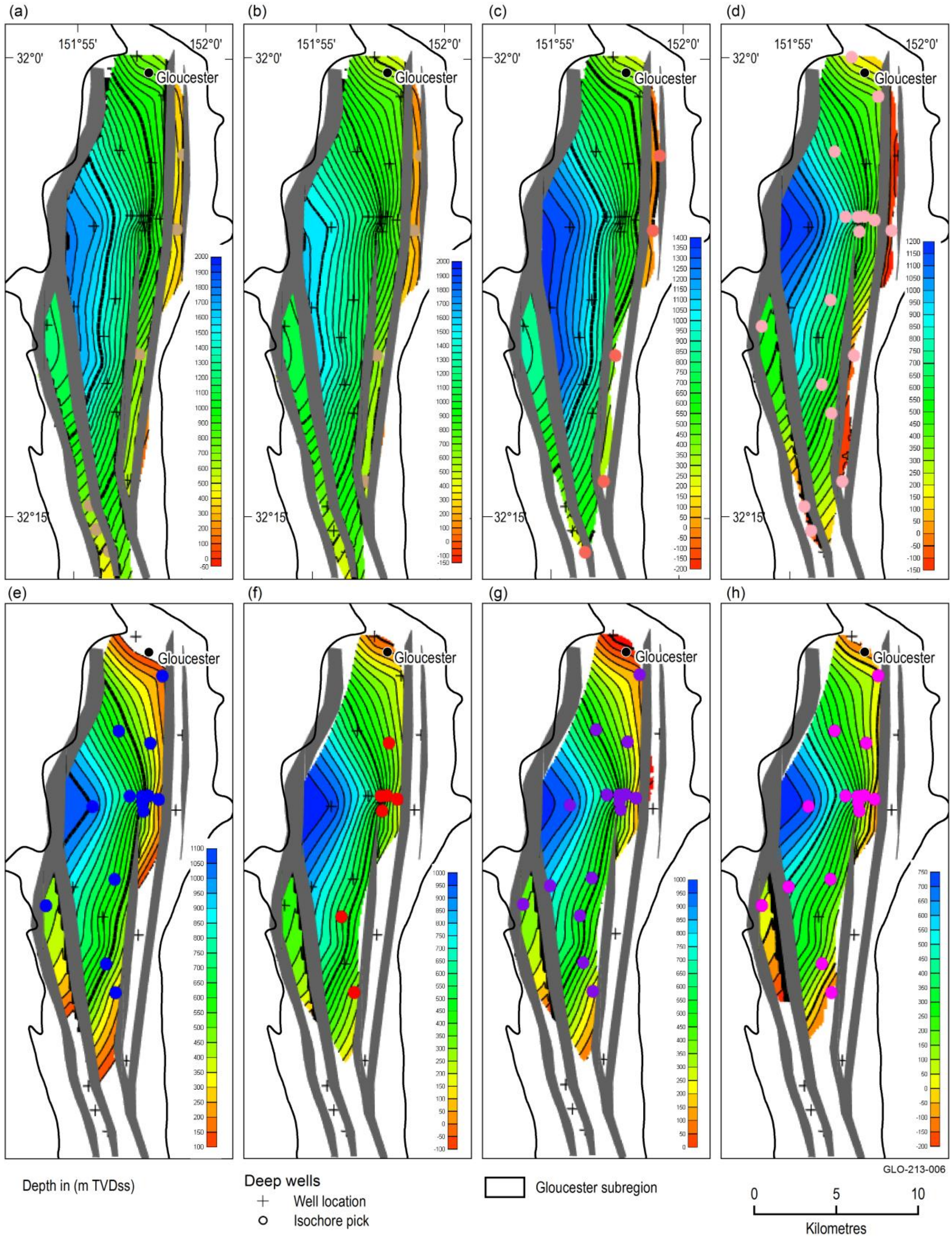


Figure 12 Depth structure maps extracted from the eroded and faulted geological model for the coal-bearing geological Gloucester Basin area modelled in three dimensions

(a) Alum Mountain Volcanics, (b) Durallie Road Formation, (c) Mammy Johnsons Formation, (d) Waukivory Creek Formation, (e) Dog Trap Creek Formation, (f) Speldon Formation, (g) Wenham Formation Wards River Conglomerate and (h) Jilleon Formation
TVDss = total vertical depth subsea reported to the Australian Height Datum; negative values represent elevation above sea level – grey lines represent the main fault trends
Data: NSW Trade and Investment (Dataset 1); Bioregional Assessment Programme (Dataset 2); Geoscience Australia (Dataset 4)

A fault size population is defined by plotting the fault size (here maximum displacement) versus the cumulative number of faults (e.g. Yielding et al., 1996). An observed characteristic of many sampled fault populations is that the size-frequency distribution is described by a power-law of the form:

$$N = aD^{-C} \quad (1)$$

where N is the number of features having a displacement greater than or equal to D, *a* is a measure of the size of the sample and C is the power-law exponent. On a plot of log N against log D, a power-law distribution is defined by a straight line segment with slope –C. The population distribution can be used to extrapolate fault size outside the sampling range and predict sub-seismic scale faults and to validate structural interpretations.

A fault size population for the Stratford CSG Prospect area was defined according to the structural interpretation of Grieves and Saunders (2003). This population can be used to constrain and calibrate the large faults in the geological model and also to predict smaller faults that have the potential to affect connectivity of coal seams and aquitards.

For instance, eighteen normal faults with measurable throw are mapped on the Top Bowen Rd split 5 (BR5 – see companion product 1.1 for the Gloucester subregion (McVicar et al., 2014) for details) horizon for the approximately 7 km^2 Stratford CSG Prospect area (Grieves and Saunders, 2003) (Figure 13a). The reported throws range from 100 to 10 m. Using a typical power-law slope of –1 (e.g. Yielding et al., 1996; Needham and Yielding, 1996; Bailey et al., 2005; Manzocchi et al., 2009), two fault populations (Stratford medium case and Stratford lower case) are proposed for the Stratford CSG Prospect area (Figure 13b and Figure 13c). Comparison with other fault populations that had been estimated in the coal-bearing Permian basins, that is Collie Basin (WA) (Figure 13d) and the Taranaki Basin (New Zealand) (Figure 13e), scaled down to the same surface area (approximately 7 km^2), suggests that the Stratford CSG Prospect area fault population (Figure 13a) could be (i) overestimated (e.g. due to over interpretation of the seismic data) and/or (ii) the displacement for these faults are overestimated (e.g. due to inaccurate horizon picking or time depth conversion). Figure 13f shows the fault size population extrapolated from the Stratford lower case fault population upscaled to the size of the Gloucester geological basin (220 km^2). It shows a higher cumulative number of faults than other fault populations from the coal-bearing Permian Collie Basin in WA (Figure 13g) and the East Pennine Coalfield in UK (EPC) (Figure 13h). This again suggests a possible overestimation of the fault size and displacement in the Stratford and Gloucester populations. A fault population for the Gloucester subregion similar to the Collie Basin (Figure 13g) would yield larger faults with maximum displacement around 1500 m which correlate with the faults needed to accommodate displacement in the geological model.

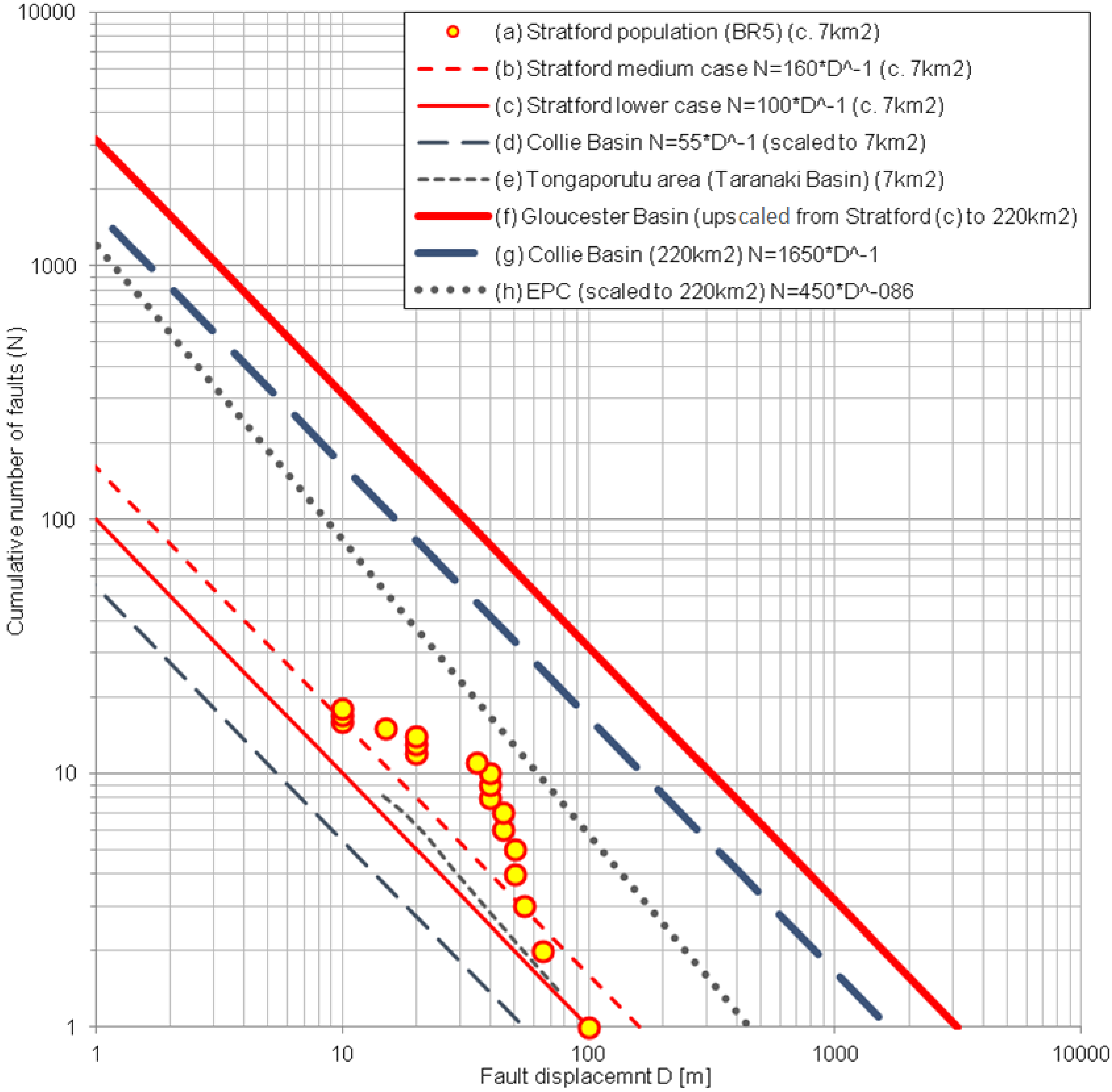


Figure 13 Fault size populations for the Gloucester subregion

Dots represent the Gloucester Gas Project fault data derived from Grieves and Saunders (2003). Thin lines (b, c, d and e) represent population scaled to the size of the Gloucester Gas Project (c. 7km^2). Thick lines (f, g and h) represent population scaled to the size of the Gloucester subregion; log scale is used

2.1.2.3 Gaps

Gloucester subregion's geological datasets are characterised by a poor spatial coverage. The main part of the subregion is poorly covered and in some areas not covered at all.

Incorporating new well data or well data not publicly available at the cut-off date of November 2013 could help to better constrain the geological framework of the Gloucester subregion. A list of the deep well reports that are either recently publicly released or that are going to be released in the coming years follows:

- AGL Energy Ltd (2010) Well Completion Report Craven 7 PEL 285 – NSW
- AGL Energy Ltd (2010) Well Completion Report Gloucester 1 PEL 285 – NSW

- AGL Energy Ltd (2010) Well completion report Wards River 2 PEL 285 – NSW
- AGL Energy Ltd (2012) Well completion report Waukivory 11 (WK11) PEL 285 – NSW
- AGL Energy Ltd (2012) Well completion report Waukivory 12 (WK12) PEL 285 – NSW
- AGL Energy Ltd (2012) Well completion report Waukivory 13 (WK13) PEL 285 – NSW
- AGL Energy Ltd (2012) Well completion report Waukivory 14 (WK14) PEL 285 – NSW
- AGL Energy Ltd (2013) Well completion report Pontlands 3 (PL03) PEL 285 – NSW.

Some other two-dimensional and three-dimensional seismic reflection data have also been acquired by the companies in the Gloucester subregion:

- AGL Energy Ltd (2010) 2009 Bucketts two-dimensional seismic survey report, PEL 285 – Gloucester Basin, NSW
- AGL Energy Ltd (2011) 2010 Mograni three-dimensional seismic survey report, PEL 285 – Gloucester Basin, NSW
- AGL Energy Ltd (2013) 2012 Thunderbolt two-dimensional seismic survey report, PEL 285 – Gloucester Basin, NSW.

However, using information from these reports was not possible due to the lack of publicly available interpretation of data. Proposing a new interpretation of these datasets would require a program of seismic interpretation and calibration with available well logs. This work could be in scope for a new phase of Gloucester subregion geological modelling.

In 2013, AGL acquired helicopter-borne magnetic and radiometric data for a large part of the geological Gloucester Basin. These data are not currently available (as of November 2013) to the Assessment team. The magnetic data in particular would be very helpful in improving geological models of the Gloucester subregion.

The geological model proposed in Section 2.1.2.2 is one possibility among many. Note that the location and orientation of most faults are unknown. This model can be updated with a stochastic distribution of the faults. Additionally, the lithology and the facies can be implemented to study flow properties and connectivity. For instance, a sub-seismic dataset, conditioned by the fault population, can be used to test the potential impact faults could have on the 3D coal connectivity at the scale of a prospect.

References

General material

Bailey W, Walsh J and Manzocchi T (2005) Fault populations, strain distribution and basement fault reactivation in the East Pennines Coalfield, UK. Journal of Structural Geology 27(5), 913–928.

Emerson (2016) Roxar. Reservoir management software products online. Viewed 25 February 2016, http://www2.emersonprocess.com/en-US/brands/roxar/reservoirmanagement/Pages/ReservoirManagementSoftware.aspx?gclid=Cj0KEQiAz5y1BRDZ4Z_K_eGa84cBEiQAtQkeaCkYwRJ2DORFamc2gzVt3uEqQ2ix75Lnzl31E-kmahAaArc-8P8HAQ.

Grieves K and Saunders J (2003) Seismic reprocessing, interpretation and mapping for the Stratford Coal Seam methane prospect, PEL 285. AJ Lucas Coal Technologies Pty Ltd and Molopo Australia, Australia.

Manzocchi T, Walsh J and Bailey WR (2009) Population scaling biases in map samples of power-law fault systems. Journal of Structural Geology 31, 1612–1626.

McVicar T, Langhi L, Barron OV, Rachakonda PK, Zhang YQ, Dawes WR, Macfarlane C, Holland KL, Wilkes PG, Raisbeck-Brown N, Marvanek SP, Li LT and Van Niel TG (2014) Context statement for the Gloucester subregion. Product 1.1 from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 28 September 2015, http://data.bioregionalassessments.gov.au/product/NSB/GLO/1.1.

Needham T and Yielding G (1996) Fault population description and prediction using examples from the offshore U.K. Journal of Structural Geology 18(2–3), 155–167.

Roberts J, Engel B and Chapman J (1991) Geology of the Camberwell, Dungog, and Bulahdelah. 1:100,000 geological series – sheets 9133, 9233, 9333. Geological Survey of New South Wales, Sydney.

Ross M, Parent M and Lefebve R (2004) 3D geological framework models for regional hydrogeology and land-use management: a case study from a quaternary basin of southwestern Quebec, Canada. Hydrogeology Journal 13, 690–707.

Wellmann JF, Horowitz FG, Schill E and Regenauer-Lieb K (2010) Towards incorporating uncertainty of structural data in 3D geological inversion. Tectonophysics 490, 141–151.

Yielding G, Needham T and Jones H (1996) Sampling of fault populations using sub-surface data: a review. Journal of Structural Geology 18(2–3), 135–146.

Well completion report list

AGL Energy Ltd (2009) Well completion Report Craven 6 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2009) Well completion Report Gloucester 2 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2009) Well completion Stratford 10 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2009) Well completion Waukivory 4 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2010) Well completion Report Wards River 1 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2010) Well completion Report Wards River 3 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2010) Well completion Report Wards River 4a PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2010) Well completion Report Wards River 5 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2010) Well completion Stratford 7 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

AGL Energy Ltd (2010) Well completion Waukivory 3 PEL 285 – New South Wales. AGL Energy Ltd, Australia.

Lucas Energy Pty Ltd (2007) Well completion LMGC 01 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion APW 01 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion Faulkland 1 Faulkland 1a PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion Faulkland 3 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion Stratford 4 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion Stratford 5 Stratford 5a PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion Stratford 8 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion Stratford 9 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion Weismantel 2 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd (2008) Well completion Weismantel 3 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd and Molopo Australia Ltd (2008) Well completion Craven 1 PEL 285 – New South Wales. Lucas Energy Pty Ltd and Molopo Australia Ltd, Australia.

Lucas Energy Pty Ltd and Molopo Australia Ltd (2008) Well completion Craven 3A PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd and Molopo Australia Ltd (2008) Well completion Waukivory 1 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Lucas Energy Pty Ltd and Molopo Australia Ltd (2008) Well completion Weismantel 1 PEL 285 – New South Wales. Lucas Energy Pty Ltd, Australia.

Datasets

Dataset 1 NSW Trade and Investment (2014) Gloucester Deep Wells Completion Reports - Geology. Bioregional Assessment Source Dataset. Viewed 28 October 2015, http://data.bioregionalassessments.gov.au/dataset/0529ae9a-4d40-460d-b52a-fb0e5f646746.

Dataset 2 Bioregional Assessment Programme (2014) BA SYD 1 sec SRTM (h) DEM and hydrological derivatives. Bioregional Assessment Derived Dataset. Viewed 21 April 2016, http://data.bioregionalassessments.gov.au/dataset/90f5ef3c-2141-4450-b44c-1afbd843236f.

Dataset 3 AGL (2014) AGL - 2013 Gloucester Airborne Survey. Bioregional Assessment Source Dataset. Viewed 28 October 2015, http://data.bioregionalassessments.gov.au/dataset/5cffc19a-0ff4-402c-824a-88935f70931a.

Dataset 4 Geoscience Australia (2011) Geoscience Australia, 1 second SRTM Digital Elevation Model (DEM). Viewed 28 October 2015, http://data.bioregionalassessments.gov.au/dataset/9a9284b6-eb45-4a13-97d0-91bf25f1187b.

2.1.3 Hydrogeology and groundwater quality

Summary

The Gloucester subregion contains 175 groundwater bores where four types of hydrogeological data were analysed: (i) groundwater level, (ii) hydraulic parameters, (iii) groundwater quality and (iv) allocation.

Mean groundwater levels and bore depths were determined for various aquifers of the Gloucester subregion including the alluvial aquifers, the fractured rock aquifers and the deep water-bearing units. This information is crucial to the identification of recharge and/or discharge areas and associated groundwater flow systems, as well as for the development of the groundwater balance for the subregion as well as aid in preliminary identification of areas that can potentially be impacted by coal seam gas extraction and coal mining activities.

Overall the availability of hydrogeological and hydrochemical data is limited for alluvial and fractured rock aquifers. For the deeper water-bearing systems, there is next to no information available.

Based on the geological setting and discrete structural-sedimentary formation (see McVicar et al., 2014, Figures 22 and 23), the geological Gloucester Basin, which underlies the Gloucester subregion, is characterised as a closed hydrogeological system. The Gloucester subregion contains two main aquifers: an alluvial aquifer and an aquifer hosted by a weathered bedrock profile occurring within 150 metres below ground level. Further detail about the hydrogeological settings of the Gloucester subregion is provided in Section 1.1.4 of the companion product 1.1 for the Gloucester subregion (McVicar et al., 2014). Multiple groundwater studies describe four main hydrogeological units within the Gloucester subregion:

1. alluvial aquifers along major creek lines (referred hereafter as alluvium)
2. relatively shallow weathered and/or fractured rock aquifers (referred hereafter as fractured rock)
3. interburden units of very low permeability which form a thick succession of low permeability coal measures (referred hereafter as deep water-bearing)
4. the impermeable Alum Mountain Volcanics Formation that underlies these three hydrogeological units.

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. Information about the quality of water within aquifers enables assessment of potential impacts from aquifer mixing and discharge of aquifer water into other receiving waters. The hydrogeologic data used in the bioregional assessment (BA) of the Gloucester subregion are detailed in Section 2.1.3.1 about observed data.

2.1.3.1 Observed data

Most of the data required for groundwater modelling are obtained from bore data. Bore data for the Gloucester subregion were obtained from the Bureau of Meteorology, but originated from NSW state groundwater databases. The data acquired extends to November 2013. Not all model parameters are available at all bore locations. Table 5 lists the datasets that have been used to obtain hydrogeological data for the Gloucester subregion. Figure 14 shows the distribution of bores within the Gloucester subregion.

Table 5 Groundwater datasets used for hydrogeology and water quality analysis in the Gloucester subregion

Observed data	Dataset	Data item name[a]
Bore construction	NSW Office of Water – National Groundwater Information System 20140701 (NSW Office of Water, Dataset 1)	Bore Construction Line NGIS_v2_20140701
	NSW allocation of aquifer for screened unit of monitoring bores (Bureau of Meteorology, Dataset 2)	Aquifers_assignment_JS_Jan13
Groundwater level	HYDMEAS – Hydstra Groundwater Measurement Update_NoW_Nov2013 (NSW Office of Water, Dataset 3)	HYDMEAS
Hydraulic parameters	State Transmissivity Estimates for Hydrogeology Cross-Cutting Project (Geoscience Australia, Dataset 4)	NSW_Pump_Test_Data_WRON_Nov2013_consolidated
		tguess_NSW_full_set
Groundwater quality	HYDMEAS – Hydstra Groundwater Measurement Update_NoW_Nov2013 (NSW Office of Water, Dataset 5)	ALL WQ IN SELECTED REGION_gw_28112013
Allocation	Gloucester Groundwater Usage Estimates v20150501 (Bioregional Assessment Programme, Dataset 6)	GLO_GW_licenses_ExtractionVolumes_BoreDepths_20150501

[a]Typography is as used in the dataset.

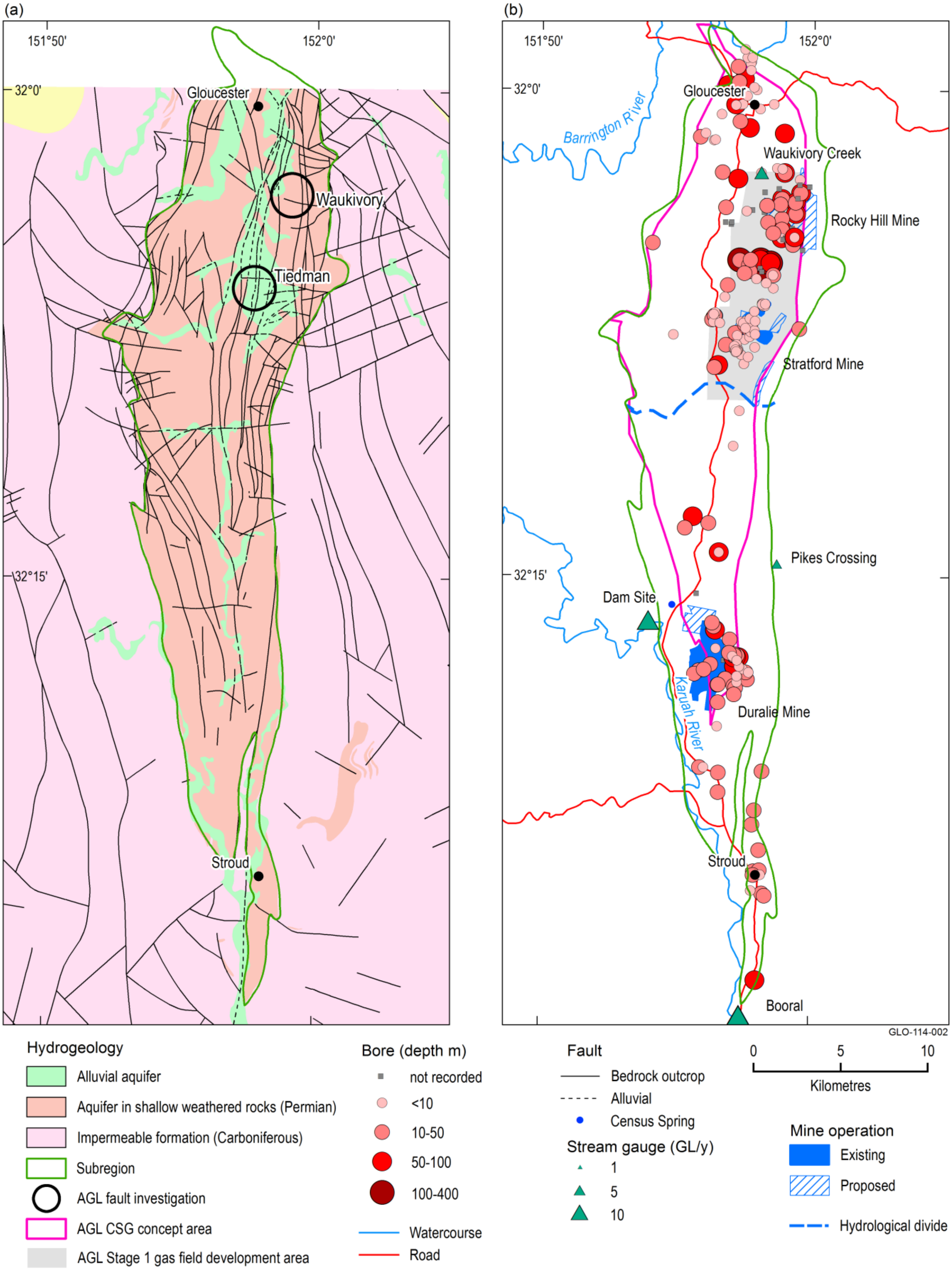


Figure 14 Spatial distribution of bores with hydrogeological information for the Gloucester subregion

Source: Figure 25 in companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)

2.1.3.1.1 Groundwater levels

Groundwater levels for the Gloucester subregion were obtained from the NSW Office of Water (Dataset 3). Water levels in this dataset are expressed as depths below the ground surface (mBGL) (i.e. a positive value indicates a watertable below the ground). Ground level elevations are missing for many bores.

Table 6 summarises the bores by groundwater-bearing unit. Almost 90% of groundwater level records in the dataset are from bores located in alluvium, with the remaining in fractured rock aquifers. Records of groundwater level for bores in deep water-bearing aquifers are not available in the NSW state groundwater dataset (NSW Office of Water, Dataset 3). There are nine bores with unknown bore depths, however they have been recorded as zero mBGL in the NSW Office of Water groundwater level database (Dataset 3).

Table 6 Summary of water level records for bores in the Gloucester subregion

Groundwater-bearing unit	Number of bores	Groundwater depth (mBGL)			Total number of monitoring records
		Minimum	Maximum	Standard deviation	
Alluvium	36	0.08	13.39	4.27	126
Fractured Rock	4	0	18.09	7.53	24
Deep water-bearing	0	NA	NA	NA	NA

'NA' means data not available.
Data: NSW Office of Water (Dataset 3)

In the NSW groundwater bore datasets (NSW Office of Water, Dataset 3), 205 monitoring records over a period of 23 years (1980 to 2002) were available from 49 bores for the Gloucester subregion. Most bores (around 24) have a single monitoring record (Table 7), although 20 bores have more than 7 monitoring records. Useful further work could include extracting data about groundwater levels available in various reports for the Gloucester subregion and assigning this data to the hydrogeology units. Due to limited availability of yearly groundwater levels in the dataset (NSW Office of Water, Dataset 3) no spatial and temporal data trend analysis is performed. Mining companies and coal seam gas resource developers often collect water level data and more information may be available at locations across the Gloucester subregion than has been reported in Dataset 3 (NSW Office of Water groundwater).

Table 7 Summary of monitoring records for bores in the Gloucester subregion

Number of monitoring records	Number of bores
1	24
2	1
4	3
5	1
7	9
8	8
9	1
12	1
14	1

Data: NSW Office of Water (Dataset 3)

2.1.3.1.2 Hydraulic parameters

Hydraulic parameters provide critical input into the numerical groundwater model – the identification of uncertainties in the hydraulic parameter fields is essential as they can contribute significantly to the overall uncertainty associated with the modelling of impacts.

The NSW groundwater data (NSW Office of Water, Dataset 1, Dataset 3; Bioregional Assessment Programme, Dataset 7) contains limited pumping test data, which usually include the date and duration of the test, initial water level, pumping rate and maximum drawdown. Available hydrogeological data sources (e.g. university theses, consultancy reports and government reports) were examined and hydrogeological records (e.g. stratigraphy, water level, pumping test results) were incorporated into the datasets (Bureau of Meteorology, Dataset 2; Geoscience Australia, Dataset 4) where appropriate.

Transmissivity values were estimated from pumping test data using the TGUESS approach (a computerised technique for estimating the hydraulic conductivity of aquifers from specific capacity data; Bradbury and Rothschild, 1985). Hydraulic conductivity was computed from the derived transmissivity data where screen interval data were available (Geoscience Australia, Dataset 4). However, where hydraulic conductivity or transmissivity was available in the original state database, this value was kept as the primary value for the statistical analysis. When multiple hydraulic conductivity or transmissivity records were present, the mean was used for the statistical analysis. No pumping test records or storage values (Ss and ST) are available for the bores located in the Gloucester subregion in the NSW bore database (NSW Office of Water, Dataset 3). No transmissivity or storage values for the bores located in the Gloucester subregion are available in the Bureau of Meteorology (Dataset 2) and Geoscience Australia (Dataset 4) datasets.

Hydraulic conductivity values for the aquifers reported in various reports (Heritage Computing, 2009, 2012; Parsons Brinckerhoff, 2013; SRK, 2010) are reproduced in Table 8.

Table 8 Range of hydraulic conductivity data for bores in the Gloucester subregion as reported in various reports

Groundwater-bearing unit	Hydraulic conductivity range (m/day)
Alluvium	0.3–500
Fractured Rock	0.01–20
Deep water-bearing	0.002–0.03

Source: Heritage Computing (2009, 2012); Parsons Brinckerhoff (2013); SRK (2010)

2.1.3.1.3 Groundwater quality

The observed water chemistry and quality data for the Gloucester subregion are sourced primarily from the NSW state groundwater dataset (NSW Office of Water, Dataset 5). It contains 1015 water chemistry sampling records from 32 groundwater bores across the Gloucester subregion. As the aquifers in which the bores in this dataset are screened are not available for any bores, the attribution to aquifer (Table 9) is based on the depth of the bore and the thickness of aquifer recorded in the various hydrogeological reports for the Gloucester geological basin. Mining companies and coal seam gas resource developers often collect water quality data and more information may be available at locations across the Gloucester subregion than has been reported in Dataset 5 (NSW Office of Water).

Table 9 Number of water chemistry records for the Gloucester subregion

Groundwater-bearing unit	Number of bores	No of water chemistry records
Alluvium	21	621
Fractured Rock	11	394

Data: Bioregional Assessment Programme (Dataset 6)

A summary of groundwater chemistry results for the bores in the NSW groundwater dataset (NSW Office of Water, Dataset 5) is provided in Table 10. Further information about the analysis of water chemistry in the Gloucester subregion is available in Section 1.5.2.2 of companion product 1.5 for the Gloucester subregion (Rachakonda et al., 2015).

Table 10 Summary of water chemistry results for the Gloucester subregion

Analyte	Unit	Minimum	Maximum	Median
Acidity as CaCO3	mg/L	0	300	25
Alkalinity (Total) as CaCO3	mg/L	17	330	210
Alkalinity as Bicarbonate (HCO3)	mg/L	20.75	687.05	125.08
Calcium as Ca – soluble	mg/L	17	160	59.50
Calcium as Ca – total	mg/L	15.23	226.85	21.04
Chloride as Cl	mg/L	27	5270	1572.50
Electrical Conductivity at 25 °C	µS/cm	106	630,000	3470
Fluoride as F – soluble	mg/L	0.02	2.66	0.17
Iron as Fe – soluble	mg/L	0.01	53	0.14
Iron as Fe – total	mg/L	0.01	82	8.27
Lead as Pb – soluble	mg/L	0.01	0.01	0.01
Magnesium as Mg – soluble	mg/L	5.2	60	45.50
Magnesium as Mg – total	mg/L	13.37	149.35	16.77
pH	---	3.1	8.6	6.90
Potassium as K – soluble	mg/L	1.56	16.81	3.80
Solids – total dissolved (calculated)	mg/L	300	4700	2500
Solids – total suspended at 105 °C	mg/L	1	872	4
Sulfate as S	mg/L	1	498	91
Sulfate as SO4	mg/L	19.21	182.03	46.11

Data: NSW Office of Water (Dataset 5)

2.1.3.1.4 Allocation

The allocation data are summarised in Table 11. Most of the licensed allocation is from alluvial aquifers, with a lesser volume from fractured rock aquifers. There is no licensed allocation to extract water from the deep water-bearing units.

An industrial report prepared by Parsons Brinckerhoff (2013) reported that annual stock and domestic bore use is approximately 1 ML/bore. Australasian Groundwater and Environmental (2013) has reported that a single groundwater facility exists (irrigation bore) in the Avon River management area with an annual entitlement of 20 ML/year from the alluvium. Further information about the analysis of entitlements and/or allocations in the Gloucester subregion is available in Section 1.5.1.2.1 of companion product 1.5 for the Gloucester subregion (Rachakonda et al., 2015).

Table 11 Summary of allocation data for the bores in the Gloucester subregion

Groundwater-bearing unit	Total number of bores	Licensed water allocation (ML/y)	Number of bores with no allocation record
Alluvium	107	1530	100
Fractured rock	53	334	42
Deep water-bearing	15	0	15
Total	175	1864	157

Data: Bioregional Assessment Programme (Dataset 6)

2.1.3.2 Statistical analysis and interpolation

This section describes the methods for assigning bores to aquifers.

Information on screening depths and stratigraphy is needed to assign bores to specific aquifers. The NSW groundwater database contains no stratigraphic data for groundwater bores in the Gloucester subregion. Following a stratigraphic assessment for the Gloucester subregion in NSW, and after a quality check of the data from the NSW groundwater database, bores were assigned to aquifers by comparing their screen intervals and depth with aquifer boundary data.

The following steps were followed during the aquifer assignment:

1. Assess the boundaries of aquifers as outlined in Section 1.1.4.1.1 of the companion product 1.1 for the Gloucester subregion (McVicar et al., 2014).
2. Determine the screen intervals of bores. The screen information was extracted from the 'Construction and Borehole' tables in the National Groundwater Information System (NGIS) V2 groundwater data archive. The keywords 'OPENING' and 'HOLE' were used to obtain the data for calculating screen intervals. The bore depth information was extracted from the NSW Water Data Transfer Format (WDTF), Hydstra, and the NGIS V2 dataset. For bores without depth information in these databases, the bore depth calculations were based on the construction information.
3. Determine the screen interval of bores for the NSW bores.
4. Filter bores for a specific area using a shape file or coordinates.
5. Cross-check the final datasets against expert knowledge and spatial context of aquifers.

Table 12 summarises the number of bores per aquifer that were extracted from the available datasets and aquifer depth ranges. Bores for which screening depth information was not available have been assigned to an aquifer based on drilled depth as per the aquifer depth ranges in Table 12. Figure 14 shows the distribution of bores and depth class within the Gloucester subregion.

The alluvium and fractured rock aquifer subgroups represent the most extracted aquifer with 107 and 53 associated bores, respectively. There are 55 bores with bore depths less than 1 mBGL; it is likely that these bores were started but not fully completed and hence are not used to currently extract groundwater. The mean of bore depths is about 89 m. Most bores are either screened to the alluvium or the outcrops of underlying bedrock aquifers. Further information about the analysis of distribution of bores and estimated groundwater usage by purpose in the Gloucester subregion is available in Section 1.5.1.2.1 of companion product 1.5 for the Gloucester subregion (Rachakonda et al., 2015).

Table 12 Number of bores with construction information according to aquifer for the Gloucester subregion

Groundwater-bearing unit	Number of bores	Depth range[a] (mBGL)
Alluvium	107	< 15
Fractured Rock	53	15 to 150
Deep water-bearing	15	>150

[a]The depth column presents the depth range of bores associated with a specific aquifer.
Data: Bioregional Assessment Programme (Dataset 7)

2.1.3.3 Gaps

While there are many groundwater bores and a large number of groundwater observation bores in the Gloucester subregion, there are some distinct data and knowledge gaps. The most significant gaps that could potentially influence achieving realistic simulation and modelling based analysis are:

- While areas around the mines have a very good coverage with shallow groundwater observation bores, there is a general lack of groundwater observation bores in other parts of the Gloucester subregion. This lack of data in some areas impacts on the uncertainty of recharge estimation for the alluvial aquifer.
- There is a general lack of deep groundwater observation bores, as most observation bores (and more generally the majority of all groundwater bores) are less than 50 m deep. While there are approximately 175 bores in the Gloucester subregion, most are relatively shallow and located either in alluvium or in fractured rock aquifer. However, as the deep water-bearing units are more than 150 m deep throughout most of the basin, the existing groundwater monitoring network is likely to capture only a small component of the hydrodynamics of the Gloucester subregion. Critical hydraulic information including water level, hydraulic properties and water chemistry of bedrock aquifers is currently missing.
- There is a general lack of nested (multi-level) bore sites throughout the Gloucester subregion. While groundwater dynamics in shallow alluvial aquifers are relatively well understood, there is very limited knowledge on characteristics such as groundwater flow direction or inter-aquifer head gradients throughout much of the bioregion.
- There are significant gaps in the groundwater databases. For example, there is no 'aquifer' layer where the screened interval of bores is assigned to a specific aquifer in the National Groundwater Information System groundwater database (Bioregional Assessment Programme, Dataset 7; NSW Office of Water, Dataset 1). More information about hydraulic properties of key aquifer units needs to be obtained. In particular, information about the deep water-bearing units is required for the numerical model development to assess the impacts associated with coal seam gas development.
- The hydraulic significance of faults is poorly understood due to the lack of nested (multi-level) groundwater monitoring sites. Only limited understanding exists about the role of

faults as potential pathways or barriers for aquifer interconnectivity or groundwater flow to the surface. More work, such as the use of remote sensing to identify faults that penetrate to the surface, may be required in the future.

- The quality of the hydrochemistry data available for this Assessment is difficult to determine, as analytical uncertainties are not reported in the dataset. The dataset includes chemical analyses of differing ages, sometimes decades apart, which will have differing levels of accuracy and precision. Additionally, bore screening interval data are unknown and stratigraphic unit information was not assigned in the database.
- A number of potentially harmful trace elements have not been reported in this product due to scarcity or absence of data. Some elements have data available for only one or two hydrogeologic units, while others have no data available at all.

References

Australasian Groundwater and Environmental (2013) Rocky Hill Coal Project Groundwater Assessment, Part 4 of the Specialist Consultant Studies Compendium. Technical report by Australasian Groundwater and Environmental Pty Ltd for Gloucester Coal Limited. Australasian Groundwater and Environmental Pty Ltd, Sydney. Viewed 10 September 2013, http://www.rockyhillproject.com.au/wp-content/uploads/2013/08/80604-Vol-2_Part-4-Groundwater.pdf.

Bradbury KR and Rothschild ER (1985) A computerised technique for estimating the hydraulic conductivity of aquifers from specific capacity data. Ground Water 23(2), 240–246.

Heritage Computing (2009) Duralie Extension Project Groundwater Assessment. A Hydrogeological Assessment of the Duralie Extension Project Environmental Assessment. Technical report by Heritage Computing Pty Limited for Duralie Coal Pty Ltd. Heritage Computing Pty Limited, Sydney. Viewed 10 September 2013, http://www.gloucestercoal.com.au/documents/Enviro_EAD_DCM_2010_Appendix_B_Groundwater%20Assessment.pdf.

Heritage Computing (2012) A Hydrogeological Assessment in Support of the Stratford Coal Project Environmental Impact Statement. Technical report by Heritage Computing Pty Limited for Stratford Coal Pty Ltd. Heritage Computing Pty Limited, Sydney. Viewed 10 September 2013, http://www.stratfordcoal.com.au/documents/environment/eis/Appendix%20A%20-%20Groundwater%20Assessment.pdf.

McVicar T, Langhi L, Barron OV, Rachakonda PK, Zhang YQ, Dawes WR, Macfarlane C, Holland KL, Wilkes PG, Raisbeck-Brown N, Marvanek SP, Li LT and Van Niel TG (2014) Context statement for the Gloucester subregion. Product 1.1 from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 18 June 2015, http://data.bioregionalassessments.gov.au/product/NSB/GLO/1.1.

Parsons Brinckerhoff (2013) Water Balance for the Gloucester Basin, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. Parsons Brinckerhoff Australia Pty Limited, Sydney. Viewed 6 September 2013, http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Gloucester/Assessments%20and%20Reports/2013/Water%20balance.pdf.

Rachakonda PK, Zhang YQ, Peña-Arancibia JL, Marvanek SP and Viney NR (2015) Current water accounts and water quality for the Gloucester subregion. Product 1.5 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 15 March 2016, http://data.bioregionalassessments.gov.au/product/NSB/GLO/1.5.

SRK (2010) Gloucester Basin Stage 1: Gas Field Development Project. Preliminary Groundwater Assessment and Initial Conceptual Hydrogeological Model. Technical report by SRK Consulting (Australasia) Pty Ltd for AGL Upstream Investments Pty Ltd. West Perth. Viewed 12 August 2013, http://agk.com.au/gloucester/assets/pdf/SRK%20Preliminary%20Groundwater%20Assessment%20-%20Desk%20study.pdf.

Datasets

Dataset 1 NSW Office of Water (2014) NSW Office of Water - National Groundwater Information System 20140701. Bioregional Assessment Source Dataset. Viewed 03 September 2015, http://data.bioregionalassessments.gov.au/dataset/7ab9820e-1e43-4600-8875-a0834345fb6d.

Dataset 2 Bureau of Meteorology (2013) NSW allocation of aquifer for screened unit of monitoring bores. Bioregional Assessment Source Dataset. Viewed 03 September 2015, http://data.bioregionalassessments.gov.au/dataset/2d5ffd17-f7cc-4b5f-bf77-bcdaf0c8ca53.

Dataset 3 NSW Office of Water (2013) HYDMEAS - Hydstra Groundwater Measurement Update_NoW_Nov2013. Bioregional Assessment Source Dataset. Viewed 03 September 2015, http://data.bioregionalassessments.gov.au/dataset/08b34518-c947-4665-82e5-c144b5b24e01.

Dataset 4 Geoscience Australia (2014) State Transmissivity Estimates for Hydrogeology Cross-Cutting Project. Bioregional Assessment Derived Dataset. Viewed 03 September 2015, http://data.bioregionalassessments.gov.au/dataset/db6643ff-f4ec-4aa3-9f5d-afdce1bce5b1.

Dataset 5 NSW Office of Water (2015) NSW Office of Water Groundwater Quality extract 28_nov_2013. Bioregional Assessment Derived Dataset. Viewed 11 June 2015, http://data.bioregionalassessments.gov.au/dataset/74da836a-7b97-4278-9034-c9a259a34fbb.

Dataset 6 Bioregional Assessment Programme (2015) Gloucester Groundwater Usage Estimates v20150501. Bioregional Assessment Derived Dataset. Viewed 11 June 2015, http://data.bioregionalassessments.gov.au/dataset/fe43baa5-0fca-4e6a-8d56-0f5749c2da58.

Dataset 7 Bioregional Assessment Programme (2013) Gloucester NGIS bores. Bioregional Assessment Derived Dataset. Viewed 11 June 2015, http://data.bioregionalassessments.gov.au/dataset/e14ca3f6-6a49-4bd2-95b9-3fef6420bf49.

2.1.4 Surface water hydrology and water quality

Summary

The Gloucester subregion contains six streamflow gauges where daily streamflow data were processed into unified six-class quality codes. The amount of missing data for each gauge was less than 4%.

The Gloucester subregion has six streamflow gauges. The source of streamflow data, site details and duration and quality of the gauged records are summarised in Section 2.1.4.1 about observed data.

Analysis of the streamflow records is reported in the contextual information reported in the companion product 1.1 for the Gloucester subregion (McVicar et al., 2014, Section 1.1.5.3). The analyses include annual and monthly flow characteristics based on the total available flow record for each gauging station at 18 August 2013. A baseflow index was calculated for each streamflow record using the Lyne and Hollick (1979) one-parameter filtering separation equation:

$$Q_b = \alpha Q_{b(i-1)} + \frac{1-\alpha}{2}\left(Q_{t(i)} + Q_{t(i-1)}\right) \quad (2)$$

where Q_t is the total daily flow, Q_b is the baseflow, i is the time step (day) number and α is a coefficient, usually taken to have a value of 0.925 (Aksoy et al., 2009; Gonzales et al., 2009).

No additional analyses have been undertaken. The streamflow data are used in the calibration of the surface water model reported in the companion product 2.6.1 for the Gloucester subregion (Zhang et al., 2018).

2.1.4.1 Observed data

Daily streamflow data were obtained from NSW Office of Water. There are six streamflow gauges in the Gloucester subregion, details of which are summarised in Table 13. Gauges 209002 and 209003 are located in the southern part of the subregion; the other four are located in the northern part of the subregion. Three of the northern gauges (208020, 208028, and 208031) have less than 11 years of observation length. The rest have more than 40 years of observation length. All gauges show strong seasonal and inter-annual variability in streamflow (see Figures 28 to 31 in the companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)).

Table 13 Gauge information for streamflow data for the Gloucester subregion

Gauge ID	Gauge name	Catchment area (km²)	Latitude	Longitude	Gauge opened	Gauge closed
208020	Gloucester River at Gloucester	253	–32.0031°	151.9589°	05 Apr 2003	No
208028	Avon River at Waukivory Creek	225	–32.0425°	151.9679°	08 Sep 2004	No
208031	Barrington River at Relfs Road	711	–31.9779°	151.9514°	03 Sep 2010	No
208003	Gloucester River at Boon Arye	1631	–31.8981°	152.0956°	01 Jun 1945	No
209002	Mammy Johnson River at Crossing	158	–32.2437°	151.9789°	19 Dec 1967	No
209003	Karuah at Booral	974	–32.4781°	151.9571°	27 Oct 1968	No

Data: Bureau of Meteorology (Dataset 1)

These daily streamflow time series are aggregated from instantaneous observations. Thus the quality of streamflow record depends on the quality of rating curves that were used to establish relationships between streamflow and stage.

Using the numerical quality codes that are part of the streamflow data records, the daily streamflow data were processed into unified six-class quality codes for each gauge (Zhang et al., 2013) (Table 14). The six unified quality 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 kept while the flow data flagged as non-conforming were excluded. The non-conforming and missing streamflow data are both labelled in the data set as –9999.

Table 14 Quality codes for the NSW gauges for the Gloucester subregion

Numerical 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: Bureau of Meteorology (Dataset 1)

Table 15 summarises the percentage of each quality code for each streamflow gauge. No streamflow gauges have non-conforming data. Most of the data falls into the categories of 'good', 'fair' and 'unverified'. The amount of missing data for all catchments accounts for less than 4%.

Table 15 Percentage of water quality category accounting for the Gloucester subregion

Gauge ID	Good (%)	Fair (%)	Poor (%)	Unverified (%)	Non-conforming (%)	Missing (%)
208020	25.1%	5.6%	5.0%	64.3%	0.0%	0.0%
208028	49.4%	50.6%	0.0%	0.0%	0.0%	0.0%
208031	0.0%	98.6%	0.0%	0.0%	0.0%	1.4%
208003	6.8%	13.4%	1.9%	75.1%	0.0%	2.8%
209002	9.2%	35.0%	10.9%	41.7%	0.0%	3.3%
209003	28.5%	16.5%	12.4%	40.4%	0.0%	2.2%

Data: Bureau of Meteorology (Dataset 1)

There is no long-term water quality monitoring programme in the Gloucester river basin. Most of water quality observations have been conducted on the Avon River and Mammy Johnsons River, reported in Section 1.5.2.1 of companion product 1.5 for the Gloucester subregion (Rachakonda et al., 2015).

2.1.4.2 Statistical analysis and interpolation

No further analyses have been undertaken other than what are reported in the context statement (companion product 1.1) for the Gloucester subregion (McVicar et al., 2014). The streamflow data are used in the calibration of surface water model reported in the companion product 2.6.1 for the Gloucester subregion (Zhang et al., 2018).

2.1.4.3 Gaps

The stream gauges have relatively few missing records, particularly the newer northern gauges. The period of record is relatively short for three of the gauges, which means they may not represent well the hydrological variability of the Gloucester river basin. Having one reliable older gauge in the northern subregion helps to address the relative short time period of the other gauged data. There is a lack of long-term consistent monitoring of electrical conductivity (EC) and pH for the Gloucester river basin. As a result, the capacity to fully understand what baseline water quality should be for this area is limited.

References

Aksoy H, Kurt I and Eris E (2009) Filtered smoothed minima baseflow separation method. Journal of Hydrology 372(1–4), 94–101. DOI: 10.1016/j.jhydrol.2009.03.037.

Gonzales AL, Nonner J, Heijkers J and Uhlenbrook S (2009) Comparison of different base flow separation methods in a lowland catchment. Hydrology and Earth System Sciences 13(11), 2055–2068.

Lyne V and Hollick M (1979) Stochastic time variable rainfall-runoff modelling. Proceedings of the Hydrology and Water Resources Symposium, Perth, 10–12 September. Institution of Engineers National Conference Publication, No. 79/10, 89–92.

McVicar T, Langhi L, Barron OV, Rachakonda PK, Zhang YQ, Dawes WR, Macfarlane C, Holland KL, Wilkes PG, Raisbeck-Brown N, Marvanek SP, Li LT and Van Niel TG (2014) Context statement for the Gloucester subregion. Product 1.1 from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 18 June 2015, http://data.bioregionalassessments.gov.au/product/NSB/GLO/1.1.

Rachakonda PK, Zhang YQ, Peña-Arancibia JL, Marvanek SP and Viney NR (2015) Current water accounts and water quality for the Gloucester subregion. Product 1.5 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 27 April 2016, http://data.bioregionalassessments.gov.au/product/NSB/GLO/1.5.

Zhang YQ, Viney N, Frost A, Oke A, Brooks M, Chen Y and Campbell N (2013) Collation of Australian modeller's streamflow dataset for 780 unregulated Australian catchments. CSIRO: Water for a Healthy Country National Research Flagship.

Zhang YQ, Viney NR, Peeters LJM, Wang B, Yang A, Li LT, McVicar TR, Marvanek SP, Rachakonda PK, Shi XG, Pagendam DE and Singh RM (2018) Surface water numerical modelling for the Gloucester subregion. Product 2.6.1 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/NSB/GLO/2.6.1.

Datasets

Dataset 1 NSW Office of Water (2013) Gloucester Surface Water Discharge & Quality extract v1 060314. Bioregional Assessment Source Dataset. Viewed 21 October 2015, http://data.bioregionalassessments.gov.au/dataset/5915baad-51c9-4637-9461-88e88426a981.

2.1.5 Surface water – groundwater interactions

Summary

There are no direct measurements of surface water – groundwater interactions in the Gloucester subregion. Estimates are made using observed stream and aquifer water levels and quality.

The direction of exchange is implied by comparing local groundwater levels to stream stage. The relative exchange between surface water and local groundwater is inferred from geochemistry data, principally stream and aquifer water salinity. A degree of validation is provided through groundwater modelling by Parsons Brinckerhoff (2013b). Using a simplified five-layer groundwater model, they provide long-term mean groundwater flow between near-surface layers, particularly between the alluvial aquifer carrying rivers and streams and the shallow weathered rock layer. These pieces of evidence indicate that streams are net gaining.

Using ratios of electrical conductivity, the baseflow contribution is estimated to be 3.0 to 4.5% in the Gloucester River, and 13 to 14% in the Avon River.

There are no direct observations or measurements of interactions between water in the river network and underlying aquifers in the Gloucester subregion. An assessment of the magnitude and direction of surface water – groundwater interactions can be made based on groundwater level measurements and the chemistry of stream and aquifer water. Details of these data are provided in Section 2.1.5.1 about observed data.

No statistical analyses have been undertaken as part of the bioregional assessment (BA) of the Gloucester subregion. Interpretation of the available data and analyses undertaken by Parsons Brinckerhoff (2013a, 2013b) are used to determine whether streams are gaining or losing, and the contribution from groundwater to stream flow (i.e. baseflow). This is reported in Section 2.1.5.2 about statistical analysis and interpretation.

2.1.5.1 Observed data

2.1.5.1.1 Stream stage and groundwater levels

Stream stage comparisons to local groundwater levels are presented in consultant reports of the water balance and conceptual groundwater model of the Gloucester subregion (Parsons Brinckerhoff, 2013a, 2013b; AGL, Dataset 2), and the data is reproduced with permission in Figure 15. These data show that bores between 4 and 662 m distant from the gauge are consistently above the measured river stage. At times in 2013 and 2014 when the gauge is at cease-to-flow levels, the bores retain a water level above this value. There is a consistent gradient shown where the most distant bore has the highest water elevation, and slopes toward the stream gauge level as closer bores have levels more similar to the stream stage. This is a necessary condition for a gaining stream.

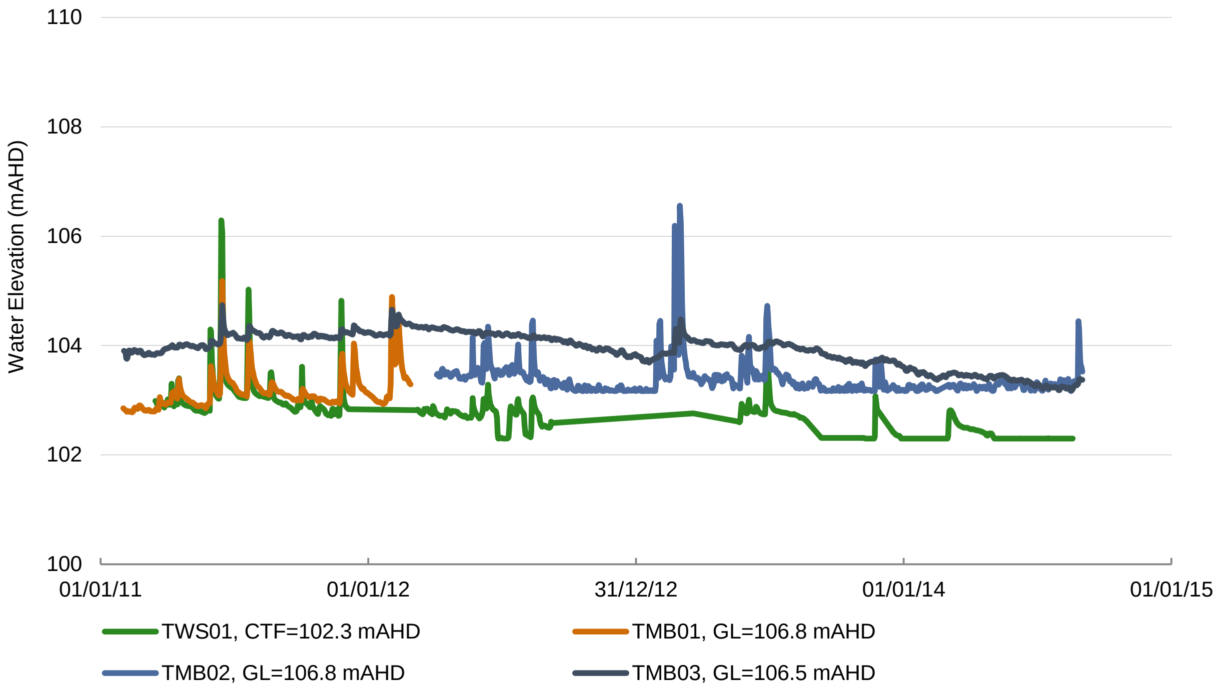


Figure 15 Stream stage (TWS01) and bore hydrograph records (TMB01, TMB02 and TMB03) for Avon River gauging site in the Gloucester subregion

CTF indicates the cease to flow point for the gauge, and GL indicates the ground elevation of each bore
Bore distances are: TMB01 4 m, TMB02 328 m, and TMB03 662 m from gauge

Data for single gauges and observation bores are presented in Figure 16. These are on tributary streams of the Avon River and show the same features as each other, and provide further support for the hypothesis that the Avon River is a net gaining system.

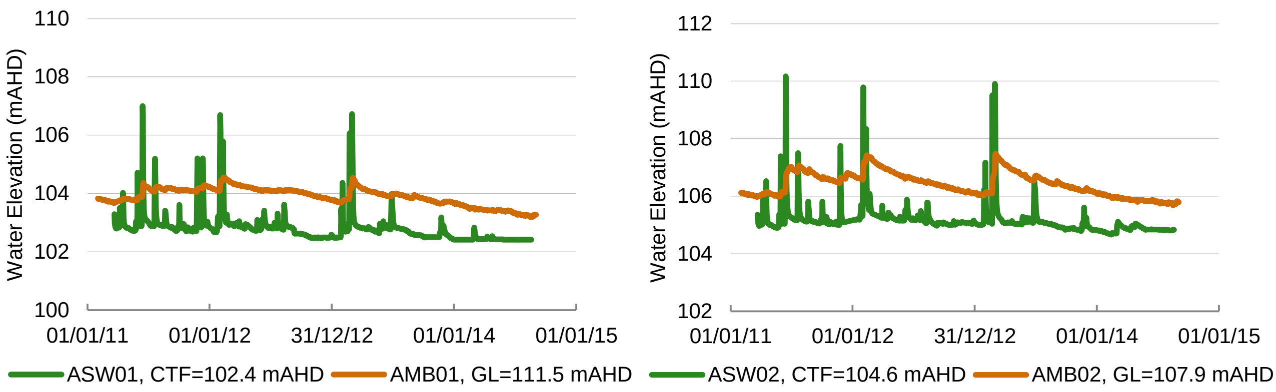


Figure 16 Stream stage and nearby bore hydrograph records for Avon River gauging sites ASW01 and ASW02 for the Gloucester subregion

CTF indicates the cease to flow point for the gauge, and GL indicates the ground elevation of each bore
Bore distances are 455 m from AMB01 to ASW01, and 18 m from AMB02 to ASW02

2.1.5.1.2 Water quality data

Flow and water quality data for the monitored streams of the Gloucester subregion were supplied by NSW Office of Water (Dataset 1). The water quality data from the NSW Office of Water consists of a series of samples taken at irregular intervals, and analysed for major anions and cations, salinity, turbidity, etc. Table 16 shows the first and last sample dates, along with the total number of electrical conductivity (EC) records over that period for Gloucester gauges.

Table 16 Temporal range and number of stream water electrical conductivity records for gauges in the Gloucester subregion

Gauge name	Gauge ID	Start date	End date	Salinity samples
Avon River at Wenhams Cox	2080019	11 Nov 1994	12 Nov 1997	33
Avon River at Gloucester	2080017	11 Nov 1994	16 Sep 1997	19
Gloucester River at Gloucester	208020	09 Mar 1999	03 Jul 2007	72
Gloucester River at Doon Ayre	208003	02 Jun 1971	06 Jun 1990	115

There is no description of the sampling strategy, storage or analysis methods included with the quality data. The simplest parameters such as EC, pH, and temperature can be made in the field, while those more complex such as specific ion concentrations will be laboratory based. The accuracy of each measurement is related to the specific techniques and instruments used in the field or laboratory to derive them, and is unknown at this time.

As part of a water monitoring investigation, Parsons Brinckerhoff (2012) analysed the water chemistry of the alluvial aquifer, shallow weathered rocks, coal seams and interburden layers. They concluded that:

> Alluvial aquifer water quality is fresh to brackish, sodium-chloride dominant, with minor dissolved metals, minor detection of naturally occurring TPH, and no detection of dissolved methane or BTEX compounds.
>
> Shallow rock water quality is brackish, sodium-chloride-bicarbonate dominant, with minor dissolved metals, low to moderate dissolved methane concentrations, and minor detections of naturally occurring TPH and toluene at a few sites.

Note that in this quote, 'TPH' is an acronym for 'total petroleum hydrocarbons' and 'BTEX' represents 'benzene, toluene, ethylbenzene and xylene'.

The water in the two aquifers appears to be similar, except that the shallow rock aquifer is more saline. This supports the hypothesis of discharge to the alluvial aquifer making it more saline, and then this water is mixed with rainfall recharge and discharged to the stream.

2.1.5.2 Statistical analysis and interpretation

The only statistic derived from the water quality data was the mean EC, both equally and flow weighted, to be compared to values from aquifer sampling. There is a large difference in the measured total dissolved solids (TDS) of water in the alluvial aquifer and stream, up to a factor of 20, and so discrimination with salinity data is likely to be robust. The two sampling sets for the Gloucester River, at Gloucester (gauge 208020) and Doon Ayre (gauge 208003), have the longest records of the four gauges and the most EC readings. The values in each of the records are consistent and the flow weighted-mean differs from the arithmetic mean EC by less than 2%, so the simpler arithmetic mean stream value was used.

Assuming all sources of a conservative tracer (such as salinity) can be discriminated, the proportion of each source can be determined in the resulting mix. Parsons Brinckerhoff (2013a) provides mean values of water quality parameters, including EC, for a sample of bores in alluvial aquifers in the Gloucester valley. We can assume that all EC is a result of salt derived from baseflow from the alluvial aquifer if (i) salt delivered in rainfall is a very small component, (ii) that salt wash off in runoff is a very small component and (iii) that EC in the alluvial aquifer is greater than in the stream. Under these conditions the ratio of EC of water in the stream to alluvial aquifer gives an upper estimate of the fraction of baseflow in the stream.

Based on EC ratios, the upper estimate for baseflow contribution to the stream for the Gloucester River at Gloucester (gauge 208020) is 3.0% and for the larger subcatchment Gloucester River at Doon Ayre (gauge 208003) is 4.5%. The estimate with far fewer data points for the Avon River at Wenhams Cox is 13.1% and for the Avon River at Gloucester is 13.9%. Using a baseflow separation technique based on recorded daily and monthly stream flows, Parsons Brinckerhoff (2014) suggests that the baseflow for the Avon River at Waukivory Creek is 6% of total flow, and baseflow in the Gloucester River of 29% at Gloucester and 28% at Doon Ayre.

Given that the alluvial aquifer is saline, and about half of the salinity of the underlying rock aquifer is ten times more saline than the stream, it is unlikely that the baseflow component is large. The estimates based solely on daily or monthly flow values take no account of the physical state of the aquifers, their physical properties or their chemical composition. These estimates are uniformly the largest, suggesting baseflow proportions of up to 29%. The physical estimates based on salinity alone provide an upper estimate with a two-component mixing model, and provide uniformly low estimates of baseflow, typically less than 5% where the longest time series of data are available. These provide values that are consistent with diffuse recharge estimates from modelling studies and are representative of the physical observations.

2.1.5.3 Gaps

The major gaps in the datasets are:

- spatial extent of bore sampling is not sufficient to adequately estimate either mean, or spatially variable, alluvial aquifer EC
- river water sampling at gauges do not provide overlapping records
- river water sampling at gauges is not generally available for contemporary time, for example in the last decade.

References

Parsons Brinckerhoff (2012) Phase 2 Groundwater Investigations – Stage 1 Gas Field Development Area, Gloucester Gas Project, Report PR_5630 for AGL Upstream Investments Pty Ltd, Sydney.

Parsons Brinckerhoff (2013a) Hydrogeological conceptual model of the Gloucester Basin. Report PR_7266 for AGL Upstream Investments Pty Ltd, Sydney.

Parsons Brinckerhoff (2013b) Water balance for the Gloucester Basin. Report PR_7296 for AGL Upstream Investments Pty Ltd, Sydney.

Parsons Brinckerhoff (2014) Gloucester Gas Project Hydrology Study. Report PR_7563 for AGL Upstream Investments Pty Ltd, Sydney.

Datasets

Dataset 1 NSW Office of Water (2013) Gloucester Surface Water Discharge & Quality extract v1 060314. Bioregional Assessments Source Dataset. Viewed March 2015, http://data.bioregionalassessments.gov.au/dataset/5915baad-51c9-4637-9461-88e88426a981.

Dataset 2 AGL (2014) Gloucester Surface Water Monitoring Data – 20141008. Bioregional Assessments Source Dataset. Viewed November 2015, http://data.bioregionalassessments.gov.au/dataset/1cc056a4-12ab-4ce8-9050-60cd6883dd5b.

2.1.6 Water management for coal resource developments

Summary

Water management information about the two existing coal mines with expansion plans, one proposed coal mine and one natural coal seam gas (CSG) project currently under development within the Gloucester subregion are summarised in this section.

In the Gloucester subregion there are two existing coal mines with expansion plans (Duralie Coal Mine and Stratford Mining Complex), one proposed coal mine (Rocky Hill, currently on hold as of 15 June 2015) and one natural CSG project (AGL Gloucester Gas Project, under development).

2.1.6.1 Duralie Coal Mine

The information summarised in this section was obtained from *Duralie Coal Mine Water Management Plan* (Duralie Coal, 2013) and Heritage Computing (2009). Duralie Coal Mine (DCM) water management is designed and operated to control water generated from surface development areas via on-site water storage. The other objective of the DCM Water Management Plan is to prevent overflow of dirty water generated within the mine workings, waste rock emplacements, water storage areas and runoff from areas where coal is handled, to the neighbouring water sources of Coal Shaft Creek or Mammy Johnsons River.

The water management system includes a combination of permanent structures that will continue to operate post closure and temporary structures that will only be required until the completion of rehabilitation works. The principal water storage areas are (Figure 17):

- Main Water Dam (MWD), located north-west of the main infrastructure area and has a constructed capacity of up to approximately 1405 ML
- Auxiliary Dam No. 1 (AD1), located upslope of the MWD and has a constructed capacity of 462 ML (with an approved capacity up to 500 ML)
- Auxiliary Dam No. 2 (AD2), located upslope of the MWD (on a different drainage line to AD1) and has a constructed capacity of 2724 ML (with an approved capacity up to 2900 ML)
- Sediment Dams – Waste Rock Emplacement (VC1), Rail Siding (RS1 & RS6)
- a smaller bunded area located in the south of the MWD, adjacent to the main infrastructure area.

MWD and AD1 are the principal on-site permanent mine water storage areas. Water from these dams comprises pit produced water (runoff/rainfall/seepage), water from specific sediment dams and surface water runoff from the Duralie industrial area (that includes the Leighton workshops and general storage). Once mining in the Weismantel Extension open pit is completed (scheduled for end of March 2013 (Heritage Computing, 2009)), the remaining void will be used as a water storage, with water preferentially pumped to it from the Clareval North West open pit in preference to the other storages, until it is filled to within 100 ML of capacity. As of 30 June 2015, progressive backfilling with waste rock is occurring and water is allowed to accumulate in the Weismantel open pit (Yancoal, 2015a). The storage capacity of the Weismantel Extension open pit has been estimated at approximately 1900 ML (excluding the 100 ML freeboard below the spill level to the active Clareval North West open pit).

The DCM has approval to construct Auxiliary Dam No. 3 to an approved capacity of 110 ML, however, construction of Auxiliary Dam No. 3 is not planned as a component of the current DCM water management system.

The stored dirty water is used on site for irrigation and dust mitigation. A mixture of pasture, woodland and cropping would be irrigated within the irrigation areas (Figure 18). Surface runoff from mine waste rock emplacements (prior to rehabilitation) would be intercepted and diverted to containment storages for reuse in the water management system. At the end of mining in 2019 (Heritage Computing, 2009), Coal Shaft Creek will be re-established. On average, DCM operates in surplus yielding more water from the mine and mine infrastructure catchments than needed for the mining and processing operations and continues disposal of excess water through irrigation.

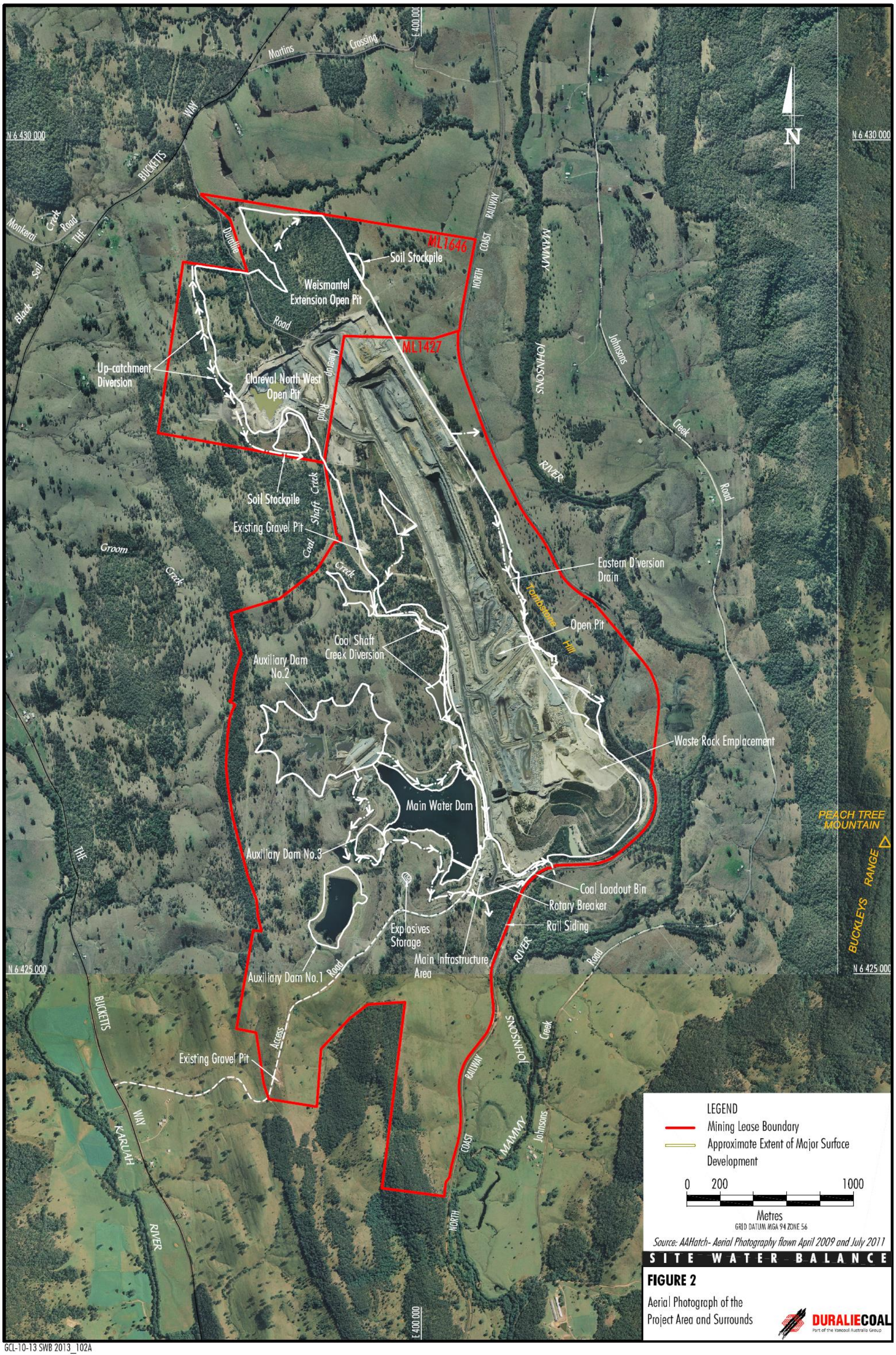


Figure 17 Water storage areas in Duralie Coal Mine in the Gloucester subregion

Source: Duralie Coal (2013). This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of Yancoal Australia.

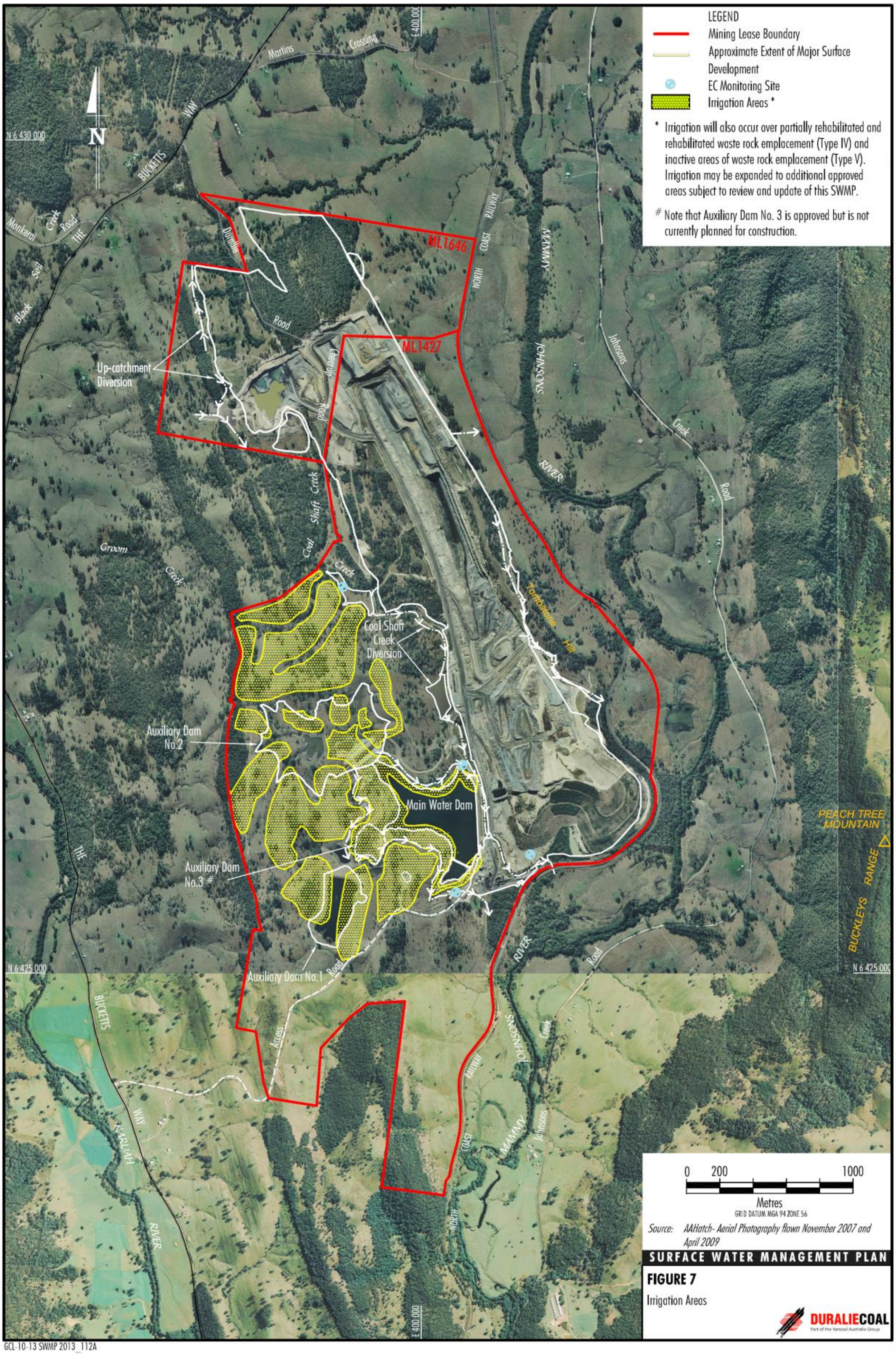


Figure 18 Location of Duralie Coal Mine irrigation areas in the Gloucester subregion

Source: Duralie Coal (2013). This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of Yancoal Australia.

2.1.6.2 Stratford Mining Complex

The information summarised in this section was obtained from *Stratford Coal Mine Water Management Plan* (Gloucester Basin, 2012) and Heritage Computing (2012). Stratford Coal Mine (SCM) water management is designed and operated to achieve no overflow from the main water storage areas (listed below) to the downstream watercourses including Avondale Creek, Dog Trap Creek and the Avon River. The main SCM water storage areas are (Figure 19):

- Stratford East Dam (2,850 ML storage capacity)
- Stratford Main Pit (37,000 ML storage capacity)
- Return Water Dam (500 ML storage capacity)
- Parkers/Bowens Road West Pit.

Once mining operations are completed in the Bowen Road North Open Cut (BRNOC) (scheduled for end in 2014 (Heritage Computing, 2012)) and Avon North Open Cut (as of June 2015 this is currently estimated to be 2018 (Heritage Computing, 2012)), the voids would also be used as contained water storage areas. As of 30 June 2015, mining in the BRNOC has ceased and no activities have commenced in the Avon North Pit, part of the Stratford Extension Project (Yancoal, 2015b). The average inflows to the open-cuts (combined) over the life of the project are predicted to be about 401.5 ML/year, with the majority (approximately 98.5%) derived from the fractured rock groundwater system (Heritage Computing, 2012). SCM currently holds sufficient licence allocation under NSW's *Water Act, 1912* for the dewatering activities (i.e. groundwater inflows) associated with the fractured rock groundwater system.

Run-of-mine (ROM) coal from the DCM is transported by rail to the SCM, where it is processed along with ROM coal from the SCM and BRNOC. The majority of water used on site is for the coal handling and preparation plant (CHPP) and for dust suppression. On average the site has operated in surplus with yielding more water on average from the mine and mine infrastructure catchments than has been needed in supply for the mining and processing operations. This excess has been managed by containment in the Stratford East Dam, storage in Stratford Main Pit and historically controlled release to Avondale Creek under Environment Protection Licence No. 5161. Since the commissioning of reject disposal in the Stratford Main Pit in 2003, the Stratford Main Pit has been used for storage of excess water and the transfer of mine water to Stratford East Dam has ceased as have controlled releases of water to Avondale Creek. Stratford East Dam remains as a contingency storage for mine water in the future.

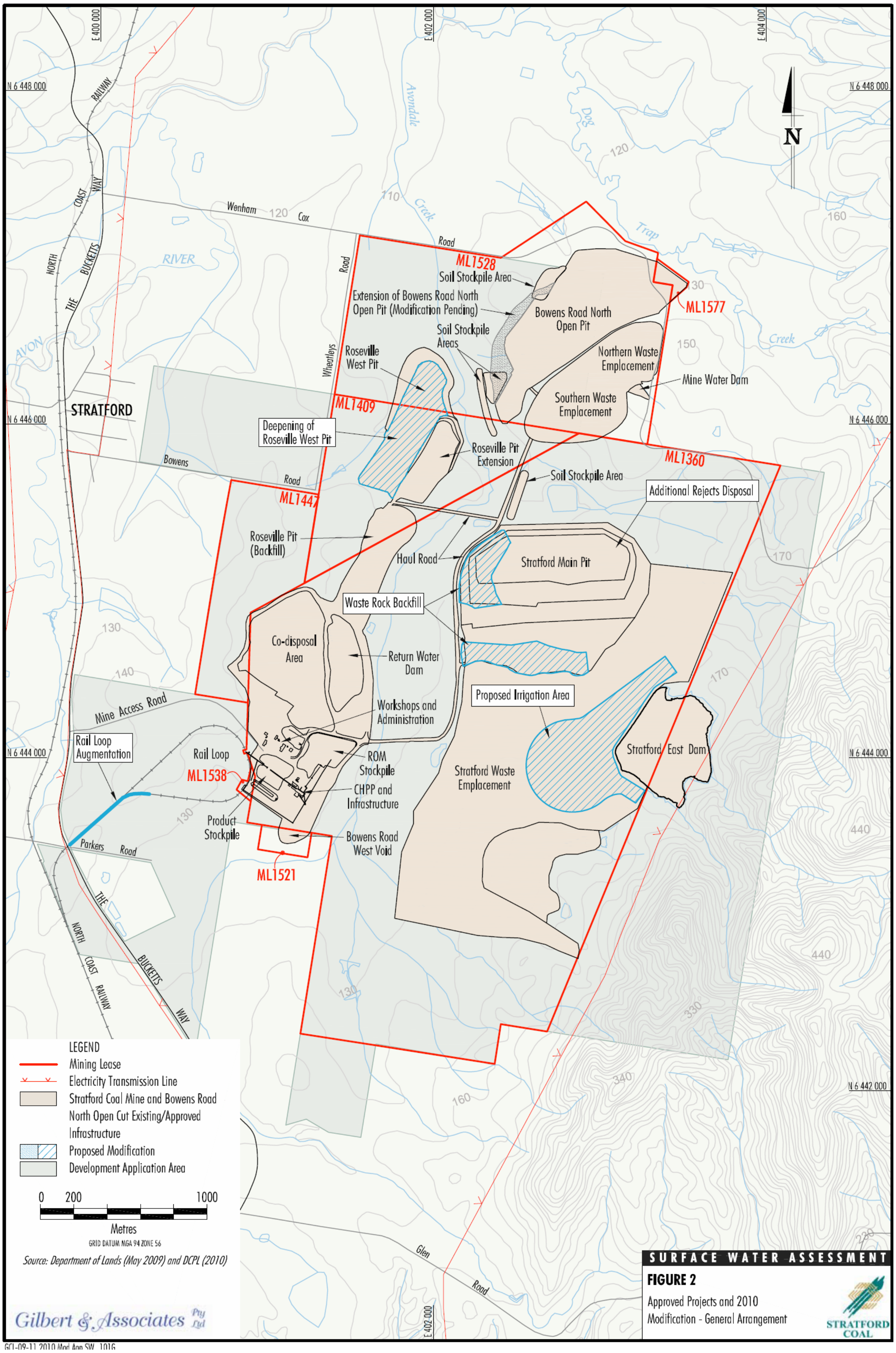


Figure 19 Location of storage and irrigation areas at Stratford Mining Complex in the Gloucester subregion

Source: Gloucester Basin (2012). This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of Yancoal Australia.

Build up of excess water in the storages is avoided by maintaining an adequate freeboard (i.e. free space above the water level to the top of the pit) against rainfall-runoff from its catchment. Irrigation of water from the Stratford East Dam over approximately 23 hectares of a rehabilitated portion of the Stratford Waste Emplacement area will occur to reduce stored water on site and to assist the current pasture cropping programme on the rehabilitated emplacement.

2.1.6.3 Rocky Hill Coal Project

As of June 2015, NSW Department of Planning and Environment placed the Rocky Hill Coal Project on hold. The information summarised in this section was obtained from the Rocky Hill Coal Project environmental impact statement (R.W.Corkery & Co. Pty Ltd, 2012a, 2012b) and the *Rocky Hill Coal Project Groundwater Assessment* (Australasian Groundwater and Environmental Pty Ltd, 2013). As of June 2015, no water management plan document exists for the Rocky Hill Coal Project. The Project plans to manage the water in contact with the disturbed area in the on-site storage areas with no outflow. Water for the mine operations would be obtained from the following sources listed preferentially in order of use (with appropriate licences in place, where required):

- groundwater and surface water accumulating within the various open-cut pits throughout the 21-year life of the proposal
- surface water drawn from on-site environmental or sediment dams
- extract water from Waukivory Creek and/or the Avon River within the limitation of the Applicant's current entitlement to extract groundwater from alluvium under water access licences of 267 ML/year or purchased licences.

Prior to Year 8 of mining and following periods of high rainfall, any water accumulating in the open-cut pits would be pumped to either or all of the Environmental dams 1, 2 and 3 (EDI, ED2 and ED3) positioned immediately east of the western and northern visibility barrier (Figure 20). The capacities of ED1, ED2 and ED3 would vary throughout their operational lives to accommodate the changing layout within the mine area. ED1, ED2 and ED3 would have capacities of approximately 50 to 300 ML, 800 ML and 1200 ML respectively. Post Year 8, excess saline water from the main pit would be pumped to defined soakage areas within the Weismantel and Avon pits where the water would be stored in the pore space within the backfilled pits. The Rocky Hill Coal Project is also planning to construct a soaking pit with a depth of 5 m to store water temporarily and to pump water into the backfilled former open-cut void. The upper water levels in any soaking area would be set at approximately 2 m below the final landform surface. It is predicted that the total inflow to the four open-cut voids will be on average 640 ML/year with a peak inflow of 1250 ML/year in Year 4 of mining.

At maximum production of coal, the Rocky Hill Coal Project estimates the on-site water usage for operational purposes would be as follows:

- CHPP – up to 400 ML/year
- dust suppression (roads, stockpiles, crushing station, coal transfer points, etc.) – 350 ML/year
- offices and amenities area and workshops – 6 ML/year (i.e. 0.04 ML per person/year).

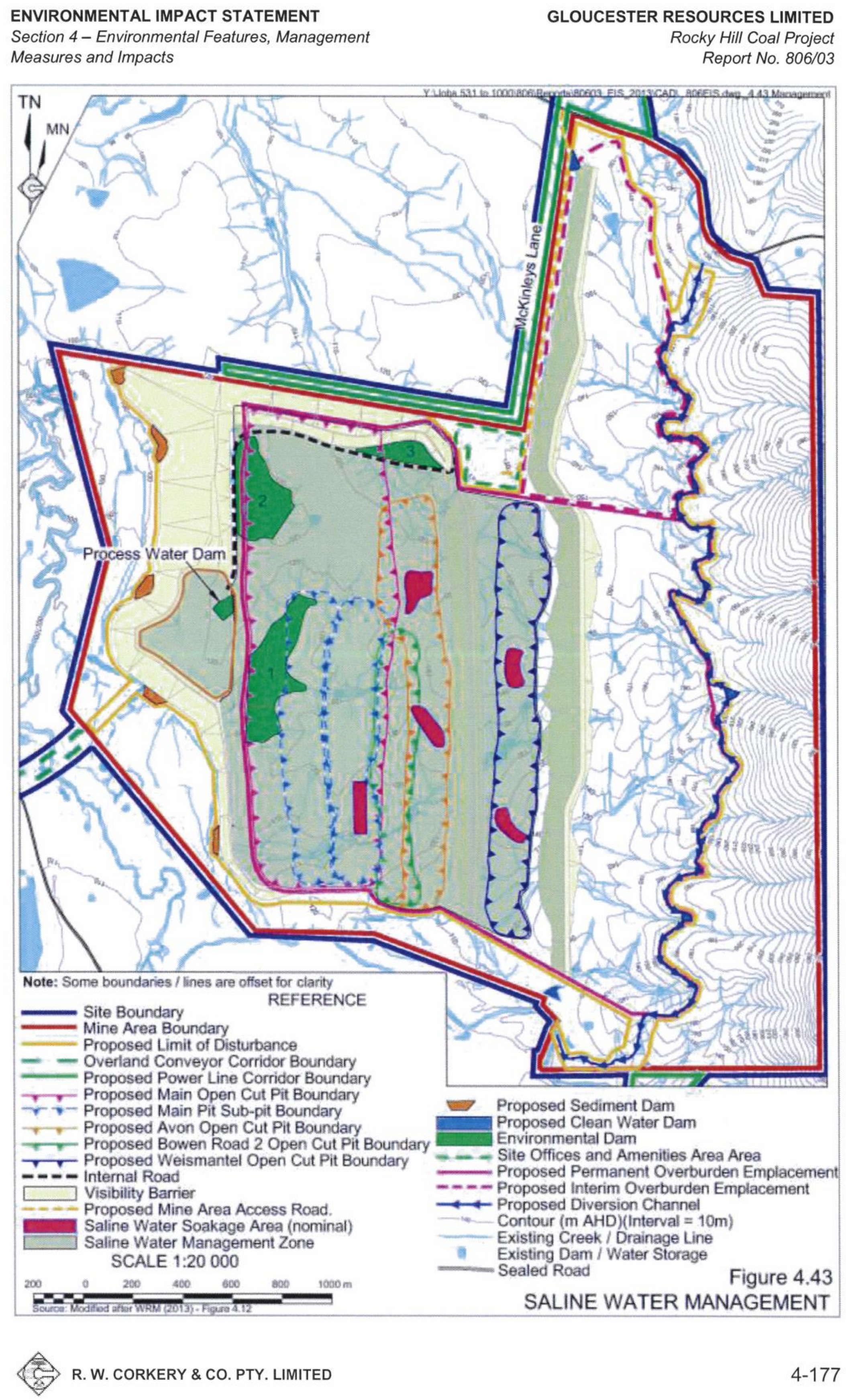


Figure 20 Saline water management for Rocky Hill Coal Project in the Gloucester subregion

Source: R.W.Corkery & Co. Pty Ltd (2012b). © Gloucester Resources Ltd 2013 (Australian Copyright)

The water balance estimations for the proposal (WRM Water & Environment Pty Ltd, 2013) has established that the water requirements for both the CHPP and dust suppression could be satisfied through the use of the saline water and/or surface water accumulating in the open-cut pits. The water balance has established there would be excess quantities of saline water from time to time throughout the proposed 21-year life of the project, some of which could be used to reduce dust lift-off from the active overburden emplacements.

2.1.6.4 AGL Gloucester Gas Project

The information in this section was obtained from various water management plans produced by AGL Energy Limited (AGL; AGL Energy Limited, 2012, 2014b, 2014c, 2015), produced water factsheets (AGL Energy Limited, 2014a) and AGL's review of environmental factors for the Waukivory Pilot Project (AGL Upstream Investments Pty Limited, 2014).

During the fracture stimulation of a CSG well, the volume of water required for fracture treatment is estimated to be between 0.9 and 2.4 ML per well and 100% of flowback water and 0.5 L/s per well of produced water are estimated to be generated. Produced water volumes per CSG well are expected to be maximum at the commencement of fracturing/testing but to quickly diminish to much lower volumes (typically an order of magnitude lower, Figure 21) (AGL Energy Limited, 2014b, 2015). As part of the Gloucester Gas Project, AGL is planning to treat produced water using reverse osmosis, a desalination technology to reduce the amount of salt in the produced water and to be used for irrigation or returned to the environment (AGL Energy Limited, 2014a). AGL is planning to store the water in dams on Tiedmans Property (Figure 22) or in on-site storage tanks.

AGL Upstream Investments Pty Limited (AGL) has the following water management plans for the Gloucester Gas Project area:

- *Water management plan for the Tiedman Irrigation Program – Gloucester* (AGL Energy Limited, 2012)
- *Produced water management plan for PEL 285* (PWMP) (AGL Energy Limited, 2014b)
- *Gloucester Gas Project extracted water management strategy* (EWMS) (Final Draft) (AGL Energy Limited, 2015)
- *Fracture stimulation management plan Waukivory Pilot Project* (AGL Upstream Investments Pty Limited, 2014).

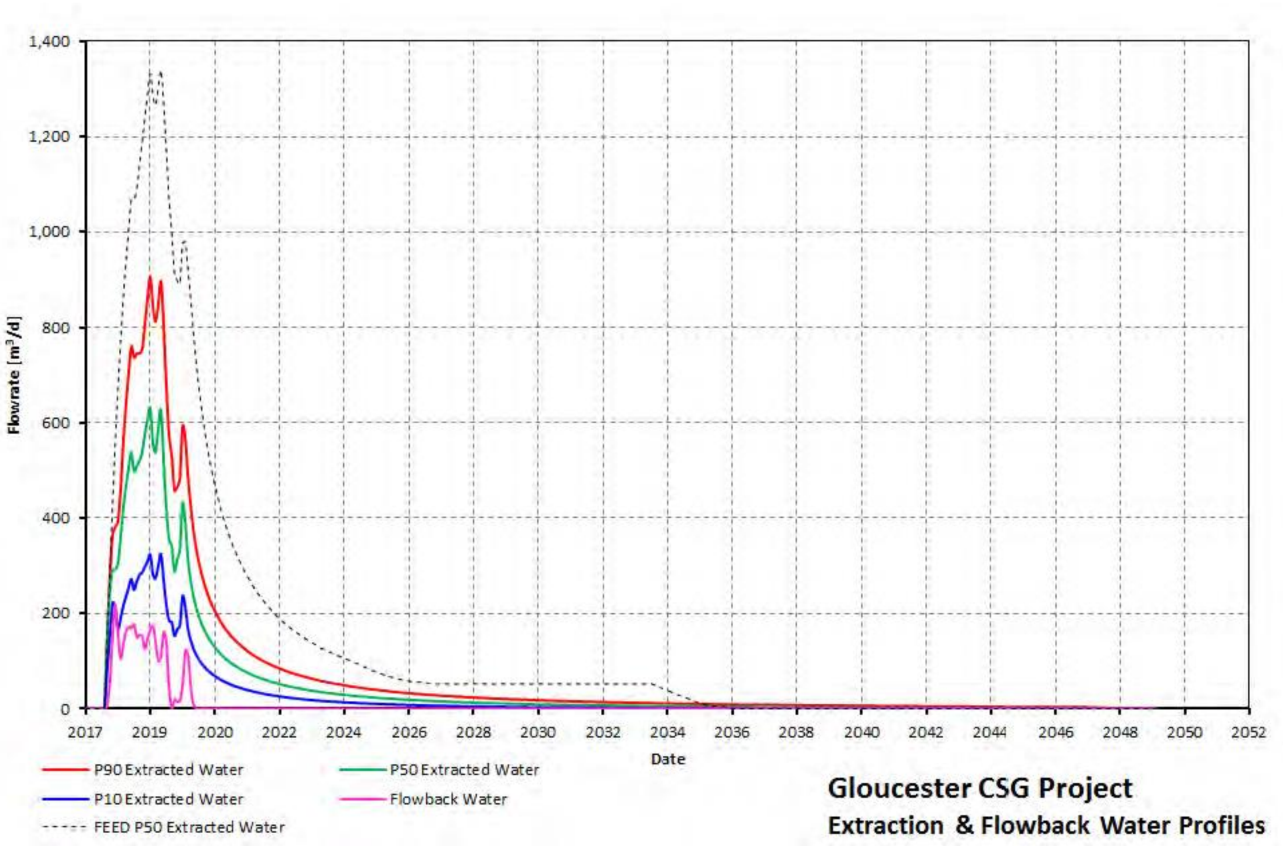


Figure 21 Predicted extracted water flow profile over life of Gloucester gas project

Source: AGL Energy Limited (2015). This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of AGL Energy Limited.

2.1.6.4.1 Water management plan for Tiedman Irrigation

The irrigation areas are located on Tiedmans Property at Stratford about 9 km south of Gloucester (Figure 22). The irrigation period is expected to be 18 to 24 months but may extend to 36 months depending on the final volume of produced water from exploration program activities. The proposal is to irrigate a volume of 70 ML of the produced water in storage over a maximum area of 40 ha over three years. This will include (i) water from exploration programs that is already stored in the Tiedman and Stratford dams, (ii) any rainfall that falls in the dams and (iii) any additional produced water from 2012–2014 exploration activities. This water will be blended with water from the Avon River at a ratio of about three parts river water to one part produced water, to optimise water quality of the irrigated water. The storage dams (Tiedman north, Tiedman south and Tiedman east) are of a ‘turkey’s nest’ style construction with a capacity of 20 ML each (Figure 22). Tiedman south dam is the primary blended water irrigation dam, whereas Tiedman north and Tiedman east dams are used for storing the untreated water pumped during CSG operations.

Two dams were constructed to capture runoff from the trial area during larger rainfall events. There will be no irrigation on the alluvial floodplain soils where there are potential pathways for the irrigated water to flow to the shallow aquifers and the Avon River (AGL Energy Limited, 2012).

AGL holds seven bore licences under NSW's *Water Act 1912* for the commercial/industrial extraction/irrigation reuse of groundwater pumped during flow testing programs with total water allocation volume of 35 ML/year. AGL also holds a water access licence (WAL 19521) and works approval (20CA204347) to extract 32 ML/year from the Avon River source adjacent to the site for irrigation. This fresher surface water will be blended with the stored produced water for irrigation of salt tolerant crops.

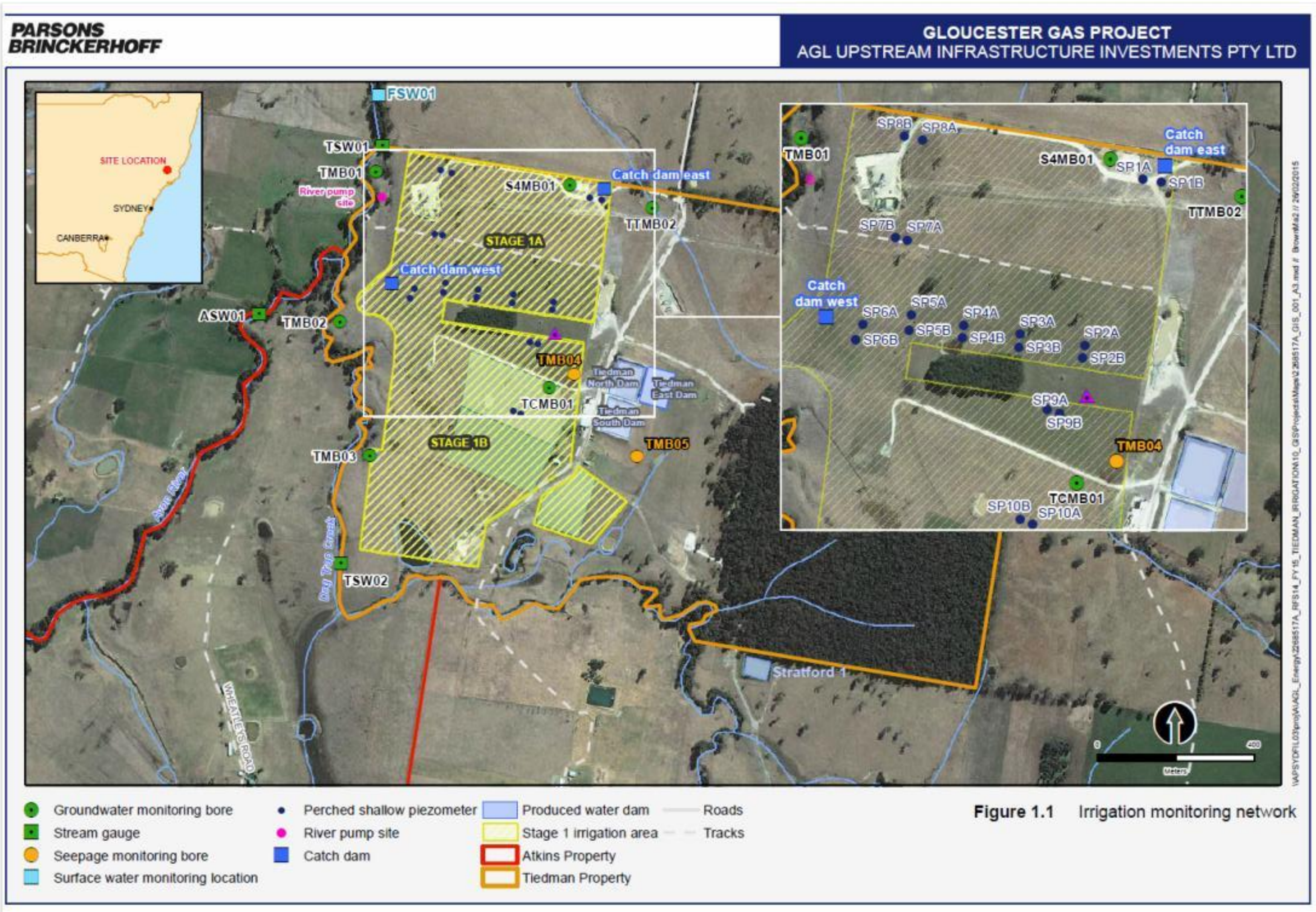


Figure 22 Tiedman Irrigation Project for the Gloucester subregion

2.1.6.4.2 Waukivory Pilot Project

Full-scale CSG operations in the Gloucester subregion have not been developed. However, AGL has been conducting CSG exploration program under the name of the Waukivory Pilot Project. Further information about this project is provided in the Section 1.2.2.2.1 of companion product 1.2 for the Gloucester subregion (Hodgkinson et al., 2014).

The Waukivory Pilot Project involves the fracture stimulation and testing of four gas wells concurrently (WK11, WK12, WK13 and WK14). The maximum volume of flowback water and produced water likely to be pumped for the four gas wells is 20 ML over the life of the program (14 ML of produced water and 6 ML of flowback water). The volume of water required for fracture treatment is estimated to be between 0.9 ML and 2.4 ML per well and around 6 ML in total for the whole fracture stimulation program expected to be completed by end of 2015. Water for hydraulic fracture stimulation will be sourced from licensed water supply works from either Pontilands (expected allocation is 20 ML per annum) or Tiedman dams, located on nearby properties owned by AGL. The on-site water management involves (Figure 23):

- water gathering lines from pilot wells to the water staging point at WK13
- storing water in dual lined dams at WK13 and monitoring storage levels
- monitoring the salinity of the flowback water
- transportation of flowback water for lawful disposal at an appropriate facility
- monitoring the salinity of the produced water
- transporting produced water via water pipeline or trucks to the Tiedmans Property for storage, blending and reuse (after treatment) for industrial/irrigation/stock/stream disposal.

According to AGL's Produced Water Management Plan (2014b), the produced water strategy is:

- storage of produced water from AGL's offsite operations and transport of this water within the Tiedmans Property
- blending of produced water with freshwater for irrigation reuse, subject to the water quality meeting relevant Australian and New Zealand Environment Conservation Council (ANZECC) criteria, a water quality guidelines
- storage for blending and/or direct reuse for stock use, subject to the water quality meeting the relevant ANZECC criteria
- storage for blending and/or direct reuse for industrial uses such as fracture stimulation, dust suppression and firefighting, subject to water quality meeting the relevant ANZECC criteria
- storage for future drilling and hydraulic fracture stimulation purposes.

It is proposed to reuse all produced water from the Waukivory Pilot Project unless the water quality exceeds a pre-blending salinity (i.e. electrical conductivity (EC)) of 15,000 µS/cm. The produced water would be blended with fresh water sources (mostly river water) to obtain a blended water mix (i.e. with a salinity level of up to 2000 µS/cm) suitable for irrigating salt tolerant crops. Produced water, flowback water and natural groundwater from the Waukivory Pilot Project are stored on site in above-ground tanks (75,000 L capacity) or open-top tanks (40,000 L capacity) and then transferred by road tanker to the Tiedman dams for either industrial use or blended water irrigation. AGL is planning to treat produced water using a desalination technology, reverse osmosis, to reduce the amount of salt to an acceptable level for irrigation or for returning (a portion of treated water) to the environment during the floods (AGL Energy Limited, 2014a).

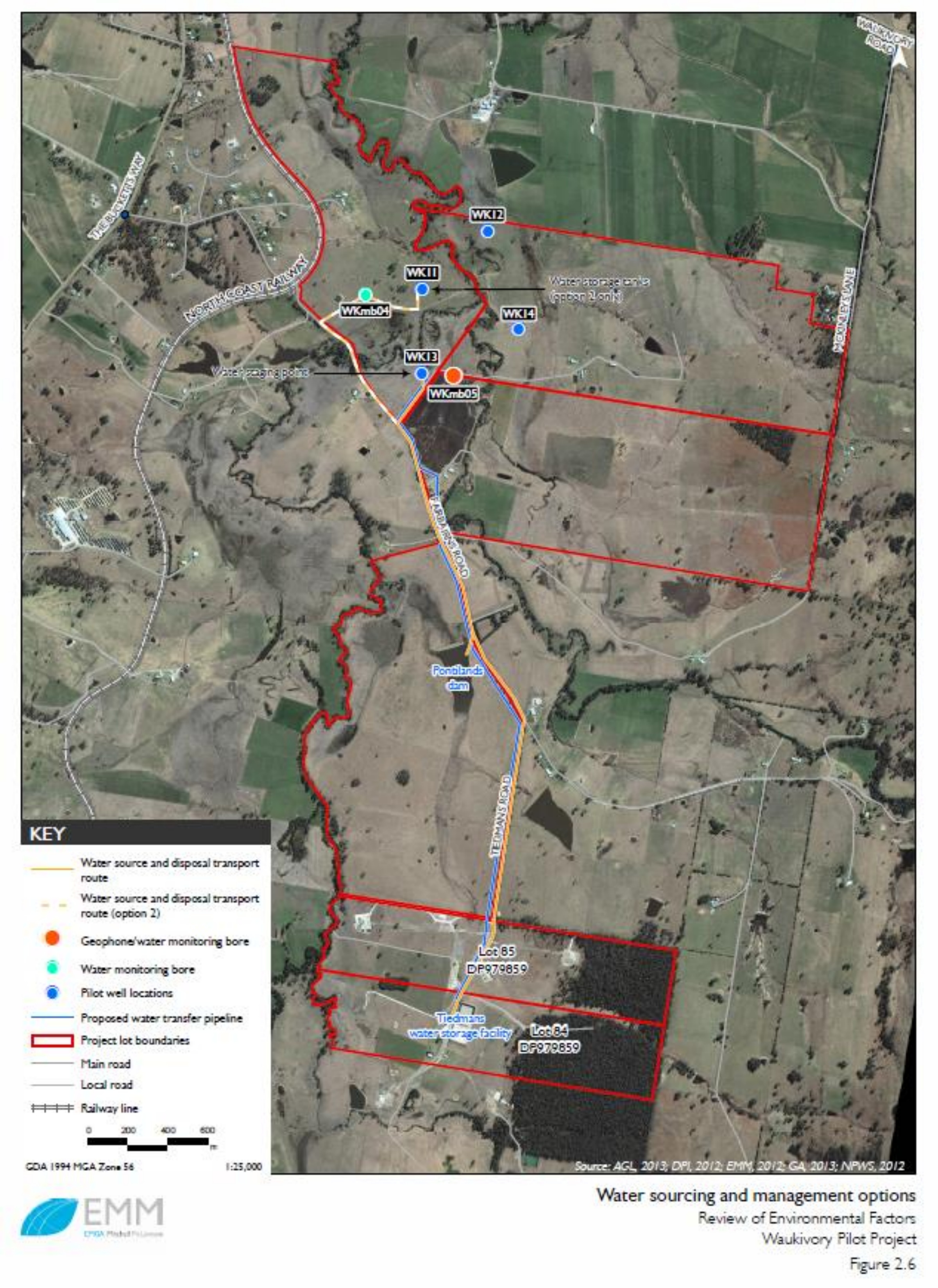


Figure 23 Water sourcing and management options for the Waukivory Pilot Project in the Gloucester subregion

Source: AGL Energy Limited (2013). This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of AGL Energy Limited.

References

AGL Energy Limited (2012) Water management plan for the Tiedman Irrigation Program – Gloucester. AGL Energy Limited, Sydney. Viewed 16 June 2015, http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Irrigation%20Program/20120514_Tiedman%20Irrigation%20Program%20%20%20Water%20Management%20Plan.pdf.

AGL Energy Limited (2013) Waukivory Pilot Project: review of environmental factors. EMGA Mitchell McLennan. Viewed 30 January 2014, http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20Community%20News/Gloucester/News%20and%20Articles/REF%20Waukivory%20Pilot%20Project%20Appendices%20A%20to%20O.pdf.

AGL Energy Limited (2014a) Fact sheet: our plan for produced water. AGL Energy Limited, Sydney. Viewed 31 March 2015, http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Fact%20Sheets/20140821_Fact%20Sheet%20GGP%20%20%20Our%20plan%20for%20produced%20water.pdf.

AGL Energy Limited (2014b) Produced water management plan for PEL 285. AGL Energy Limited, Sydney. Viewed 16 June 2015, http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Water%20Plans/20141022_Produced%20Water%20Management%20Plan%20for%20PEL%20285.pdf.

AGL Energy Limited (2014c) Surface water and groundwater management plan for the Waukivory Pilot Program – Gloucester Gas Project. AGL Energy Limited, Sydney. Viewed 16 June 2015, http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Water%20Plans/20141022_Surface%20Water%20and%20Groundwater%20Management%20Plan%20for%20the%20Waukivory%20Pilot%20Program.pdf.

AGL Energy Limited (2015) Gloucester Gas Project – extracted water management strategy (Final Draft). AGL Energy Limited, Sydney. Viewed 21 December 2015, https://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Water%20Plans/20150904_GGP%20%20%20Extracted%20Water%20Management%20Strategy%20%20%20Final%20Draft.pdf.

AGL Upstream Investments Pty Limited (2014) Fracture stimulation management plan Waukivory Pilot Project, Gloucester NSW. AGL Upstream Investments Pty Limited, Sydney. Viewed 16 June 2015, http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Review%20of%20Environmental%20Factors/20140630_AGL%20Fracture%20Stimulation%20Management%20Plan%20Gloucester%20Waukivory%20V2%20June%202014.pdf.

Australasian Groundwater and Environmental Pty Ltd (2013) Rocky Hill Coal Project groundwater assessment, Part 4 of the Specialist Consultant Studies Compendium. Technical report by Australasian Groundwater and Environmental Pty Ltd for Gloucester Coal Limited. Australasian Groundwater and Environmental Pty Ltd, Sydney. Viewed 10 September 2013, http://www.rockyhillproject.com.au/wp-content/uploads/2013/08/80604-Vol-2_Part-4-Groundwater.pdf.

Duralie Coal (2013) Duralie Coal Mine water management plan. Duralie Coal Mine, Sydney. Viewed 16 June 2015, http://www.duraliecoal.com.au/documents/community_environment/WAMP-R02-D.pdf.

Heritage Computing (2009) Duralie Extension Project groundwater assessment. A hydrogeological assessment of the Duralie Extension Project environmental assessment. Technical report by Heritage Computing Pty Limited for Duralie Coal Pty Ltd. Heritage Computing Pty Limited, Sydney. Viewed 10 September 2013, http://www.gloucestercoal.com.au/documents/Enviro_EAD_DCM_2010_Appendix_B_Groundwater%20Assessment.pdf.

Heritage Computing (2012) A hydrogeological assessment in support of the Stratford Coal Project environmental impact statement. Technical report by Heritage Computing Pty Limited for Stratford Coal Pty Ltd. Heritage Computing Pty Limited, Sydney. Viewed 10 September 2013, http://www.stratfordcoal.com.au/documents/environment/eis/Appendix%20A%20-%20Groundwater%20Assessment.pdf.

Hodgkinson JH, Pinetown KL, Wilkes PG, McVicar TR and Marvanek SP (2014) Coal and coal seam gas resource assessment for the Gloucester subregion. Product 1.2 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 16 June 2015, http://data.bioregionalassessments.gov.au/product/NSB/GLO/1.2.

Parsons Brinckerhoff (2015) Tiedman Irrigation Program – Water Compliance Report for the Period 5 July to 31 December 2014. Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Limited. Parsons Brinckerhoff Australia Pty Limited, Sydney. Viewed 16 June 2015, http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/Gloucester%20Document%20Repository/Irrigation%20Program/20150226_Tiedman%20Irrigation%20Program%20%20%20Water%20Compliance%20Report.pdf.

R.W.Corkery & Co. Pty Ltd (2012a) Environmental impact statement, Rocky Hill Coal Project, Section 2: description of the proposal. Technical Report by R.W.Corkery & Co. Pty Ltd for Gloucester Resources Limited. R.W.Corkery & Co. Pty Ltd, Sydney. Viewed 16 June 2015, https://majorprojects.affinitylive.com/public/57b22dfaca01c9184d709863ee383722/14.%20Rocky%20Hill%20Coal%20Project%20EIS%20-%20Section%202_Description%20of%20the%20Proposal%202.6%20to%202.16.pdf.

R.W.Corkery & Co. Pty Ltd (2012b) Environmental impact statement, Rocky Hill Coal Project, Section 4: environmental features, management measures and impacts. Technical Report by R.W.Corkery & Co. Pty Ltd for Gloucester Resources Limited. R.W.Corkery & Co. Pty Ltd, Sydney. Viewed 16 June 2015, https://majorprojects.affinitylive.com/public/690a4a86107a605f403f66f5104f963e/16.%20Rocky%20Hill%20Coal%20Project%20EIS%20-%20Section%204_Env%20Features,%20Mgt%20Measures%20and%20Impacts%204.1%20to%204.11.pdf.

Gloucester Basin (2012) Stratford Coal Mine water management plan. Stratford Coal Mine, Sydney. Viewed 16 June 2015, http://www.stratfordcoal.com.au/documents/environment/Stratford_Mining_Complex_Water_Management_Plan.pdf.

WRM Water & Environment Pty Ltd (2013) Rocky Hill Coal Project surface water assessment, Part 5 of the Specialist Consultant Studies Compendium. Technical report by WRM Water & Environment Pty Ltd for Gloucester Coal Limited. WRM Water & Environment Pty Ltd, Sydney. Viewed 16 June 2015, http://www.rockyhillproject.com.au/wp-content/uploads/2013/08/80604-Vol-2_Part-5-Surface-Water-Sections-1-to-2.pdf, http://www.rockyhillproject.com.au/wp-content/uploads/2013/08/80604-Vol-2_Part-5-Surface-Water-Sections-3-to-5.pdf, http://www.rockyhillproject.com.au/wp-content/uploads/2013/08/80604-Vol-2_Part-5-Surface-Water_Appendices-A-and-B.pdf, http://www.rockyhillproject.com.au/wp-content/uploads/2013/08/80604-Vol-2_Part-5-Surface-Water_Appendices-C-and-D.pdf.

Yancoal (2015a) Duralie coal annual review – 2015. Yancoal Australia Limited. Viewed 18 December 2015, http://www.duraliecoal.com.au/documents/community_environment/Duralie%20Annual%20Review%202015_Finalv3.pdf.

Yancoal (2015b) Stratford Mining Complex annual review – 2015. Yancoal Australia Limited. Viewed 18 December 2015, http://www.stratfordcoal.com.au/documents/environment/Stratford%20Annual%20Review%202015_Finalv3.pdf.

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.

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 wells 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.

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.

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

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.

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

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

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

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).

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)

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.

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

Gloucester subregion: The Gloucester subregion covers an area of about 348 km^2. The Gloucester subregion is defined by the geological Gloucester Basin. It is located just north of the Hunter Valley in NSW, approximately 85 km north-north-east of Newcastle and relative to regional centres is 60 km south-west of Taree and 55 km west of Forster.

groundwater: water occurring naturally below ground level (whether in an aquifer or other low permeability material), 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 hydrogeology: the study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of interactions between water and rock

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 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).

recharge: see groundwater recharge

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

sensitivity: the degree to which the output of a model (numerical or otherwise) responds to uncertainty in a model input

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)

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

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs

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.

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 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.

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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