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 Hunter subregion

Product 2.1-2.2 for the Hunter 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.

Bureau of Meteorology

The Bureau of Meteorology is Australia's national weather, climate and water agency. Under the *Water Act 2007*, the Bureau is responsible for compiling and disseminating Australia's water information. The Bureau is committed to increasing access to water information to support informed decision making about the management of water resources. For more information, visit http://www.bom.gov.au/water/.

CSIRO

Australia is founding its future on science and innovation. Its national science agency, CSIRO, is a powerhouse of ideas, technologies and skills for building prosperity, growth, health and sustainability. It serves governments, industries, business and communities across the nation. For more information, visit http://www.csiro.au.

Geoscience Australia

Geoscience Australia is Australia's national geoscience agency and exists to apply geoscience to Australia's most important challenges. Geoscience Australia provides geoscientific advice and information to the Australian Government to support current priorities. These include contributing to responsible resource development; cleaner and low emission energy technologies; community safety; and improving marine planning and protection. The outcome of Geoscience Australia's work is an enhanced potential for the Australian community to obtain economic, social and environmental benefits through the application of first class research and information. For more information, visit http://www.ga.gov.au.

ISBN-PDF 978-1-925315-53-0

Citation

Herron NF, Frery E, Crosbie R, Peña-Arancibia J, Zhang YQ, Viney N, Rachakonda PK, Ramage A, Marvanek SP, Gresham M, McVicar TR, Wilkins A (2018) Observations analysis, statistical analysis and interpolation for the Hunter subregion. Product 2.1-2.2 for the Hunter 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/HUN/2.1-2.2.

Authorship is listed in relative order of contribution.

Cover photograph

Oblique view west of Muswellbrook showing Bengalla coal storage (left foreground) with irrigated agriculture and riparian vegetation either side of the Hunter River and Mount Arthur coal mine in the distance (right background), NSW, 2014

Australian Government
Department of the Environment and Energy
Bureau of Meteorology
Geoscience Australia

CSIRO

v20180301

Contents

Contributors to the Technical Programme x

Acknowledgements xii

Currency of scientific results xiii

Introduction 1

The Bioregional Assessment Programme 1
Methodologies 3
Technical products 5
About this technical product 8
References 8

2.1 Observations analysis for the Hunter subregion 9

2.1.1 Geography 10

2.1.1.1 Observed data 10
2.1.1.1.1 Physical geography 10
2.1.1.1.2 Climate 12
2.1.1.2 Statistical analysis and interpolation 13
2.1.1.3 Gaps 16
References 16
Datasets 17

2.1.2 Geology 19

2.1.2.1 Observed data 20
2.1.2.1.1 Deep wells dataset 21
2.1.2.1.2 Geological maps and geophysical datasets 26
2.1.2.2 Statistical analysis and interpolation 27
2.1.2.2.1 Workflow 27
2.1.2.2.2 Data selection and processing 28
2.1.2.2.3 Three-dimensional non-faulted and non-eroded geological model 34
2.1.2.2.4 Preliminary three-dimensional geological model 40
2.1.2.3 Gaps 43
References 45
Datasets 53

2.1.3 Hydrogeology and groundwater quality 55

2.1.3.1 Observed data 56
2.1.3.1.1 Recharge 56

2.1.3.1.2 Regolith depth and alluvium extent 57
2.1.3.1.3 Observed depths to watertable 59
2.1.3.2 Statistical analysis and interpolation 63
2.1.3.2.1 Recharge 63
2.1.3.2.2 Hydraulic conductivity 71
2.1.3.3 Gaps 82
References 82
Datasets 84

2.1.4 Surface water hydrology and water quality 87

2.1.4.1 Observed data 88
2.1.4.1.1 Stage and streamflow data 88
2.1.4.1.2 River cross-sections 94
2.1.4.2 Statistical analysis and interpolation 94
2.1.4.2.1 River cross-sections at simulation nodes 94
2.1.4.2.2 River reach lengths 97
2.1.4.2.3 Irrigation areas and crop types 97
2.1.4.2.4 Hunter River Salinity Trading Scheme discharges 98
2.1.4.2.5 Node-link interpolation 101
2.1.4.3 Gaps 105
References 106
Datasets 107

2.1.5 Surface water – groundwater interactions 111

2.1.5.1 Observed data 111
2.1.5.2 Statistical analysis and interpolation 111
2.1.5.2.1 Groundwater contributions to stream flow 111
2.1.5.3 Gaps 113
References 113

2.1.6 Water management for coal resource developments 115

2.1.6.1 Data sources 117
2.1.6.1.1 Mine footprints 117
2.1.6.1.2 Flow rates 128
2.1.6.2 Translating surface water mine footprint areas into time series of hydrological changes 129
2.1.6.2.1 Calculating final void areas for surface water modelling 133
2.1.6.3 Summary of baseline and coal resource development pathway model data for surface water and groundwater modelling 134
2.1.6.4 Gaps 152
References 153
Datasets 171

Glossary 175

2.2 Statistical analysis and interpolation 181

Figures

Figure 1 Schematic diagram of the bioregional assessment methodology 2

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment 6

Figure 3 Spatial variation of precipitation from 1980 to 2009 14

Figure 4 Spatial variation of maximum air temperature (Tmax) from 1980 to 2009 15

Figure 5 Spatial variation of minimum air temperature (Tmin) from 1980 to 2009 15

Figure 6 Spatial distribution of petroleum wells within the Hunter subregion 26

Figure 7 Distribution of regional horizon tops from the wells derived dataset for the Hunter subregion 32

Figure 8 Surface topography and offshore bathymetry of the Hunter subregion 33

Figure 9 Non-eroded and non-folded regional horizon maps for Hunter subregion reference horizons: (a) P900, (b) P500, (c) P100 and (d) P000 35

Figure 10 Isopach maps showing distribution of formation thicknesses from the wells derived dataset for the Hunter subregion 37

Figure 11 Depth structure maps of folded and non-eroded horizons extracted from the geological model for the Hunter subregion 39

Figure 12 Three-dimensional perspective view of the eroded and folded geological model for the Hunter subregion 41

Figure 13 Three-dimensional perspective view of the regional lithology pattern in the geological model for the Hunter subregion 42

Figure 14 Depth structure maps extracted from the folded and eroded geological model for the Hunter subregion 43

Figure 15 Depth of regolith over the Hunter subregion 58

Figure 16 Spatial extent of the alluvium and coastal sands in the Hunter subregion 59

Figure 17 Observation points in the HYDMEAS database categorised by the number of observations recorded 60

Figure 18 Observed depth to watertable at three locations within the Hunter subregion 61

Figure 19 Mean depth to watertable (metres below ground surface) at groundwater bore locations across the Hunter subregion 62

Figure 20 Inputs into the chloride mass balance method of estimating recharge 65

Figure 21 Relationship between mean annual rainfall and mean annual recharge for groupings of surface geology 67

Figure 22 Upscaled estimates of mean annual recharge over the Sydney Basin 68

Figure 23 Relationship between mean annual rainfall and mean annual recharge considering the uncertainty in the chloride deposition and the regression equation for groupings of surface geology 70

Figure 24 Uncertainty in the recharge estimation across the Hunter subregion and Sydney Basin bioregion displayed as the (a) 5th, (b) 50th and (c) 95th percentiles from 100 replicates 71

Figure 25 Hydraulic conductivity differentiated by measurement type and correlated with depth 72

Figure 26 Hydraulic conductivity differentiated by lithology class and correlated with depth ... 74

Figure 27 Hydraulic conductivity differentiated by stratigraphy, and correlated with depth for Hunter groundwater model layers (a) 0 (bottom), (b) 2 and 3, (c) 4, (d) 5, (e) 6, (f) 7 and (g) 8, 9 and 10 78

Figure 28 Hydraulic conductivity differentiated by geographic area, and correlated with depth 78

Figure 29 Hydraulic conductivity (on a linear scale) and its relation with depth 80

Figure 30 Hydraulic conductivity for coal, rock and alluvium, and correlated with depth 81

Figure 31 Porosity correlated with depth 81

Figure 32 Location of stream gauges in the Hunter subregion (listed in Table 8)....................... 91

Figure 33 Percentage of streamflow data in each quality code class by gauging station 93

Figure 34 Cross-section of a Cippoletti (trapezoidal) weir 95

Figure 35 Box plots of water discharge for each sector during dry and wet years 101

Figure 36 Link-node mapping for (a) the lower Hunter River and (b) upper Hunter, Goulburn and Wyong River modelled river networks 103

Figure 37 Number of mine footprint polygons obtained from NSW Department of Trade and Investment data by year 126

Figure 38 Maximum footprint areas for baseline mines used in surface water and groundwater models.. 143

Figure 39 Maximum mine footprint areas for the additional coal resource developments (ACRD) used in surface water and groundwater models 144

Figure 40 Time series graphs of open-cut and underground mine footprint areas for surface water modelling 147

Figure 41 Time series graphs of open-cut and underground mine flow rates used in groundwater modelling 152

Tables

Table 1 Methodologies 4

Table 2 Technical products delivered for the Hunter subregion 7

Table 3 List of petroleum wells with well completion reports publicly available in the Hunter subregion 22

Table 4 Relationship between regional horizons and stratigraphic units in the coalfields of the Hunter subregion 29

Table 5 Depth to top of regional horizons from deep wells across the Hunter subregion 29

Table 6 Key datasets used for groundwater modelling for the Hunter subregion 56

Table 7 Key datasets for surface water modelling for the Hunter subregion 88

Table 8 Gauge information for streamflow data for the Hunter subregion 89

Table 9 Quality codes for the NSW gauges for the Hunter subregion 92

Table 10 Characteristics and dimensions (used in the Cippoletti weir) of derived cross-sections used in AWRA-R modelling for the Hunter subregion 96

Table 11 Characteristics of derived cross-sections used in AWRA-R modelling for the Hunter subregion 97

Table 12 Crop types and areas used for modelling in each AWRA-R reach for the Hunter subregion 98

Table 13 Details for sites in the Hunter River Salinity Trading Scheme (HRSTS) with discharge records 99

Table 14 Gauges, streamflow thresholds and mean annual discharge volumes and discharge/streamflow ratio used in the simplified discharge scheme for the Hunter subregion 101

Table 15 Location details of non-model nodes used to inform the Hunter River link-node mapping 104

Table 16 Datasets used to represent mine water management in hydrological modelling for the Hunter subregion 116

Table 17 Data sources for mine footprints and mine flow rates used in the groundwater modelling for the Hunter subregion 118

Table 18 Data sources for mine footprints used in the surface water modelling for the Hunter subregion 122

Table 19 Mine footprint areas for open-cut mines in the Hunter subregion between 1987 and 2006 128

Table 20 Assumptions made in surface water modelling for representing hydrological impacts of mines and generation of time series data 130

Table 21 Open-cut mines used to define the ratio of final void area to maximum footprint area 133

Table 22 Key characteristics of data used to represent mine impacts in the surface water model for the Hunter subregion 135

Table 23 Key characteristics of data used to represent mine impacts in the groundwater model for the Hunter subregion 138

Contributors to the Technical Programme

The following individuals have contributed to the Technical Programme, the part of the Bioregional Assessment Programme that undertakes bioregional assessments.

Role or team	Contributor(s)
Assistant Secretary	Department of the Environment and Energy: Matthew Whitfort
Programme Director	Department of the Environment and Energy: Anthony Swirepik
Technical Programme Director	Bureau of Meteorology: Julie Burke
Projects Director	CSIRO: David Post
Principal Science Advisor	Department of the Environment and Energy: Peter Baker
Science Directors	CSIRO: Brent Henderson Geoscience Australia: Steven Lewis
Integration	Bureau of Meteorology: Richard Mount (Integration Leader) CSIRO: Becky Schmidt
Programme management	Bureau of Meteorology: Louise Minty CSIRO: Paul Hardisty, Warwick McDonald Geoscience Australia: Stuart Minchin
Project Leaders	CSIRO: Alexander Herr, Kate Holland, Tim McVicar, David Rassam Geoscience Australia: Tim Evans Bureau of Meteorology: Natasha Herron
Assets and receptors	Bureau of Meteorology: Richard Mount (Discipline Leader) Department of the Environment and Energy: Glenn Johnstone, Wasantha Perera, Jin Wang
Bioregional Assessment Information Platform	Bureau of Meteorology: Lakshmi Devanathan (Team Leader), Derek Chen, Trevor Christie-Taylor, Melita Dahl, Angus MacAulay, Christine Price, Paul Sheahan, Kellie Stuart, Carl Sudholz CSIRO: Peter Fitch, Ashley Sommer Geoscience Australia: Neal Evans
Communications	Bureau of Meteorology: Jessica York CSIRO: Clare Brandon Department of the Environment and Energy: John Higgins, Lea Locke, Miriam McMillan, Milica Milanja Geoscience Australia: Rachel Houlahan
Coordination	Bureau of Meteorology: Brendan Moran, Eliane Prideaux, Sarah van Rooyen CSIRO: Ruth Palmer Department of the Environment and Energy: Anisa Coric, Lucy Elliott, James Hill, Andrew Stacey, David Thomas, Emily Turner
Ecology	CSIRO: Anthony O'Grady (Discipline Leader), Caroline Bruce, Tanya Doody, Brendan Ebner, Craig MacFarlane, Patrick Mitchell, Justine Murray, Chris Pavey, Jodie Pritchard, Nat Raisbeck-Brown, Ashley Sparrow

Role or team	Contributor(s)
Geology	CSIRO: Deepak Adhikary, Emanuelle Frery, Mike Gresham, Jane Hodgkinson, Zhejun Pan, Matthias Raiber, Regina Sander, Paul Wilkes Geoscience Australia: Steven Lewis (Discipline Leader)
Geographic information systems	CSIRO: Jody Bruce, Debbie Crawford, Dennis Gonzalez, Mike Gresham, Steve Marvanek, Arthur Read Geoscience Australia: Adrian Dehelean, Joe Bell
Groundwater modelling	CSIRO: Russell Crosbie (Discipline Leader), Tao Cui, Warrick Dawes, Lei Gao, Sreekanth Janardhanan, Luk Peeters, Praveen Kumar Rachakonda, Adam Ramage, Wolfgang Schmid, Saeed Torkzaban, Chris Turnadge, Andy Wilkins, Binzhong Zhou
Hydrogeology	Geoscience Australia: Tim Ransley (Discipline Leader), Chris Harris-Pascal, Jessica Northey, Emily Slatter
Information management	Bureau of Meteorology: Brendan Moran (Team Leader), Christine Panton CSIRO: Qifeng Bai, Simon Cox, Phil Davies, Geoff Hodgson, Brad Lane, Ben Leighton, David Lemon, Trevor Pickett, Shane Seaton, Ramneek Singh, Matt Stenson Geoscience Australia: Matti Peljo
Products	CSIRO: Becky Schmidt (Products Manager), Maryam Ahmad, Helen Beringen, Clare Brandon, Heinz Buettikofer, Sonja Chandler, Karin Hosking, Allison Johnston, Maryanne McKay, Linda Merrin, Sally Tetreault-Campbell, Catherine Ticehurst Geoscience Australia: Penny Kilgour, Kathryn Owen
Risk and uncertainty	CSIRO: Simon Barry (Discipline Leader), Jeffrey Dambacher, Jess Ford, Keith Hayes, Geoff Hosack, Adrien Ickowicz, Warren Jin, Dan Pagendam
Surface water hydrology	CSIRO: Neil Viney (Discipline Leader), Santosh Aryal, Mat Gilfedder, Fazlul Karim, Lingtao Li, Dave McJannet, Jorge Luis Peña-Arancibia, Xiaogang Shi, Tom Van Niel, Jai Vaze, Bill Wang, Ang Yang, Yongqiang Zhang

Acknowledgements

This technical product was reviewed by several groups:

- Discipline Leaders: Russell Crosbie (groundwater modelling), Neil Viney (surface water hydrology)
- Senior Science Leaders: David Post (Projects Director), Steven Lewis (Science Director, Geoscience Australia), Becky Schmidt (Products Manager)
- 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
- Additional Reviewers: Mark Armstrong (NSW Department of Primary Industry, Resources and Energy (Geological Survey of NSW)).

Currency of scientific results

The modelling results contained in this product were completed in June 2016 using the best available data, models and approaches available at that time. The product content was completed in April 2017.

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.

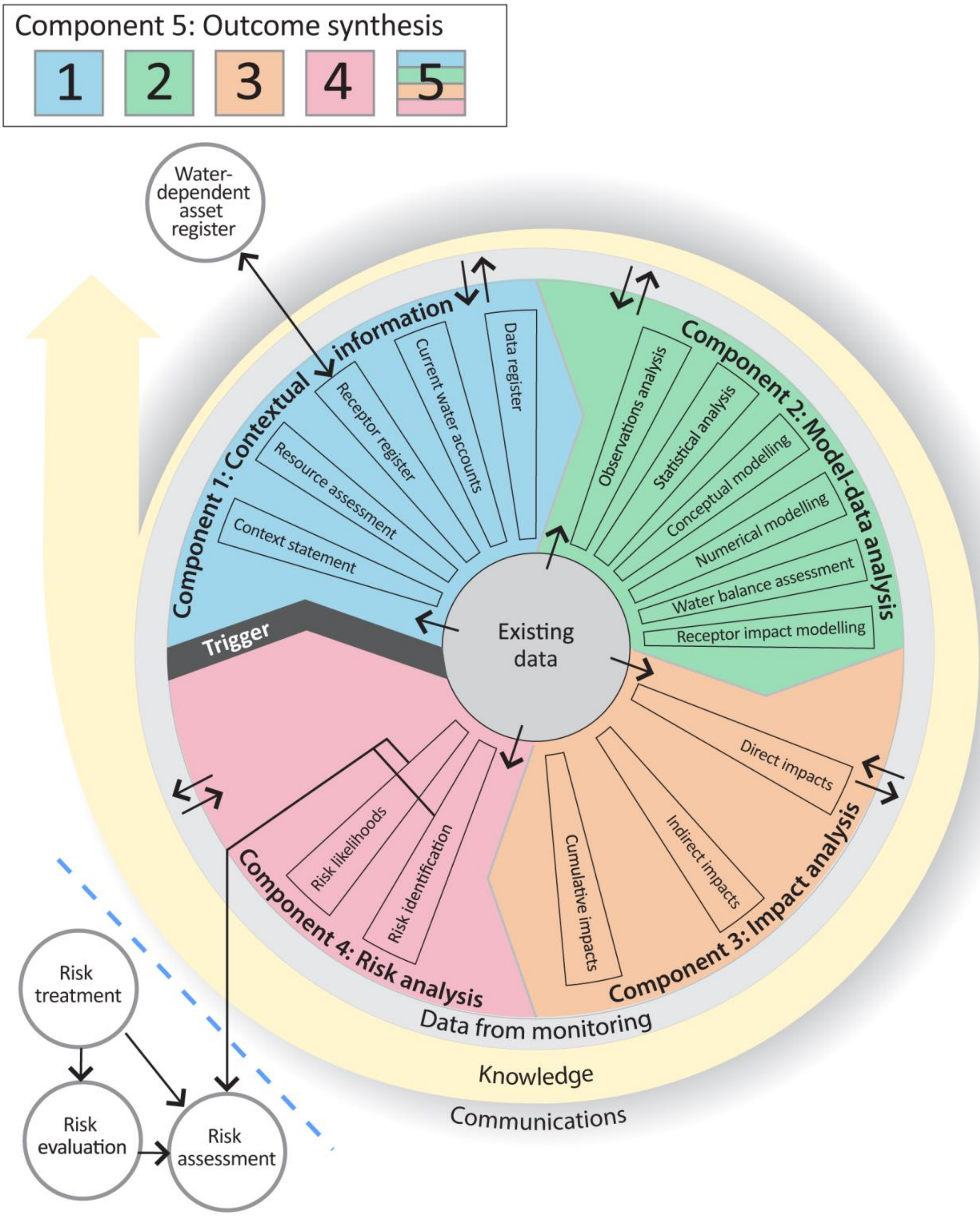


Figure 1 Schematic diagram of the bioregional assessment methodology

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), in the first instance, to support the consistency of their work across the BAs and, secondly, to open the approach to scrutiny, criticism and improvement through review and publication. In some instances, methodologies applied in a particular BA may differ from what is documented in the submethodologies – 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.

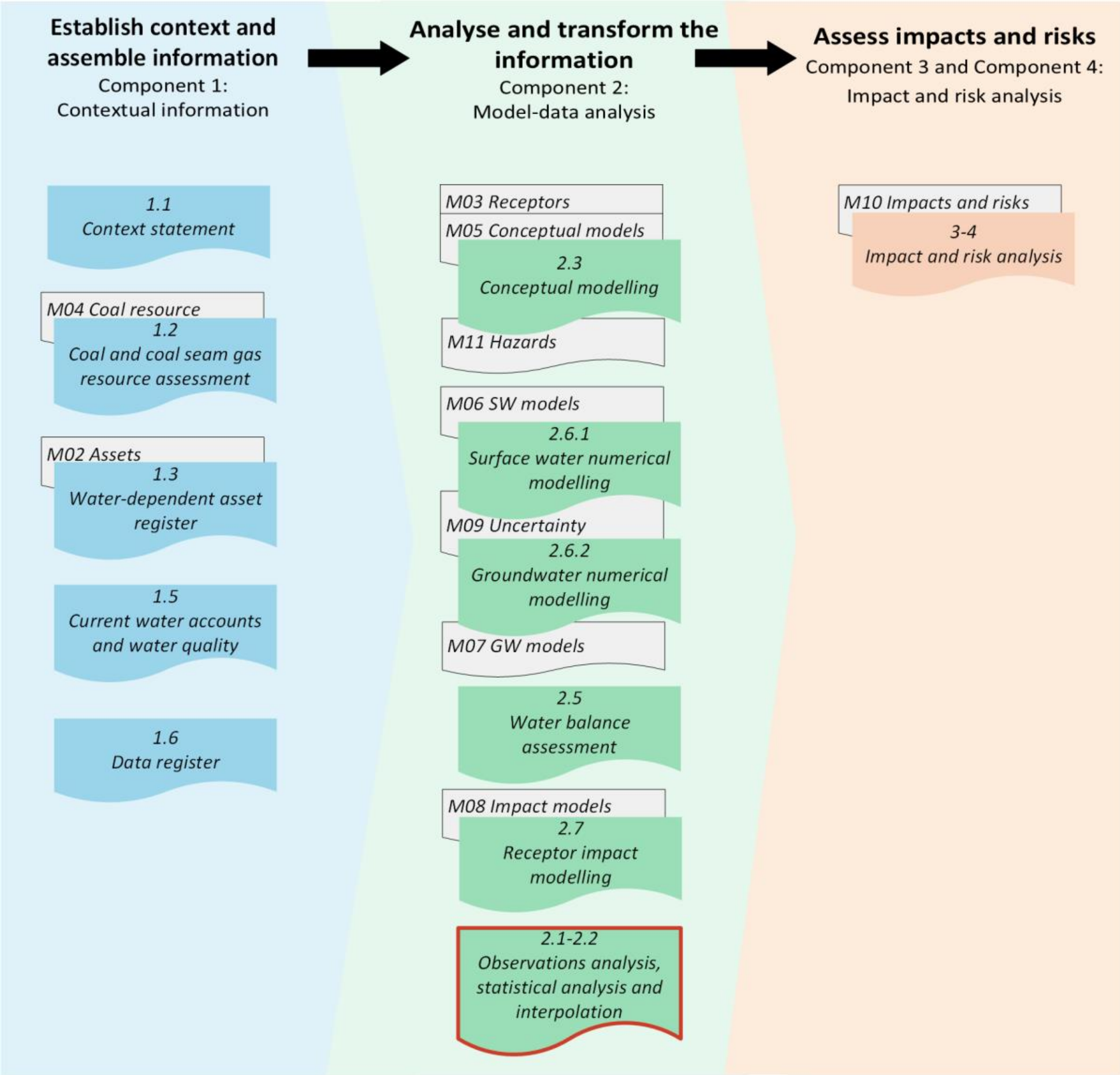


Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Hunter 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 product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling). There is no product 2.4. Originally this product was going to include two- and three-dimensional representations as per Section 4.2 of the BA methodology, but these are instead included in products such as product 2.3 (conceptual modelling), product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling).

Component	Product code	Title	Section in the BA methodology[b]	Type[a]
Component 1: Contextual information for the Hunter 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 Hunter 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 Hunter subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Hunter 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 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°.
- Visit http://bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived Datasets, the created date is used.

References

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 1 March 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 1 March 2018, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

2.1 Observations analysis for the Hunter subregion

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

The data are categorised according to the following disciplines:

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

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

The statistical analysis and interpolation aims to develop a quantitative understanding of the Hunter 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, of geographic datasets used to inform the hydrological modelling for the Hunter subregion.

For physical geography brief descriptions are provided for (i) digital elevation model (DEM) data, (ii) vegetation height and (iii) land use datasets.

For climate data brief descriptions are provided for (i) precipitation (P), (ii) maximum and minimum air temperature (Tmax and Tmin, respectively) and (iii) net radiation (Rn).

Subregion-specific characterisation of errors of the input climate data for the long-term (from January 1980 to December 2009) monthly relative error values are reported. These errors have little impact on prediction of additional coal resource development (ACRD) impacts, but could improve the model calibrations.

All geographic data specific to the bioregional assessment (BA) of the Hunter 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 Hunter subregion boundary such that subregion characteristics could be identified and simple statistics calculated (e.g. areas, maximum elevation). Details of the source data and/or methods are provided in Section 2.1.1.1 about observed data.

Spatial analyses specific to the Hunter 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

A digital elevation model (DEM) is needed in both the groundwater model and the landscape water balance model (Australian Water Resources Assessment (AWRA) landscape model, AWRA-L) to define surface topography for representing hydraulic gradients, flow directions and defining contributing areas. The DEM (Bioregional Assessment Programme, Dataset 1) was obtained from 3-second (~90 m) resolution data from the Shuttle Radar Topography Mission (SRTM), flown in February 2000 (Farr et al., 2007). The technique, known as interferometric synthetic aperture radar, uses two radar antennas, positioned 60 m apart, to acquire pairs of images of Earth, from which phase difference measurements can be calculated to compute elevations at Earth’s surface. The positional accuracy (x, y) of the SRTM data are in the order of 10 m (Smith and Sandwell, 2003; Rodriguez et al., 2006). For Australia, these data were processed according to Gallant et al. (2011) and the elevational accuracy (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).

The groundwater modelling domain extends offshore, beyond the area covered by the 3-second DEM. To extend the digital elevation model to include the topography of the ocean floor, the 9-second Australian Bathymetry and Topography Grid produced by Geoscience Australia (2009) (Dataset 2) was resampled to 3 seconds and stitched onto the SRTM DEM. This has been generated from a number of different datasets, including single beam and multi-beam bathymetry data, laser airborne depth sounder data, satellite measurements and various topographic and DEM data. Each dataset was gridded at 9 seconds without smoothing, and overlayed with the most accurate grid on top and the least accurate grid at the bottom.

The combined grid of the groundwater modelling domain for the Hunter subregion is a derived product of the Bioregional Assessment Programme (Dataset 3).

Vegetation height

The groundwater model uses information derived from vegetation height to differentiate between deep-rooted and shallow-rooted vegetation. While there can be enormous variability in the relationship between vegetation height and root depth due to site-specific factors such as soil depth, nutrient availability and water availability, observation data indicates that trees generally have deeper root systems than shrubs and herbaceous plants. For example, Canadell et al. (1996) compiled and analysed a dataset containing 290 observations of maximum rooting depth from major terrestrial biomes across the globe and found that the mean and standard error of maximum rooting depths for trees, shrubs and herbaceous plants were 7.0±1.2 m, 5.1±0.8 m and 2.6±0.1 m, respectively.

Vegetation height data for the groundwater modelling domain were obtained from a global 1 km grid resolution vegetation height dataset (Caltech/JPL, Dataset 4). This dataset was derived from measurements made by a satellite-based light detection and ranging system (lidar) between 20 May 2005 and 23 June 2005 using the Geoscience Laser Altimeter System (GLAS) aboard ICESat (Ice, Cloud and Land Elevation Satellite). Using a regression tree approach, Simard et al. (2011) modelled overstorey vegetation height globally 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.

The model uses this vegetation height surface to define a spatially-variable evapotranspiration extinction depth (i.e. the depth below which water cannot be extracted from the soil via plant roots) that is used in scaling potential evapotranspiration (PET) to actual evapotranspiration (AET).The evapotranspiration extinction depth parameter is a fixed parameter in the groundwater modelling. Specification of this parameter is likely to have a moderate impact on model predictions (see Section 2.6.2.8 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018)).

Land use

The AWRA-R river model needs details of irrigated areas and crop types along each section of the river network in order to distribute non-spatial irrigation diversion data appropriately in the model. Land use data were clipped using reach boundaries to derive irrigated areas and crop types. Land use data for the Hunter subregion were obtained from the Catchment Scale Land Use Management (CLUM) raster surface compiled November 2012 (ABARES, 2012) (Dataset 5). 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 November 2012 dataset is a combined 50 m raster for Australia, with edge-matching errors corrected for NSW (for which there were no new data provided compared to the previous version). The land use surface is based on data collected between 1997 and 2009, from sources ranging from 1:25,000 to 1:250,000 in scale. Section 2.1.4.2.3 contains the specific details for representing areas of irrigation in the river modelling.

2.1.1.1.2 Climate

For retrospective climate analysis the following variables are required for hydrological modelling of the Hunter subregion: (i) precipitation (P), (ii) maximum and minimum air temperature (Tmax and Tmin, respectively) and (iii) net radiation (Rn). Gridded climate surfaces (Bureau of Meteorology, Dataset 6) have been used in the calculation of PET and catchment runoff. This dataset contains daily data for the aforementioned climate variables for the whole Australian continent at a 0.05 degree (or ~5 km) grid cell resolution from 1 January 1900.

Precipitation

Daily precipitation grids (Bureau of Meteorology, Dataset 6) are generated by the Bureau of Meteorology using optimal geostatistics techniques, which take account of elevation, to interpolate daily and monthly station P totals between isolated stations (Jones et al., 2009). Daily time step data were used as input to surface water modelling, with groundwater models using monthly input data. Given that precipitation is the most spatially discontinuous meteorological process, it is the on-ground observation network that has the highest 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 precipitation 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 precipitation was 54.3 mm/month with a RMSE of 21.2 mm/month (Jones et al., 2009, Table 3a). This represents a relative error of 39% (calculated as RMSE/mean). These errors will have little impact on prediction of ACRD changes, which are calculated as the difference between the CRDP and baseline futures and use the same rainfall time series. However, the errors can impact on model calibrations, as the quality of the input data is fundamental to obtaining an acceptable calibration.

Temperature

Daily maximum temperature (Tmax) and minimum temperature (Tmin) grids (Bureau of Meteorology, Dataset 6) are generated by the Bureau of Meteorology using optimal geostatistics techniques that take elevation into account (the environmental lapse rate) to interpolate daily extremes of air temperature measured at isolated stations (Jones et al., 2009). 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).

Solar radiation

Daily solar radiation (Rn) data are available from 1900 onwards as part of the Bureau of Meteorology gridded climate surfaces for Australia (Bureau of Meteorology, Dataset 6). The dataset comprises two distinct periods: post-1982, daily solar radiation values are based on observations from ground-based and satellite instruments; prior to 1982, the daily values are based on the long-term climatologies from the post-1982 period. This means, for example, that the solar radiation on 1 January is the same for every year from 1900 to 1981 and reflects the average solar radiation on 1 January in the years since 1981. Uncertainties in the solar radiation data arise from the effect of cloud cover (~5%) and water vapour in the atmosphere (~2%). Comparisons with ground-based measurements (made with pyranometers) indicate that satellite methods tend to slightly over estimate the radiant exposure in wet, cloudy conditions and to under estimate in dry conditions (Bureau of Meteorology, 2016).

2.1.1.2 Statistical analysis and interpolation

All geographic data specific to the Hunter subregion were obtained from state or national datasets. This means no statistical analysis or interpolation was performed within the BA process to generate any of the geographic datasets. However, to characterise errors of the input climate data used for the water balance modelling, some subregion-specific spatial analysis was undertaken.

In addition to generating daily and monthly grids of meteorological variables (P, Tmax and Tmin), the Bureau of Meteorology (Jones et al., 2009) also generate daily and monthly RMSE grids of the same variables. These daily and monthly RMSE grids are a combined measure of the observational error and geostatistical error, the latter 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 and RMSE values for rainfall (P), max temperature (Tmax) and minimum temperature (Tmin) were calculated. Relative errors, expressed as a percentage, were calculated by dividing monthly RMSE mean grid by the monthly mean grids for each meteorological variable.

The spatially-averaged long-term monthly mean rainfall for the Hunter subregion is 64 mm/month (Figure 3a) with a RMSE of 30 mm/month (Figure 3b). This results in a relative error of 48% in the input rainfall grids (Figure 3c). The relatively high error is due in part to the high spatial and temporal variability in rainfall and relatively low degree of spatial autocorrelation, which may not be sufficiently captured through the network of meteorological stations. Relative error tends to be lower in the coastal areas and around the larger inland towns, reflecting the denser network of rainfall gauges, and higher in the less populous areas, such as the conservation areas in the south-west, where the rainfall station network is sparse.

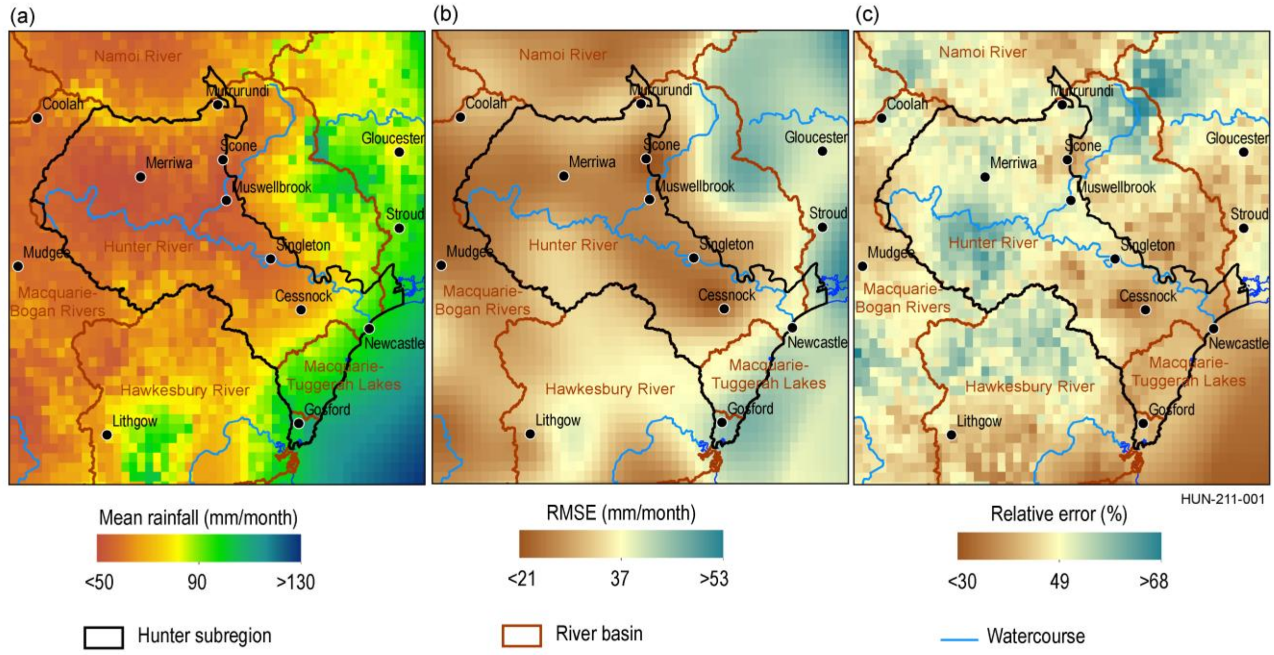


Figure 3 Spatial variation of precipitation from 1980 to 2009

(a) monthly mean precipitation, (b) monthly mean root mean square error (RMSE) precipitation and (c) monthly mean precipitation relative error for the Hunter subregion and proximal surface water basins
Data: Bureau of Meteorology (Dataset 6), Bioregional Assessment Programme (Dataset 7)

For air temperatures, a meteorological field that has higher spatial autocorrelation than rainfall, the regional distribution is governed by topography and distance from the ocean. The Tmax spatially-averaged long-term monthly mean is 22.9 °C (Figure 4a) with a RMSE of approximately 0.4 °C (Figure 4b) for the Hunter subregion. This results in a relative error of 1.8% for Tmax (Figure 4c). Tmin has a similar spatial pattern, with a spatially-averaged long-term monthly mean of 10.5 °C (Figure 5a), a RMSE of approximately 0.6 °C (Figure 5b) and a relative error of 6.1% (Figure 5c).

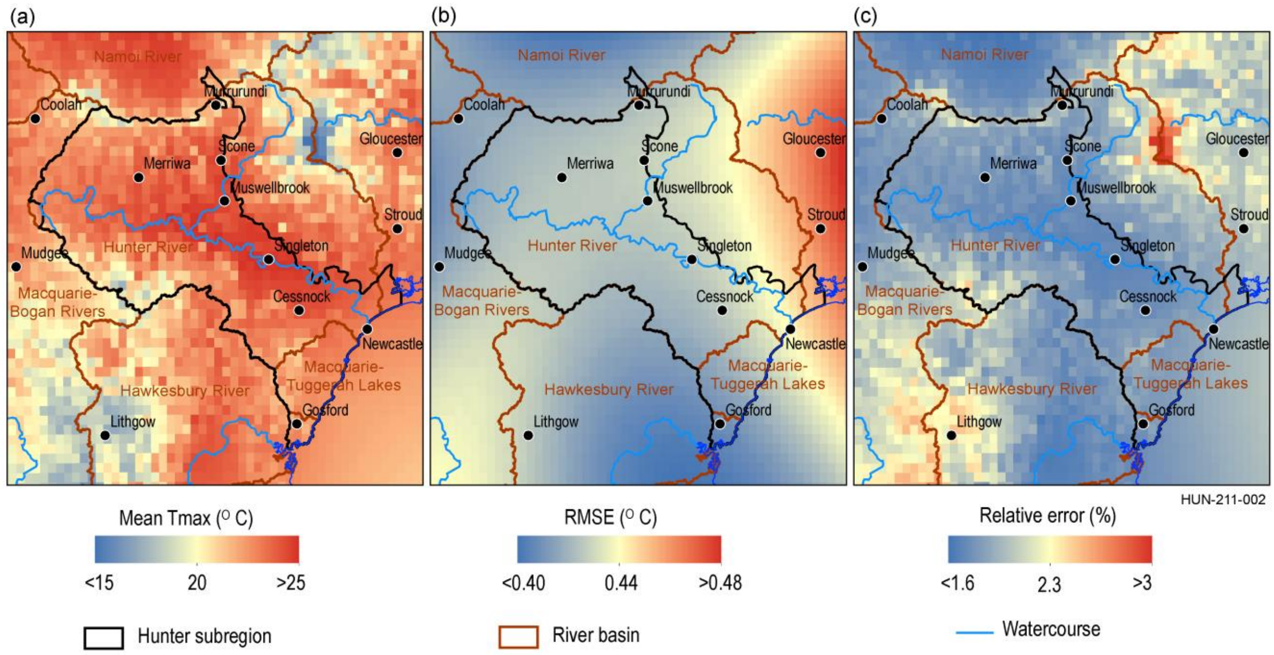


Figure 4 Spatial variation of maximum air temperature (Tmax) from 1980 to 2009

(a) monthly mean Tmax, (b) monthly mean root mean square error (RMSE) Tmax and (c) monthly mean Tmax relative error for the Hunter subregion and proximal surface water basins
Data: Bureau of Meteorology (Dataset 6), Bioregional Assessment Programme (Dataset 7)

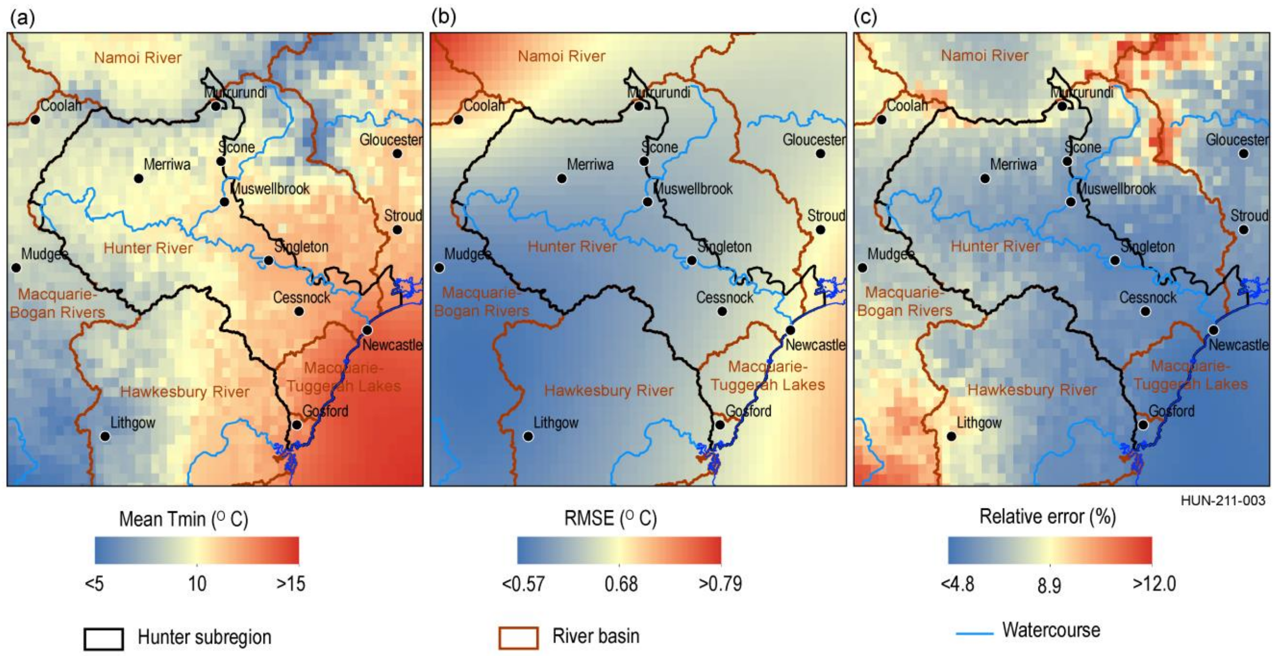


Figure 5 Spatial variation of minimum air temperature (Tmin) from 1980 to 2009

(a) monthly mean Tmin, (b) monthly mean root mean square error (RMSE) Tmin and (c) monthly mean Tmin relative error for the Hunter subregion and proximal surface water basins
Data: Bureau of Meteorology (Dataset 6), Bioregional Assessment Program (Dataset 7)

2.1.1.3 Gaps

The characterisation of input data errors in Section 2.1.1.2 suggests that having a denser network of rainfall gauging stations would reduce the uncertainty of the precipitation grid and hence the uncertainty in the results of the numerical models.

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.

Canadell J, Jackson RB, Ehleringer, JR, Mooney HA, Sala OE and Schulze E-D (1996) Maximum rooting depth of vegetation types at the global scale. Oecologia 108, 583–595. Viewed 29 July 2016, ftp://ftp.aphis.usda.gov/foia/FOLDER_10/AR00038244%20Canadell%20et%20al%201996.pdf.

Bureau of Meteorology (2016) Solar radiation definitions. Viewed 12 February 2016, http://www.bom.gov.au/climate/austmaps/solar-radiation-glossary.shtml.

Chiew FHS, Teng J, Vaze J, Post DA, Perraud JM, Kirono DGC and Viney NR (2009) Estimating climate change impact on runoff across southeast Australia: Method, results, and implications of the modeling method. Water Resources Research 45. DOI: 10.1029/2008wr007338.

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.

Herron NF, Peeters L, Crosbie R, Marvanek SP, Pagendam D, Ramage A, Rachakonda PK and Wilkins A (2018) Groundwater numerical modelling for the Hunter subregion. Product 2.6.2 for the Hunter 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/HUN/2.6.2.

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.

Li L, Donohue R, McVicar T, Van Niel T, Teng J, Potter N, Smith I, Kirono D, Bathols J, Cai W, Marvanek S, Gallant S, Chiew F and Frost A (2009) Climate data and their characterisation for hydrological scenario modelling across northern Australia. A report to the Australian Government from the CSIRO Northern Australia Sustainable Yields Project. CSIRO Water for a Healthy Country Flagship, Canberra.

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.

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.

Datasets

Dataset 1 Bioregional Assessment Programme (2012) Geoscience Australia, 3 Second Hillshade (3 second DEM-S). Bioregional Assessment Derived Dataset. Viewed 12 February 2016, http://data.bioregionalassessments.gov.au/dataset/98a3350f-7079-4a82-931f-516cb8ee7be9.

Dataset 2 Geoscience Australia (2009) Bathymetry GA 2009 9sec v4. Bioregional Assessment Source Dataset. Viewed 18 September 2015, http://data.bioregionalassessments.gov.au/dataset/60fb8bf5-b97d-49c9-b7fb-e7d594d2c75b.

Dataset 3 Bioregional Assessment Programme (2014), HUN GW modelling DEM v01. Bioregional Assessment Derived Dataset. Viewed 08 August 2016, http://data.bioregionalassessments.gov.au/dataset/f0927e8a-cc41-419b-ae68-660d5d5fa47b.

Dataset 4 Caltech/JPL (2014) Vegetation height for Australia (Simard). Bioregional Assessment Source Dataset. Viewed 12 February 2016, http://data.bioregionalassessments.gov.au/dataset/09f0ceb4-d401-410c-bd4f-dfbc5276ef8b.

Dataset 5 Australian Bureau of Agricultural and Resource Economics – Bureau of Rural Sciences (ABARE-BRS) (2010) Land use of Australia, Version 4 2005/2006 (September 2010 release, BRS). Bioregional Assessment Source Dataset. Viewed 27 January 2016, http://data.bioregionalassessments.gov.au/dataset/a18dbf2b-c0fe-4a26-b39a-e553bf6c39b5.

Dataset 6 Bureau of Meteorology (2013) BILO Gridded Climate Data: Daily Climate Data for each year from 1900 to 2012. Bioregional Assessment Source Dataset. Viewed 12 February 2016, http://data.bioregionalassessments.gov.au/dataset/7aaf0621-a0e5-4b01-9333-53ebcb1f1c14.

Dataset 7 Bioregional Assessment Programme (2015) BILO Climate Relative Error Grids V01. Bioregional Assessment Derived Dataset. Viewed 12 February 2016, http://data.bioregionalassessments.gov.au/dataset/c0c139f5-3648-4e0f-9acf-a884b7cc859b.

2.1.2 Geology

Summary

A regional scale geological model for the Hunter subregion has been built. This model represents the Carboniferous to Triassic strata of the northern part of the Sydney geological basin.

The geological model is an interpretation of the subsurface geometry, composition and structure of part of the Sydney Basin. The interpretation is based on petroleum exploration wells, geological maps and geophysical datasets and takes into account their inherent uncertainties and resolution. The well data provide critical point source information to constrain the depth of the main stratigraphic horizons, and understand the main rock types and sedimentary facies. The uncertainty surrounding these data increases with the distance from the wells. Geological maps and geophysical data were used to constrain the modelled interpolation of the point source well data.

Isopach maps (i.e. stratigraphic thickness maps) were built and used to define the basin scale architecture. Each isopach map was calibrated against well picks at the formation scale and constrained by trends observed within each interval. Definition of a reference regional horizon and the stacking of the successive isopach maps resulted in an initial non-eroded geological model. Major folds and fault trends were reviewed and the model was corrected based on the main anticlinal and synclinal axes, as this reduced correlation errors between the initial geological model and the formation tops in wells. The geological model was then eroded to conform with the present-day topographic surface and each stratigraphic unit populated with stochastic facies calibrated from well data and regional stratigraphic columns.

While there is considerable opportunity to improve upon the Hunter regional scale geological model through making use of more of the available data, the current version is fit for the purposes of the regional-scale groundwater modelling. The groundwater model is used to simulate hydrological changes across a wide range of parameter values to reflect regional differences and account for the uncertainty in the geological model. The groundwater model emulators provide a means of incorporating better local-scale information, where it is available, to constrain the results from the regional groundwater model (see companion product 2.6.2 (groundwater numerical modelling) for the Hunter subregion (Herron et al., 2018)).

This section outlines the rationale and describes the methods for building a geological model of the Hunter subregion. For bioregional assessment (BA) purposes, a three-dimensional geological model of the Hunter subregion was needed to define regional-scale geological architecture for modelling the impacts of coal mining on groundwater, particularly in terms of connectivity to the surface water system and to the subregion's water-dependent assets. The Hunter subregion covers a specific geological area of the Sydney Basin, including Newcastle Coalfield, Hunter Coalfield and parts of the Western Coalfield as well as minor parts of the Gunnedah and Werrie geological basins. Additional documentation about the geology of the Hunter subregion is summarised in companion product 1.1 for the Hunter subregion (McVicar et al., 2015), particularly information relevant to the development of a regional geological model.

A number of coal seam gas (CSG) models have been developed for this region. Many focus on CSG distribution and quality in the individual coalfields (e.g. Creech, 1994; Faiz et al., 2003; Faiz et al., 2007; Burra and Esterle, 2012; Pinetown, 2010, 2014; Thomson et al., 2008), although some are at the scale of the Sydney Basin (e.g. Burra et al., 2015). These models provide details of CSG maturity and geochemistry but do not provide a regional geological interpretation at the scale of the Hunter subregion.

Other existing models do focus on the geological framework of the Sydney Basin, but were developed for understanding the geological basement structure and have limited resolution of the Permo-Triassic stratigraphy. Coal measures occur within the Permian age units, which when not outcropping at the surface lie below Triassic units. It is the Permo-Triassic stratigraphy then that is of most relevance for a geological model to underpin the Hunter bioregional assessment. It is the basement structure and main structural trends that have been particularly well investigated in the pre-existing geological models – for example: in a study that integrated multidisciplinary datasets, such as deep reflection seismic, gravity and magnetic datasets (Blevin et al., 2007); in a synthesis of the Sydney Basin deep, regional structure by SRK Consulting (Woodfull et al., 2004); more recently, a geological model was built to refine the gravity interpretation (Danis et al., 2011); and NSW Trade and Investment have undertaken a study based on Chemical Abrasion Isotope Dilution Thermal Ionisation Mass Spectrometry (CA-IDTIMS) tuff dating and stratigraphic correlation at the scale of the geological Sydney-Gunnedah Basin (Oliveira et al., 2014). This last study provides a regional-scale interpretation of a few stratigraphic intervals within the sedimentary pile such as the Permo-Triassic limit, the upper coal measures interval, the Greta Coal Measures and the top of the Dalwood Group.

Following a review of existing geological datasets and models available, it was concluded that a BA-specific geological model for the Hunter subregion could provide better representation of the Permo-Triassic stratigraphy and provide an independent review and interpretation of the hard datasets (i.e. original datasets, with the minimum of interpretation) in the time frame of the Assessment (June 2014 to February 2015). Quaternary alluvium is not represented in the geological model, but is incorporated into the groundwater model where it is needed to represent alluvial aquifers and connections between groundwater and surface water.

Details of the observed datasets are provided in Section 2.1.2.1. Note that the Hunter geological model is based on publicly available datasets. 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.

2.1.2.1 Observed data

Three types of observed data were used to develop and build a geological model for the Hunter subregion: deep wells datasets (DTIRIS NSW, Dataset 1; CSIRO, Dataset 2, Dataset 4; Bioregional Assessment Programme, Dataset 3), surface geological maps (Geoscience Australia, Dataset 5) and geophysical datasets (Geoscience Australia, Dataset 6, Dataset 7).

The deep wells dataset consists of stratigraphic and lithological data extracted from petroleum exploration well completion reports (WCRs) (WCR details are included within the list of references following Section 2.1.2.3). Other well data are available, such as groundwater bores and coal bores that could provide more detail within each shallow geological level, but they were not integrated into the model due to time and resource constraints and the objective of building a model fit for regional-scale groundwater modelling.

The geophysical and geological maps datasets comprise regional-scale data that could be incorporated into a model with a 2 km^2 grid cell resolution within the available time and resources. The selected datasets comprise SRTM (Shuttle Radar Topography Mission) topography (Geoscience Australia, Dataset 7), bathymetry (Geoscience Australia, Dataset 6) and deep structure datasets, the 1:2,500,000 scale Geological Map of NSW (Scheibner, 1999) and the stratigraphy, structural and isopach maps described in companion product 1.1 for the Hunter subregion (McVicar et al., 2015). Maps based on these datasets are published in this companion product as follows:

- Figure 29 Structural elements of the Sydney Basin (Stewart and Alder, 1995)
- Figure 30 Surface geological map of the Hunter subregion (modified from Stewart and Alder, 1995 and Geoscience Australia 2012)
- Figure 31 Thickness contour map of the upper coal measures of the Sydney Basin (modified from Blevin et al., 2007)
- Figure 33 Generalised stratigraphic column of the Permian and Triassic units in the main coalfields of the Sydney Basin (Geoscience Australia, 2014)
- Figure 35 Structural elements of the Newcastle Coalfield (Agnew et al., 1995)
- Figure 36 Structural elements of the Western Coalfield (Yoo et al., 1995).

2.1.2.1.1 Deep wells dataset

The deep wells data (DTIRIS NSW, Dataset 1; CSIRO, Dataset 2, Dataset 4; Bioregional Assessment Programme, Dataset 3) provide information about the rock types and stratigraphic unit limits of the Hunter subregion from geophysical logs, core and cutting analyses summarised in the WCRs (see the listing of WCRs within the list of references following Section 2.1.2.3).

The first wells were drilled in the 1920s by the Thrift Mineral Prospecting Syndicate. The rate of deep well drilling increased in the 1960s with the Australian Oil and Gas Corporation Ltd exploration campaigns. In the late 1980s and early 1990s, CSG emerged as a viable development opportunity and provided the motivation to drill more wells. Sydney Gas Ltd, Sydney Gas Operations, Macquarie Energy Pty Ltd and AGL Energy Limited have been responsible for most of the drilling in the last 15 years.

In all, 105 WCRs were consulted and included all onshore deep wells in the Hunter subregion, as well as those within 50 km of its boundaries (104 wells) and one offshore well, located within 50 km of the subregion (Table 3). The offshore well is New Seaclem 1 and was drilled in 2011 (Advent Energy, 2011). A full listing of the WCRs is provided within the list of references following Section 2.1.2.3.

Table 3 List of petroleum wells with well completion reports publicly available in the Hunter subregion

Well name	Date	Company	Latitude	Longitude	Total depth (m MD KB[a])
Allambi 1C	2007	Eastern Star Gas Limited	–31.9229°	149.6865°	385
Balmain 1	1937	Natural Gas and Oil Corporation Ltd	–33.8517°	151.1777°	1504
Baulkham Hills 1	1961	Australian Oil and Gas Corporation Ltd	–33.7502°	151.0084°	1067
Belford 1	1965	Australian Oil and Gas Corporation Ltd	–32.6529°	151.2847°	1175
Belford Dome 1	1930	Unknown	–32.6472°	151.2852°	472
Berkshire Park 1	1968	Australian Oil and Gas Corporation Ltd	–33.6798°	150.7905°	1091
Big Adder Hill 1	1995	Amoco Australia Development Company Ltd	–32.4771°	150.7760°	657
Black Springs 1	2008	Sydney Gas Ltd	–32.1636°	150.6523°	761
Bootleg 2A	1982	Australian Gas Light Company Ltd / OXY	–33.6871°	151.0604°	1411
Bootleg 3	1982	Australian Gas Light Company Ltd / OXY	–33.1433°	151.4179°	406
Bootleg 4	1982	Australian Gas Light Company Ltd / OXY	–33.3790°	151.4720°	748
Bootleg 5	1981	Australian Gas Light Company Ltd / OXY	–33.1299°	150.6927°	1099
Bootleg 6	1982	Australian Gas Light Company Ltd / OXY	–33.2022°	150.9740°	898
Bootleg 7	1982	Australian Gas Light Company Ltd / OXY	–33.4329°	150.8632°	1072
Brawboy 1	2009	Santos QNT Pty Ltd	–31.8974°	150.6419°	1435
Brawboy 2	2010	Santos QNT Pty Ltd	–31.9043°	150.6425°	1089
Bulga 1	1994	Amoco Australia Petroleum Company Ltd	–32.6939°	151.0158°	1097
Camberwell 1	1966	Australian Oil and Gas Corporation Ltd	–32.5405°	151.1018°	1903
Camberwell 2	1986	Sydney Oil Company Pty Ltd	–32.5412°	151.1055°	1173
Cape Three Points 1	1974	Robertson Research Australia Pty Ltd	–33.4779°	151.4405°	610
Catherine Hill Bay 1	2009	Macquarie Energy Pty Ltd	–33.1620°	151.6301°	1099
Coolahville 1C	2007	Eastern Star Gas Limited	–31.8444°	155.6986°	396
Cuan 1	2010	Santos QNT Pty Ltd	–31.9724°	150.6433°	1422
Dartbrook 1	2009	AGL Energy Limited	–32.1349°	150.8001°	895
Doolans Creek 1	1995	Amoco Australia Petroleum Company Ltd	–32.2154°	150.3090°	945
Dural 1	1957	Australian Oil and Gas Corporation Ltd	–33.6856°	151.0567°	1586
Dural 3	1958	Australian Oil and Gas Corporation Ltd	–33.6667°	151.0163°	1971
Dural South 1	1966	Shell Development Pty Ltd	–33.7084°	151.0161°	3059
East Dunlop 1	1995	Amoco Australia Petroleum Company Ltd	–32.1390°	150.2987°	1094
East Maitland 1	1963	Planet Exploration Company Pty Ltd	–32.7609°	151.6176°	3049
Elizabeth Macarthur 21V	2004	Sydney Gas Ltd	–34.1138°	150.7261°	640

Well name	Date	Company	Latitude	Longitude	Total depth (m MD KB[a])
Farley 1	1935	W. Maskell	–32.7510°	151.5106°	1635
Farley 2	1959	Sun Oil and Gas Company of California	–32.7316°	151.4922°	632
Fullerton 1	2011	Dart Energy Limited	–32.8086°	151.8379°	901
Fullerton 2	2011	Dart Energy Limited	–32.8406°	151.8369°	1152
Fullerton 3	2011	Dart Energy Limited	–32.8308°	151.8251°	853
Fullerton 4	2011	Dart Energy Limited	–32.8180°	151.8793°	750
Goulburn River 1	1995	Amoco Australia Development Company Ltd	–32.4236°	150.6534°	609
Hawkesbury Bunnerong 1	1993	Pacific Power	–33.9702°	151.2300°	1251
Hawkesbury Eveleigh 1	1995	Pacific Power	–33.8958°	151.1938°	1317
Hawkesbury Lisarow 1	1991	Pacific Power	–33.3757°	151.3846°	1000
Hawkesbury Munmorah 1	1992	Pacific Power	–33.2328°	151.4994°	260
Hawkesbury Munmorah 2	1993	Pacific Power	–33.2341°	151.5001°	269
Hawkesbury Munmorah 3	1994	Pacific Power	–33.2351°	151.4952°	245
Higher Macdonald 1	1968	Australian Oil and Gas Corporation Ltd	–33.2137°	150.9339°	628
Howes Swamp 1	1970	Esso Exploration and Production Australia Inc	–33.1289°	150.6919°	2570
Hunter Bulga 1	2004	Sydney Gas Ltd	–32.7412°	151.1051°	537
Hunter Bulga 2	2004	Sydney Gas Ltd	–32.7433°	151.1108°	531
Hunter Corehole 3	2007	Sydney Gas Ltd	–32.6473°	150.9852°	906
Hunter Corehole 1	2009	Sydney Gas Ltd	–32.6580°	151.1319°	900
Hunter Coricudgy 1	1992	Pacific Power	–32.8557°	150.3477°	865
Hawkesbury Llanillo 1	1991	Pacific Power	–32.4360°	150.8365°	766
Hawkesbury Randwick Park 1	1991	Pacific Power	–32.439°	150.8026°	700
Jerrys Plains 1	1969	Esso Exploration and Production Australia Inc	–32.4730°	150.9412°	1595
Jilliby 1	2004	Sydney Gas Operations (Wyong)	–33.2543°	151.3865°	621
Jilliby 13	2005	Sydney Gas Operations (Wyong)	–33.2420°	151.3881°	613
Jilliby 1B	2004	Sydney Gas Operations (Wyong)	–33.2560°	151.3867°	500
Jilliby 2	2004	Sydney Gas Operations (Wyong)	–33.2366°	151.3723°	591

Well name	Date	Company	Latitude	Longitude	Total depth (m MD KB[a])
Kenthurst 1	1963	Australian Oil and Gas Corporation Ltd	–33.6615°	151.0183°	1067
Knight 1	2002	Sydney Gas Company NL	–32.7009°	151.0540°	748
Kulnura 1	1964	Australian Oil and Gas Corporation Ltd	–33.2138°	151.1972°	2473
Kurrajong Heights 1	1962	Australian Oil and Gas Corporation Ltd	–33.5268°	150.6196°	2783
Loder 1	1927	Oil And Gas Investigations Ltd	–32.6268°	151.1260°	729
Loder 1	1963	Australian Oil and Gas Corporation Ltd	–32.6322°	151.1334°	2063
Longley 1	1973	North West Oil and Minerals Company NL	–33.3561°	151.2886°	1031
Lower Portland 1	1968	Australian Oil and Gas Corporation Ltd	–33.4326°	150.8635°	886
Macdonald 2	1971	Metals Investment Holdings NL	–33.3182°	150.9632°	752
Maison Dieu 1	2008	Sydney Gas Ltd	–32.5148°	151.0698°	292
Martindale 1/1A	1967	Australian Oil and Gas Corporation Ltd	–32.5160°	150.6153°	1181
Meads Crossing 1	2011	Planet Gas Limited	–32.2656°	150.0916°	590
Mellong 1	1964	Australian Oil and Gas Corporation Ltd	–32.9995°	150.7122°	905
Millfield 1	1966	Australian Oil and Gas Corporation Ltd	–32.8759°	151.2077°	644
Monkey Place 1	2010	AGL Energy Limited	–32.7459°	151.1468°	556
Monkey Place 2	2010	AGL Energy Limited	–32.7425°	151.1450°	571
Monkey Place 3	2010	AGL Energy Limited	–32.7467°	151.1422°	571
Monkey Place 4	2010	AGL Energy Limited	–32.7478°	151.1477°	685
Mt Murwin 1	1963	Australian Oil and Gas Corporation Ltd	–32.8492°	150.9504°	887
New Seaclem	2011	Advent Energy Limited	–32.9304°	153.3736°	750
North Castlereagh 1	1993	Amoco Australia Petroleum Company Ltd	–33.6387°	150.6780°	1320
North Colah 1	1971	Metals Investment Holdings NL	–33.6098°	151.1089°	837
Oakdale 1	2009	Santos QNT Pty Ltd	–31.7587°	155.8618°	892
Paynes Crossing 1	2008	Sydney Gas Ltd	–32.8757°	151.0826°	1082
Pinegrove 1	2002	Sydney Gas Ltd	–32.5624°	150.9650°	511
Riverstone 1	1992	Amoco Australia Petroleum Company Ltd	–33.6769°	150.8130°	1537
Rothanal 1	2008	Sydney Gas Ltd	–32.6783°	151.2651°	866
Rouchel Rouchel 1	2009	Santos QNT Pty Ltd	–31.9881°	150.8061°	484
Rouchel Rouchel 2	2009	Santos QNT Pty Ltd	–31.9881°	150.8061°	999
Roughit 1	2008	Sydney Gas Ltd	–32.5724°	151.2575°	1064
Sedgefield 1	1964	Australian Oil and Gas Corporation Ltd	–32.5113°	151.2546°	687
Shearman 1	1989	Command Petroleum NL	–32.8436°	151.8105°	739
Singleton 1	1992	Amoco Australia Petroleum Company Ltd	–32.5334°	151.1411°	1299

Well name	Date	Company	Latitude	Longitude	Total depth (m MD KB[a])
St Albans 1	1970	Metals Investment Holdings NL	–33.3559°	150.9787°	845
Terrigal 1	1961	J. Stevens	–33.4393°	151.4312°	1886
Turill 1	2010	Santos QNT Pty Ltd	–32.0627°	150.0555°	1110
Turnermans 1	2009	AGL Energy Limited	–32.4787°	150.6772°	727
Wappinguy 1	2009	Sydney Gas Ltd	–32.2089°	150.4841°	901
Whybrow 2	1986	Sydney Oil Company Pty Ltd	–32.6774°	150.9822°	610
Windermere 1	2010	AGL Energy Limited	–32.6400°	151.0220°	623
Windermere 2	2010	AGL Energy Limited	–32.6431°	151.0208°	615
Windermere 3	2010	AGL Energy Limited	–32.6400°	151.0158°	609
Windermere 4	2010	AGL Energy Limited	–32.6433°	151.0252°	733
Windy Hill 1	1992	Amoco Australia Petroleum Company Ltd	–32.8543°	151.6417°	928
Wollombi Brook 1	1994	Amoco Australia Petroleum Company Ltd	–32.7633°	151.0769°	996
Woodbury 1	1966	Planet Exploration Company Pty Ltd	–32.7892°	151.6822°	671
Wybong 1	1995	Amoco Australia Petroleum Company Ltd	–32.2734°	150.6548°	763

[a]depths are measured depth (MD) relative to the kelly bushing (KB). A kelly bushing is an adapter that connects the rotary table to the kelly which transmits the rotary motion to the drillstring during drilling.
Data: see the listing of well completion reports within the list of references following Section 2.1.2.3

Well distribution varies across the Hunter subregion (Figure 6). The highest concentrations are in the Hunter Coalfield around Singleton, and the Newcastle Coalfield between Lake Macquarie and Tuggerah Lakes. However, much of the subregion has sparse deep wells data. The measured depths (MD) of these wells vary between 245 m MD (well Hawkesbury Munmorah 3) and 3059 m MD (well Dural South 1) relative to the kelly bushing (KB) at the top of each well, just above ground level (a kelly bushing is an adapter that connects the rotary table to the kelly – a square or hexagonal steel bar with a hole drilled through the middle for a fluid path – which transmits the rotary motion to the drillstring during drilling). The quality of the stratigraphic and structural interpretations is variable, reflecting the ages of the wells and differences in geological interpretation from one company to another and from one coalfield to another. The data that can be used to construct a regional geological model are identified as part of the statistical analysis (Section 2.1.2.2.3).

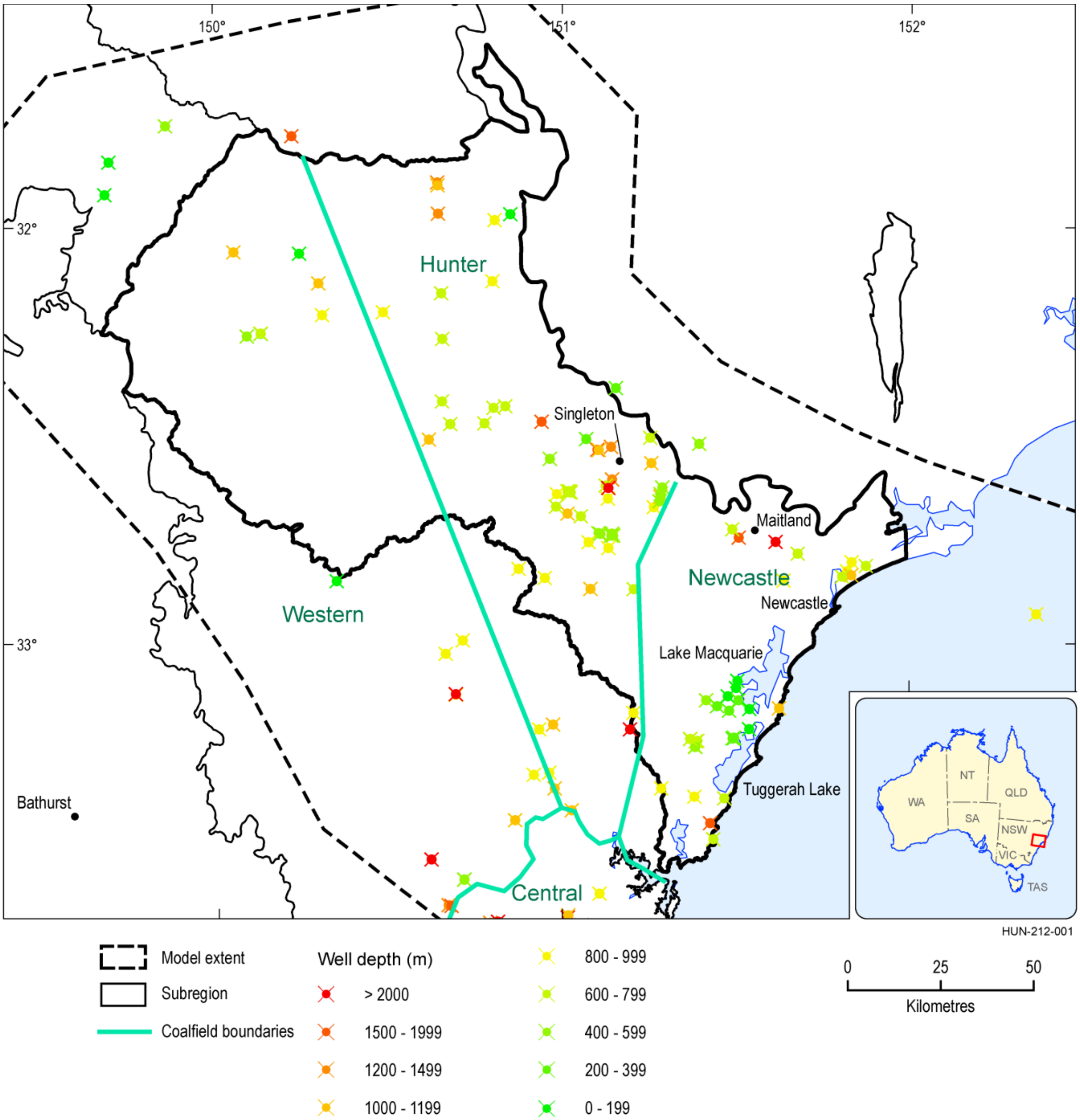


Figure 6 Spatial distribution of petroleum wells within the Hunter subregion

GL = ground level; well depths are relative to ground level in this figure
Data: CSIRO (Dataset 2)

2.1.2.1.2 Geological maps and geophysical datasets

Onshore topography and offshore bathymetric datasets were used to map the upper surface of the Hunter subregion. The surface topography used in the geological model was extracted from a 3-second digital elevation model (DEM) (Geoscience Australia, Dataset 7). The offshore bathymetric surface was extracted from 9-second bathymetry data (Geoscience Australia, Dataset 6). Both datasets are described in Section 2.1.1. The grids were reprojected to Australian Map Grid (AMG) zone 56 with a cell resolution of 90 m to fit with the petroleum well coordinate system and get the best from the data with reasonable computer processing performance. This resolution is compatible with the 2 km^2 cell size of the model. The base of the Hunter subregion geological model was extracted from the Structurally Enhanced view of Economic Basement data (known as OZ SEEBASE) (FrOG Tech, Dataset 8). This dataset provides depth to basement model all over Australia and was used because it is publicly available.

Existing data about geological structures (folds and faults), as well as stratigraphic unit extents and thicknesses, are in Section 1.1.3 of companion product 1.1 for the Hunter subregion (McVicar et al., 2015). These data, which are also listed in Section 2.1.2.1, were digitised and integrated in the three-dimensional model calibration dataset (see Section 2.1.2.2.3).

2.1.2.2 Statistical analysis and interpolation

Observed datasets (Section 2.1.2.1) were analysed and processed to form derived datasets for use in the bioregional assessment of the Hunter subregion. These datasets were analysed and interpolated to develop a three-dimensional geological model of the Carboniferous to Triassic stratigraphic sequences of the Hunter subregion. The three-dimensional geological model with 2 km^2 cell size was built using Roxar Reservoir Management Software (Roxar RMS). Developed by Emerson (2016), this product is traditionally used in the oil and gas industry to make hydrocarbon reservoir or basin-scale models. Other packages are available, such as GOCAD® Mining Suite or Leapfrog® three-dimensional geological mining software. Roxar RMS was adopted because it has the option of computing 3D facies grids based on a stratigraphic analysis approach within the grid cells (see Emerson (2016) for more details).

2.1.2.2.1 Workflow

Having established the need to build a regional geological model for bioregional assessment purposes, a workflow was defined to construct the first-order subsurface structural and stratigraphic architecture of the Hunter subregion. The approach is based on classical three-dimensional geological modelling approaches (Ross et al., 2004) to produce a simple regional model from poorly constrained datasets. The aim of this workflow is to model the large-scale stratigraphic units without introducing structural complexity into the grid geometry that is not supported by the available hard data (Wellmann et al., 2010). The workflow comprised:

1. selection and processing of the observed data to form derived datasets and implementing the model numerical database (see Section 2.1.2.2.2), including:
    a. defining regional horizons
    b. determining horizon tops and lithological datasets from the deep well dataset and geological maps
    c. mapping the topography and bathymetry of the subregion from DEM data
2. three-dimensional non-faulted and non-eroded geological modelling (see Section 2.1.2.2.3):
    a. selecting reference horizons and creating a horizon depth map
    b. isopach mapping
    c. building a preliminary (non-faulted and non-eroded) geological model
    d. extracting depth structure maps from the geological model
3. fold and fault analysis to refine the geological model (see Section 2.1.2.2.4).

2.1.2.2.2 Data selection and processing

Spatial distribution of the deep wells data in the Hunter subregion is poor: only heterogeneous scattered well data are available as shown by Figure 6. These types of data are point source and do not provide much insight into the three-dimensional structure of the geological units at depth.

Generalised stratigraphic columns for the Hunter, Newcastle, Western and Central coalfields (shown in the geology section of the companion product 1.1 for the Hunter subregion (McVicar et al., 2015)) and correlations proposed by NSW Trade and Investment (Oliveira et al., 2014) were used to define 'regional horizons' for the purpose of this Assessment. Nine regional horizons were determined. They are named according to the nomenclature used by NSW Trade and Investment, with 'M' referring to Mesozoic and 'P' to Paleozoic. The relationship between these regional horizons and the stratigraphic units in each of the four coalfields are shown in Table 4.

Well completion reports (WCR) were analysed to determine the top depth of regional horizons. Of the 105 wells in the original dataset, 44 wells had information that could be used in the model. The markers of the horizon top depths in the wells are called 'well picks'. Table 5 summarises for each well in the derived dataset the pick depths and the top of regional horizon to which it corresponds. The uncertainties in the depths to the tops of the horizons are not known. They are a function of the original well stratigraphic interpretation; a new integrated interpretation of all the well logs could remove some uncertainty at this stage. However, due to operational constraints, this type of integrated interpretation could not be achieved for this geological model.

The well top data and relevant structural contours from the outcrop limits and mapped isopachs in the Newcastle Coalfield (see Figure 35 in companion product 1.1) and Western Coalfield (see Figure 36 in companion product 1.1) were mapped for each of the regional horizons (Figure 7). P500 and P100 are the best constrained horizons in terms of number of well tops. Figure 7 shows the distribution of the nine horizon tops in nine separate maps.

Table 4 Relationship between regional horizons and stratigraphic units in the coalfields of the Hunter subregion

Regional horizon name	Age (geological stage)	Newcastle Coalfield	Hunter Coalfield	Western Coalfield	Central or Southern coalfields
M600	Top Anisian	Top Hawkesbury Sandstone	Top Hawkesbury Sandstone	Top Hawkesbury Sandstone	Base Wianamatta Group
M700	Top Olenekian	Base Hawkesbury Sandstone	Base Hawkesbury Sandstone	Base Hawkesbury Sandstone	Base Hawkesbury Sandstone
P000	Top Changhsingian	Base Narrabeen Group	Base Narrabeen Group	Base Narrabeen Group	Base Narrabeen Group
P100	Upper Wuchiapingian	Base Newcastle Coal Measures	Base Newcastle Coal Measures	Top Watts Sandstone	Top Bargo Claystone
P500	Mid Capitanian	Base Tomago Coal Measures	Base Wittingham Coal Measures	Base Illawarra Coal Measures	Base Illawarra Coal Measures
P550	Top Wordian	Base Mulbring Siltstone	Base Mulbring Siltstone	Base Berry Siltstone	Base Berry Siltstone
P600	Mid Roadian	Base Maitland Group	Base Maitland Group	Base Shoalhaven Group	Base Shoalhaven Group
P700	Upper Kungurian	Base Greta Coal Measures	Base Greta Coal Measures		
P900	Base Serpukhovian	Base Seaham Formation	Base Seaham Formation		

Refer to the Sydney Basin stratigraphic column in Hodgkinson et al. (2016) for more details

Table 5 Depth to top of regional horizons from deep wells across the Hunter subregion

Well name	Regional horizon top	Pick depth (m TVD ss[a])	Well name	Regional horizon top	Pick depth (m TVD ss[a])
Allambi_1C	M700	–367.84	Howes_Swamp_1	P600	1545.87
Allambi_1C	P000	–258.84	Howes_Swamp_1	P900	2256.96
Allambi_1C	P500	–154.24	Hunter_Bulga_1	P000	24.53
Allambi_1C	P550	–138.04	Hunter_Bulga_1	P100	30.59
Allambi_1C	P900	–103.54	Hunter_Bulga_1	P500	463
Baulkham_Hills_1	M600	–89.4	Hunter_Bulga_2	P000	34.46
Baulkham_Hills_1	M700	154.44	Hunter_Bulga_2	P100	50.28
Baulkham_Hills_1	P500	977.4	Hunter_Bulga_2	P500	449.44
Berkshire_Park_1	M600	396.3	Hunter_Coricudgy_1	M700	–947.2
Berkshire_Park_1	M700	1062.3	Hunter_Coricudgy_1	P000	–462.2
Berkshire_Park_1	P000	3281.6	Hunter_Coricudgy_1	P500	403.15
Berkshire_Park_1	P500	3490.6	Jilliby_13	M700	5.3
Big_Adder_Hill_1	P500	550.32	Jilliby_13	P000	389.41
Black_Springs_1	P000	24.88	Jilliby_13	P100	550.69
Brawboy_1	M700	–356.18	Jilliby_13	P500	601.3

Well name	Regional horizon top	Pick depth (m TVD ss[a])	Well name	Regional horizon top	Pick depth (m TVD ss[a])
Brawboy_1	P000	238.92	Kenthurst_1	M600	0
Brawboy_1	P100	550.8	Kenthurst_1	M700	259.08
Brawboy_1	P500	667.12	Kenthurst_1	P000	856.18
Brawboy_2	M700	–171.5	Kenthurst_1	P100	1067.1
Brawboy_2	P000	225	Kulnura_1	M600	0
Brawboy_2	P100	534	Kulnura_1	M700	94.48
Brawboy_2	P500	638	Kulnura_1	P000	836.67
Catherine_Hill_Bay_1	P000	–42.3	Kulnura_1	P100	981.76
Catherine_Hill_Bay_1	P100	369.1	Kulnura_1	P500	1446.27
Catherine_Hill_Bay_1	P500	1003.7	Kulnura_1	P550	1904.39
Coolahville_1C	M700	–430.84	Kulnura_1	P600	2472.53
Coolahville_1C	P000	–280.94	Longley_1	M700	–180.7
Coolahville_1C	P500	–156.34	Longley_1	P000	627
Coolahville_1C	P550	–129.14	Longley_1	P100	1031.1
Coolahville_1C	P900	–125.34	Meads_Crossing_1	M700	–59.39
Cuan_1	M700	–297.5	Meads_Crossing_1	P000	79.9
Cuan_1	P000	54.5	Meads_Crossing_1	P500	168.09
Cuan_1	P100	448.1	Mellong_1	M600	0
Cuan_1	P500	978	Mellong_1	M700	112.77
Dartbrook_1	P100	–205.83	Mellong_1	P000	755.9
Dartbrook_1	P500	618.65	Mellong_1	P100	905.25
Dural_1	M700	265.17	Monkey_Place_1	P000	–101
Dural_1	P000	844.29	Monkey_Place_1	P100	–33.67
Dural_1	P100	1150.62	Monkey_Place_1	P500	452
Dural_1	P500	1150.62	Monkey_Place_2	P000	–88.43
Dural_1	P600	1368.55	Monkey_Place_2	P100	–60.39
Dural_1	P700	1422.5	Monkey_Place_2	P500	479.57
Dural_South_1	M600	–161.23	Monkey_Place_3	P000	–95.3
Dural_South_1	M700	76.52	Monkey_Place_3	P100	–16.11
Dural_South_1	P000	634.3	Monkey_Place_3	P500	472.7
Dural_South_1	P100	787.61	Monkey_Place_4	P000	–105.2
Dural_South_1	P500	1416.41	Monkey_Place_4	P100	–24.9
Dural_South_1	P550	2217.12	North_Colah_1	M700	–5.79
Dural_South_1	P600	2851.72	North_Colah_1	P000	681.95
Dural_South_1	P900	2851.72	North_Colah_1	P500	745.84

Well name	Regional horizon top	Pick depth (m TVD ss[a])	Well name	Regional horizon top	Pick depth (m TVD ss[a])
Elizabeth_Macarthur_1H	M700	137.82	Oakdale_1	M700	–262.5
Elizabeth_Macarthur_1H	P000	507.7	Oakdale_1	P000	30.9
Fullerton_2	P500	1140.23	Oakdale_1	P100	105
Fullerton_4	P500	157.5	Oakdale_1	P500	167.3
Hawkesbury_Bunnerong_1	M600	–25	Oakdale_1	P550	231.5
Hawkesbury_Bunnerong_1	M700	211.78	Oakdale_1	P900	250.8
Hawkesbury_Bunnerong_1	P000	776.02	Riverstone_1	M600	68
Hawkesbury_Bunnerong_1	P500	1226.05	Riverstone_1	M700	287
Hawkesbury_Eveleigh_1	M600	25	Riverstone_1	P000	96
Hawkesbury_Eveleigh_1	M700	290	Rouchel_Rouchel_1	P000	–289.9
Hawkesbury_Eveleigh_1	P000	912	Rouchel_Rouchel_2	P100	329.2
Hawkesbury_Eveleigh_1	P500	1317	Tangorin1	P700	–18.66
Higher_Macdonald_1	M700	3.38	Turnermans_1	P100	–21.8
Higher_Macdonald_1	P000	567.87	Wappinguy_1	P000	166.86
Higher_Macdonald_1	P500	606.88	Wappinguy_1	P500	669.42
Howes_Swamp_1	M600	–300.61	Windermere_1	P500	479.69
Howes_Swamp_1	M700	–216.79	Windermere_3	P500	512.64
Howes_Swamp_1	P000	429.69	Windermere_4	P500	–14.15
Howes_Swamp_1	P500	1288.92			

[a]TVD ss = total vertical depth subsea reported to the Australian Height Datum
Data: see the listing of well completion reports within the list of references following Section 2.1.2.3

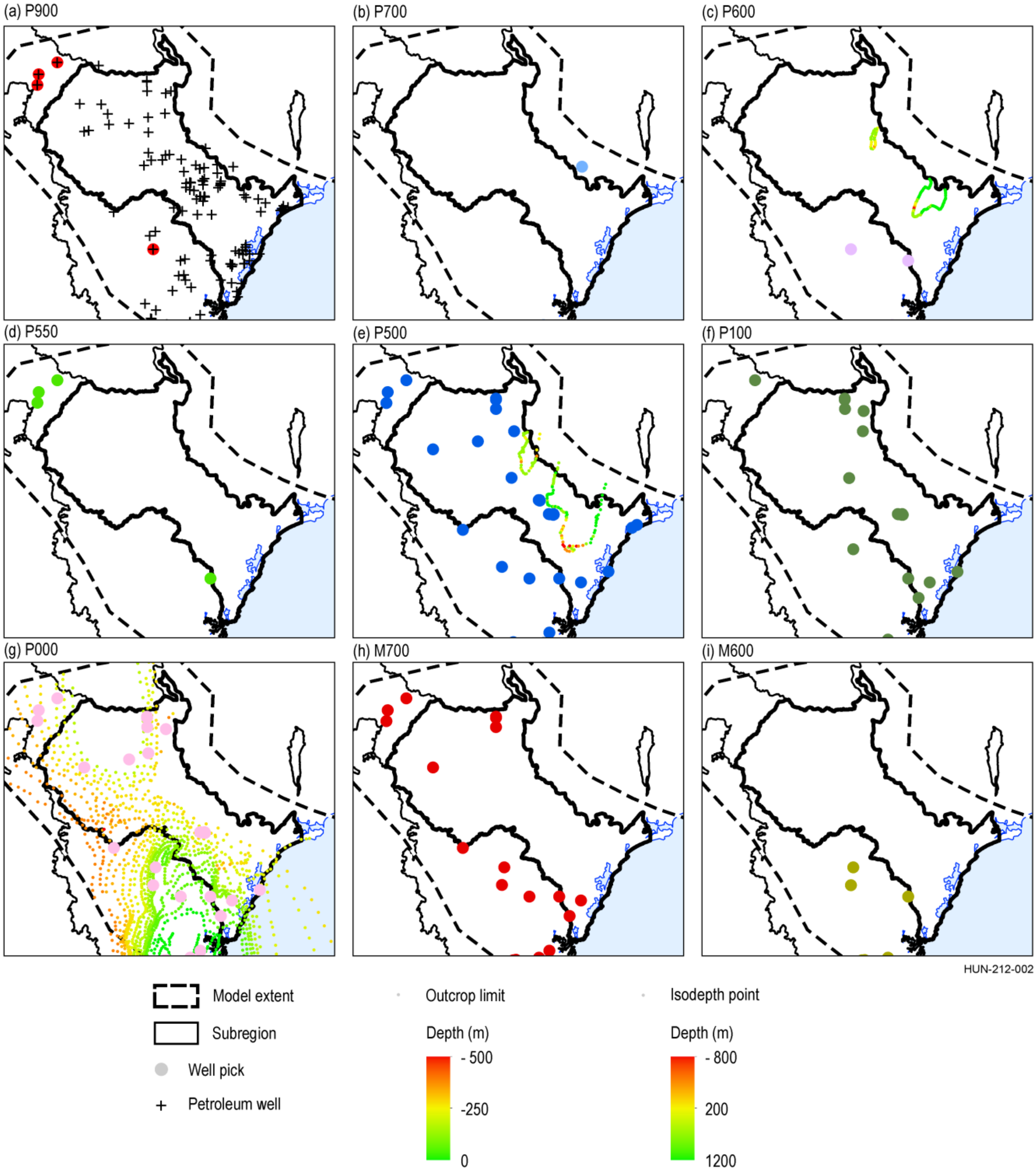


Figure 7 Distribution of regional horizon tops from the wells derived dataset for the Hunter subregion

(a) P900 shows all 105 petroleum wells. The 45 well picks that contained sufficient information to define a formation top are coloured differently for each horizon: (a) P900, (b) P700, (c) P600, (d) P550, (e) P500, (f) P100, (g) P000, (h) M700 and (i) M600. 'Well picks' are the markers of the formation top depths in the wells.
Outcrop limits are shown for the (c) P600 and (e) P500 horizons.
Isodepth points are shown for (g) P000
Data: DTIRIS NSW (Dataset 1), CSIRO (Dataset 2, Dataset 4), Bioregional Assessment Programme (Dataset 3)

The 3-second DEM and 9-second bathymetry data (see Section 2.1.2.1.1) were extrapolated with a local B-spline algorithm (Roxar package) to produce a topographic and bathymetric map of the Hunter subregion (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: this method generates stable and functional results for all types of mapping (Emerson, 2016).

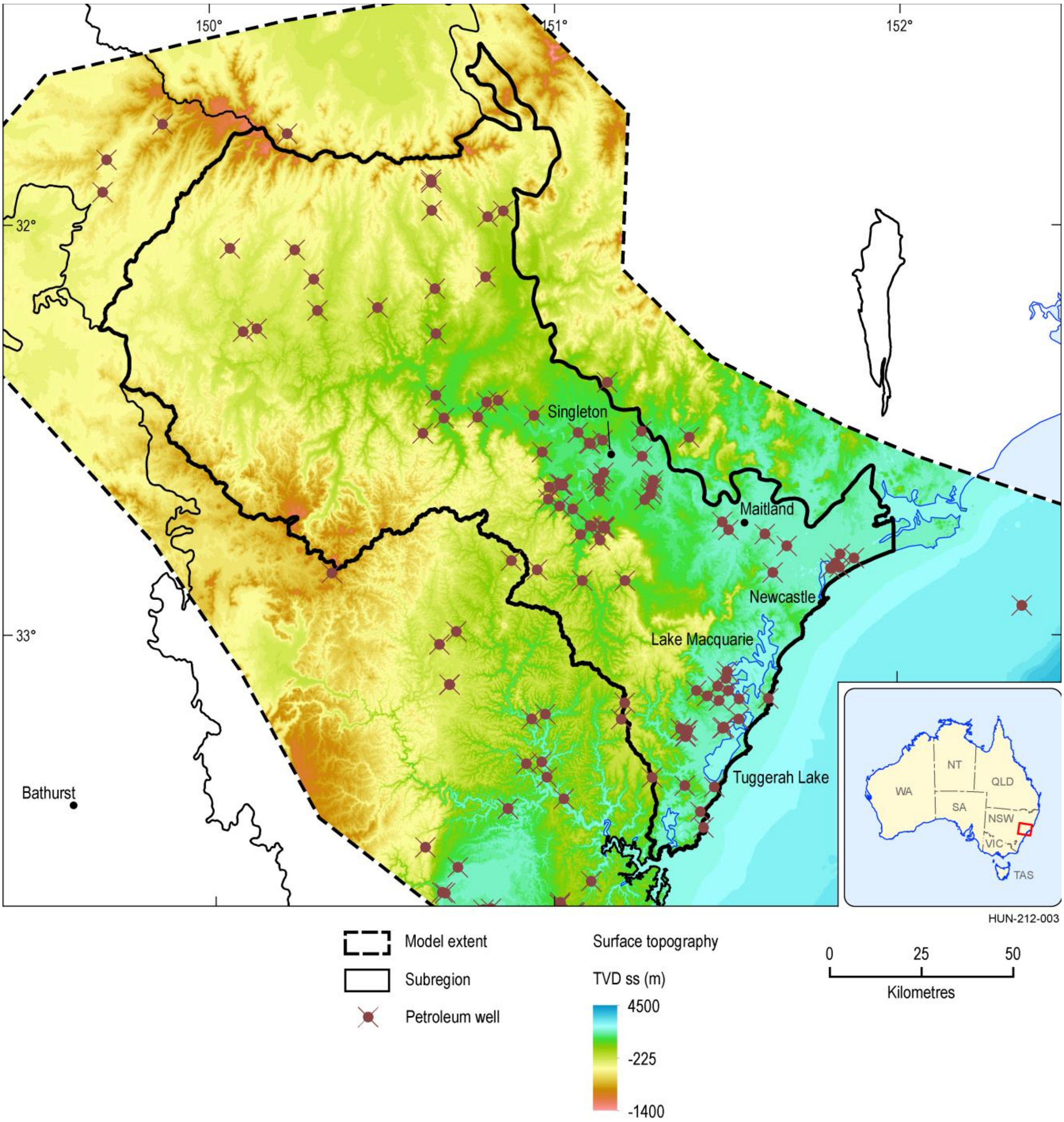


Figure 8 Surface topography and offshore bathymetry of the Hunter subregion

TVD ss = total vertical depth subsea reported to the Australian Height Datum; negative values represent elevation above sea level
Data: Bioregional Assessment Programme (Dataset 3), Geoscience Australia (Dataset 5, Dataset 6)

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

The stratigraphic reference horizons selected for the Sydney Basin geological model of the Hunter subregion were the P900, P500, P100 and P000 horizons (Figure 9). These were chosen because they have the highest density of well picks or are important regional stratigraphic markers in the Sydney Basin (Oliveira et al., 2014).

Horizon P900 is the base of the Sydney Basin sedimentary sequence (i.e. the surface of the geological basement). The horizon depth map for P900 (Figure 9a) was obtained using a global B-spline algorithm with a 500 m lateral step (x and y). The modelled depth varies between +5780 and –730 m total vertical depth subsea (TVD ss). This reference is used in the well database (Table 5) and is kept in the geological model for consistency purposes. Modelled depths have been compared with the OZ SEEBASE dataset and the calibration with well picks. Basement highs occur onshore along the western and north-east borders of the Sydney Basin; and offshore along a north-east to south-west trend. This basement structure is located deeper than 3000 m below sea level in the central and eastern parts of the basin where thick Permian and Mesozoic sediment layers are observed (purple colours, Figure 9a). This map is an intermediary modelling result that only considers the well picks of P900, without correlation with other structural data and the present-day surface topography.

The P500, P100 and P000 horizons are all important levels within the geological model as they are the stratigraphic boundaries of the main upper Permian coal-bearing units: the Newcastle, Wittingham, Illawarra and Tomago coal measures (Table 4). The initial modelling step maps each horizon independently and does not account for the present-day erosional level (as explained in the workflow, Section 2.1.2.2.1). The horizons were mapped with a 500 m increment in x and y based on the well picks and available mapping data. P500 depth varies between +1830 and –730 m TVD ss, P100 between 1050 and –733 m, P000 between 918 and –796 m. At this stage of the model development, the resulting horizon depth maps are non-deterministic, and the level of geological uncertainty increases proportionally with decreased number of data points. The horizons only conform to the available well data and regional maps, and are not further constrained by other sources of stratigraphic information. This means that there may be a poor level of consistency between different horizons, and in some cases they may even overlap at depth. To build a more coherent stratigraphic model, the next step is to generate isopach maps (thickness maps) of each geological unit, which can be used to constrain the three-dimensional structure of each horizon away from the wells (Figure 9 and Figure 10).

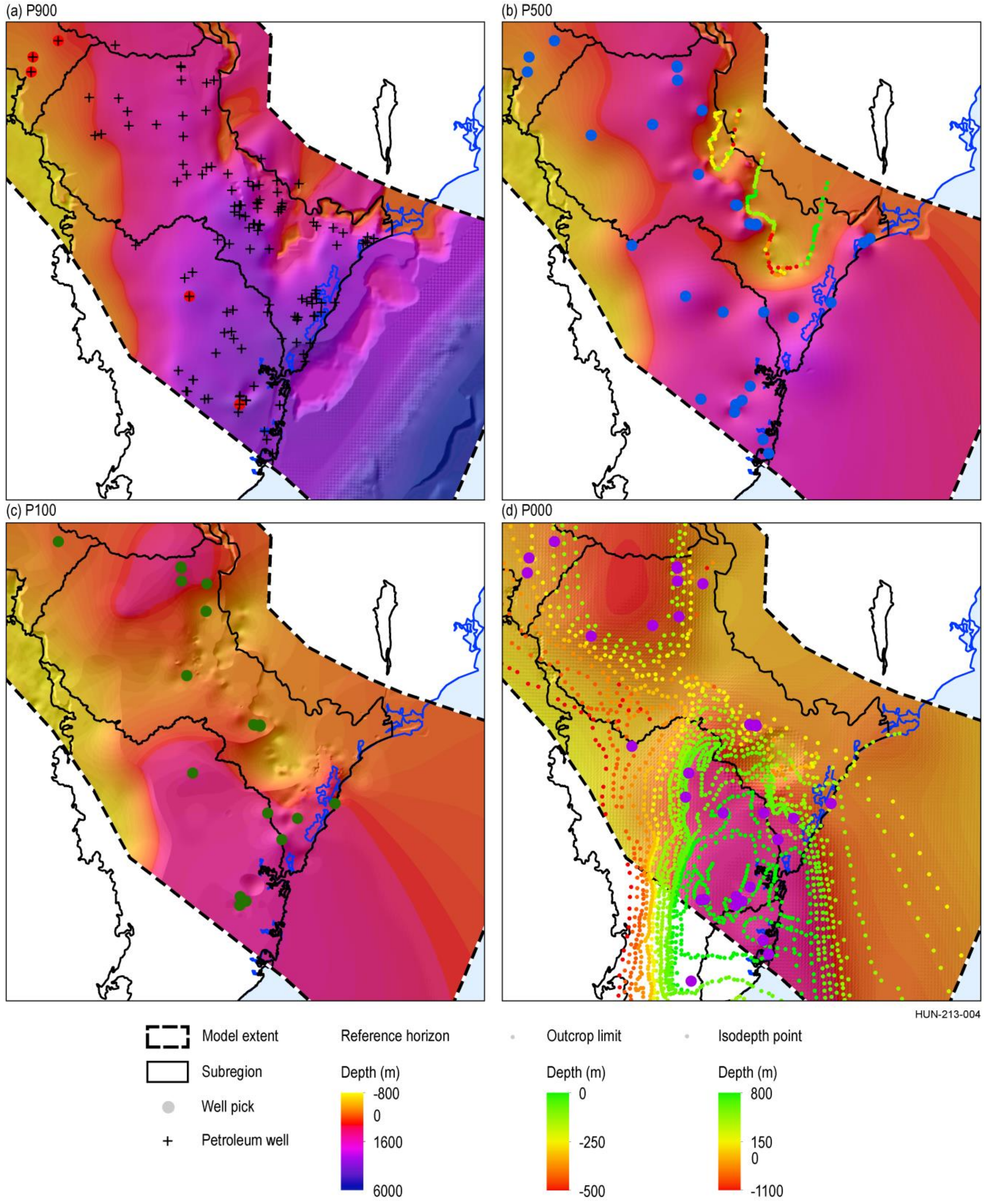


Figure 9 Non-eroded and non-folded regional horizon maps for Hunter subregion reference horizons: (a) P900, (b) P500, (c) P100 and (d) P000

(a) P900 shows all 105 petroleum wells. Well picks used to define formation tops are coloured differently for each horizon. 'Well picks' are the markers of the formation top depths in the wells.
Outcrop limits are shown in (b) for the P500 horizon.
Isodepth points are shown for (d) P000
Data: DTIRIS NSW (Dataset 1), CSIRO (Dataset 2, Dataset 4), Bioregional Assessment Programme (Dataset 3)

Six isopach maps were developed by extrapolation away from the calibration points defined by the 44 input wells and with reference to existing mapping (Table 4, Figure 7, Figure 9, Figure 10). The calibration points are called isodepths. An isodepth is the difference between two well picks for a given stratigraphic unit at a given well location. To obtain an isodepth measurement, two consecutive stratigraphic well tops must be available within the well dataset:

1. top of P700 to top of P900 – lower Permian volcanic-bearing conglomerate, siltstone and sandstone units of the Dalwood Group
2. top of P600 to top of P700 – Greta Coal Measures
3. top of P500 to top of P550 – siltstone-dominated units, including Mulbring Siltstone in Newcastle and Hunter coalfields, and Berry Siltstone in Western Coalfield
4. top of P000 to top of P100 – upper Permian coal-bearing units including the Newcastle Coal Measures in Hunter and Newcastle coalfields, and Illawarra Coal Measures in the Western Coalfield (base of Narrabeen Group to top of Watts Sandstone)
5. top of M700 to top of P000 –Triassic Narrabeen Group
6. top of M600 to top of M700 –Hawkesbury Sandstone.

These maps provide a two-dimensional representation of geological unit thickness. For the isopach maps that show the top of P000 to top of P100 (Figure 10d) and top of M700 to top of P000 (Figure 10e), thickness varies between 200 to 790 m and 154 to 789 m, respectively. Thickening occurs from the central Hunter subregion towards the north and south-east of the subregion.

For the other isopach maps, there are no obvious thickness trend variations and a constant thickness has been adopted. Average value of these thicknesses have been determined based on the well pick depths (Table 5) and thickness of formations given in Section 1.1.3.2 of companion product 1.1 (McVicar et al., 2015):

- 365 m for the Dalwood Group (top of P700 to top of P900)
- 88 m for Greta Coal Measures (top of P600 to top of P700)
- 500 m for Mulbring Siltstone in Newcastle and Hunter coalfields and the Berry Siltstone in the Western Coalfield (top of P500 to top of P550)
- 290 m for Hawkesbury Sandstone (top of M600 to top of M700).

The resulting isopach maps are non-deterministic and the uncertainty increases as the isopach data concentration decreases. These isopach maps are another intermediary step in the development of the final geological model and do not represent the final isopach data in the Hunter subregion geological model.

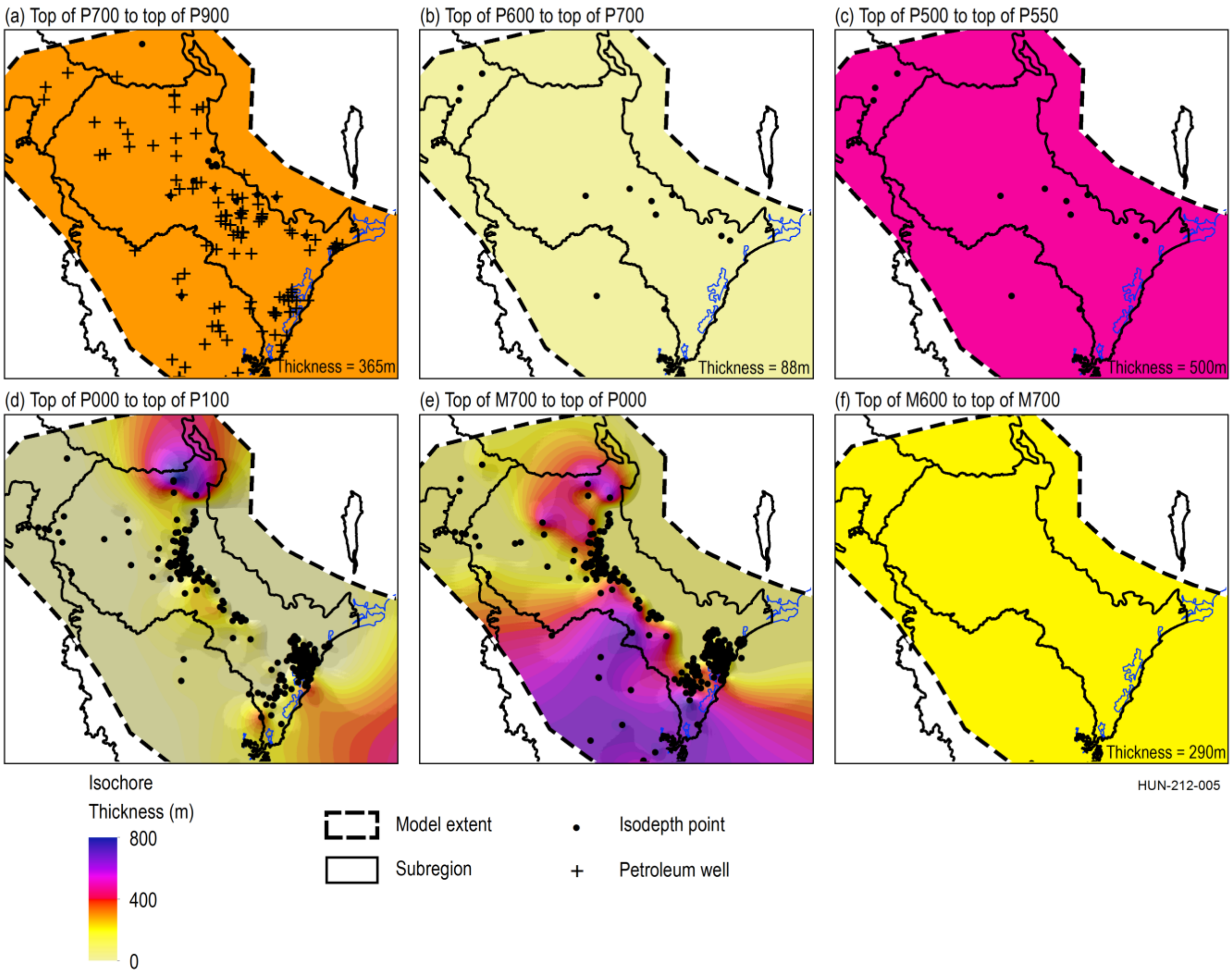


Figure 10 Isopach maps showing distribution of formation thicknesses from the wells derived dataset for the Hunter subregion

(a) Top of P700 to top of P900, (b) Top of P600 to top of P700, (c) Top of P500 to top of P550, (d) Top of P000 to top of P100, (e) Top of M700 to top of P100 and (f) Top of M600 to top of M700
An isodepth is the difference between two well picks for a given stratigraphic unit at a given well location
Data: DTIRIS NSW (Dataset 1), CSIRO (Dataset 2, Dataset 4), Bioregional Assessment Programme (Dataset 3)

The reference structural maps of P900, P500, P100, P000 (Figure 9) and the isopach maps (Figure 10) were used as input to build a non-faulted and non-eroded geological model. The geological modelling option of the Roxar RMS software takes all this information into account and can generate different simulations depending on the weight given to each dataset. A scenario giving a weight of ‘1’ to the reference horizons and ‘0.5’ to the isopachs was selected. The weighting adjustment is a classical approach in geological modelling, used to minimise the differences between the model results and the input data (Caumon et al., 2009). In this case, the reference horizons are known to be more constrained than the isopachs (Figure 9 and Figure 10) and can thus be used to build the model. The geological modelling option corrects the potential errors in each horizon interpolation, taking into account the interaction between all horizons to respect a minimum thickness between each horizon as well as the geological chronology (for example, P500 cannot occur above P100). This model has a horizontal resolution of 2 km × 2 km (x, y), with 109 layers along the vertical (z) for a total of 511,118 cells. The layers along the vertical can have variable size: 109 layers were adopted to allow a maximum thickness of 200 m to each cell and enable the generation of a facies grid with a non-homogeneous lithology within each unit. The depth ranges between 1185 m above sea level (the highest elevation known in the subregion) and 5062 m below sea level (the deepest part of the sedimentary infill sequence of the Sydney Basin).

Figure 11 shows depth structure maps of the non-faulted and non-eroded horizons extracted from the geological model.

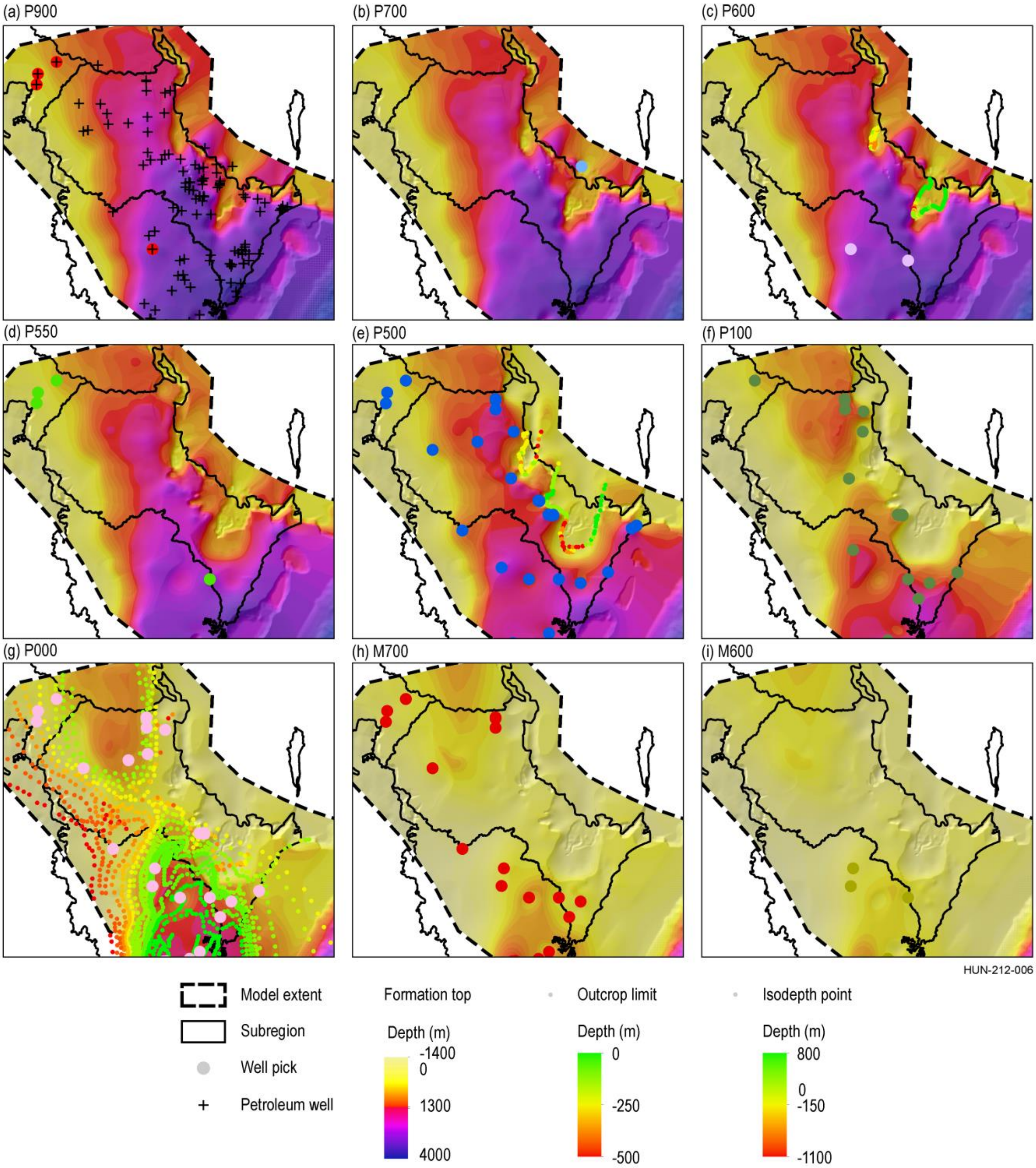


Figure 11 Depth structure maps of folded and non-eroded horizons extracted from the geological model for the Hunter subregion

Outcrop limits are shown on (e) and (c) and the isodepth points on (g).
'Well picks' are the markers of the formation top depths in the wells.
The depths are in TVD ss AHD = total vertical subsea reported to Australian Height Datum; negative values represent elevation above sea level
Data: DTIRIS NSW (Dataset 1), CSIRO (Dataset 2, Dataset 4), Bioregional Assessment Programme (Dataset 3)

2.1.2.2.4 Preliminary three-dimensional geological model

The extracted non-eroded horizons (Figure 11) were compared with the well data in the geomodelling software (Roxar RMS) and the difference between the datasets was minimised as a function of the main fold trends observed within the Hunter subregion. Then, the resulting horizons were eroded by the topographic level to obtain a preliminary three-dimensional present-day geological model (CSIRO, Dataset 9). Folding seems to be the dominant first-order structure influencing the regional horizon structures: anticline and synclines are indeed the most represented structure within the subregion (Stewart and Alder, 1995).

Fault and fractures are present within the basin but there is insufficient information about their three-dimensional structure, dip, throw and displacement to inform the model in the time frame of the Assessment. Therefore, faults have not been represented in the model (see Section 2.1.2.3).

The three-dimensional structure of the preliminary geological model and the facies distribution within the structural grid are illustrated in Figure 12 and Figure 13. The facies were simply defined at regional scale from the regional generalised stratigraphic column of the Permian and Triassic units in the main coalfields of the Sydney geological basin (Figure 33 of companion product 1.1. for the Hunter subregion (McVicar et al., 2015)). Figure 13 provides an overview of the facies architecture, illustrating the mixed facies of the Permian coal-bearing intervals capped in the central and western parts of the basin by more uniform Triassic sandstone, siltstone and mudstone formations. Figure 14 shows the regional horizon tops extracted from this folded and eroded geological model. The main fold trends affect the entire stratigraphic sequence and the white areas reflect the zones eroded at present day. The model had been folded through several numerical iterations of Roxar RMS stratigraphic modelling plugging to minimise the difference between the primary maps (Figure 11) and the well picks (Table 4). While Figure 14 also shows the surface expressions of faults from previous geological mapping, they are not included in the Hunter geological model.

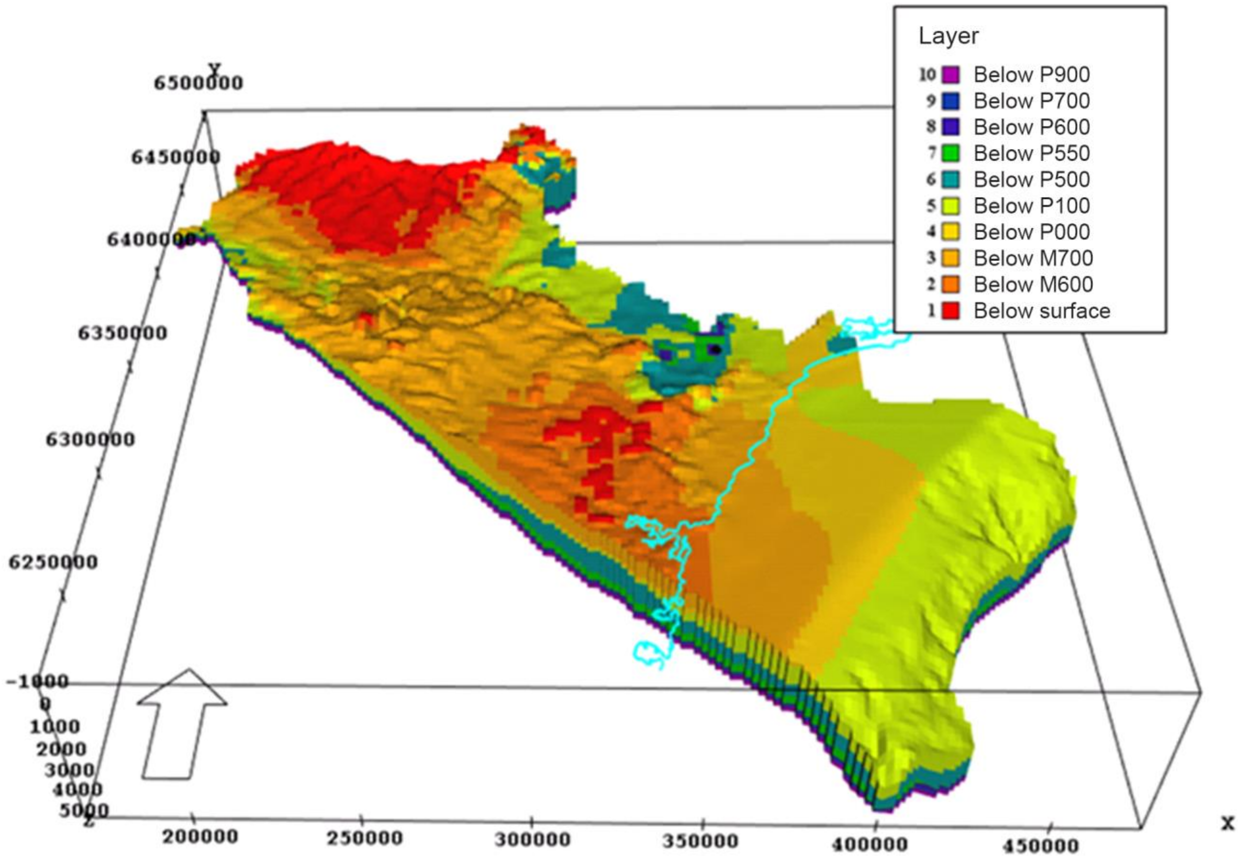


Figure 12 Three-dimensional perspective view of the eroded and folded geological model for the Hunter subregion

View from the south, showing the surface expression of model horizons across the subregion. Upland areas are dominated by horizon 1; in the more eroded areas, the Newcastle, Tomago, Wittingham and Illawarra Coal Measures (horizons 4 and 5) are at or closer to the surface, and are the main mining areas of the Hunter and Western coalfields where a mix of open-cut and underground mining occur; only underground mining occurs in the Newcastle Coalfield along the coast where the Greta Coal Measures (horizon 8) are deeper.
Data: CSIRO (Dataset 9)

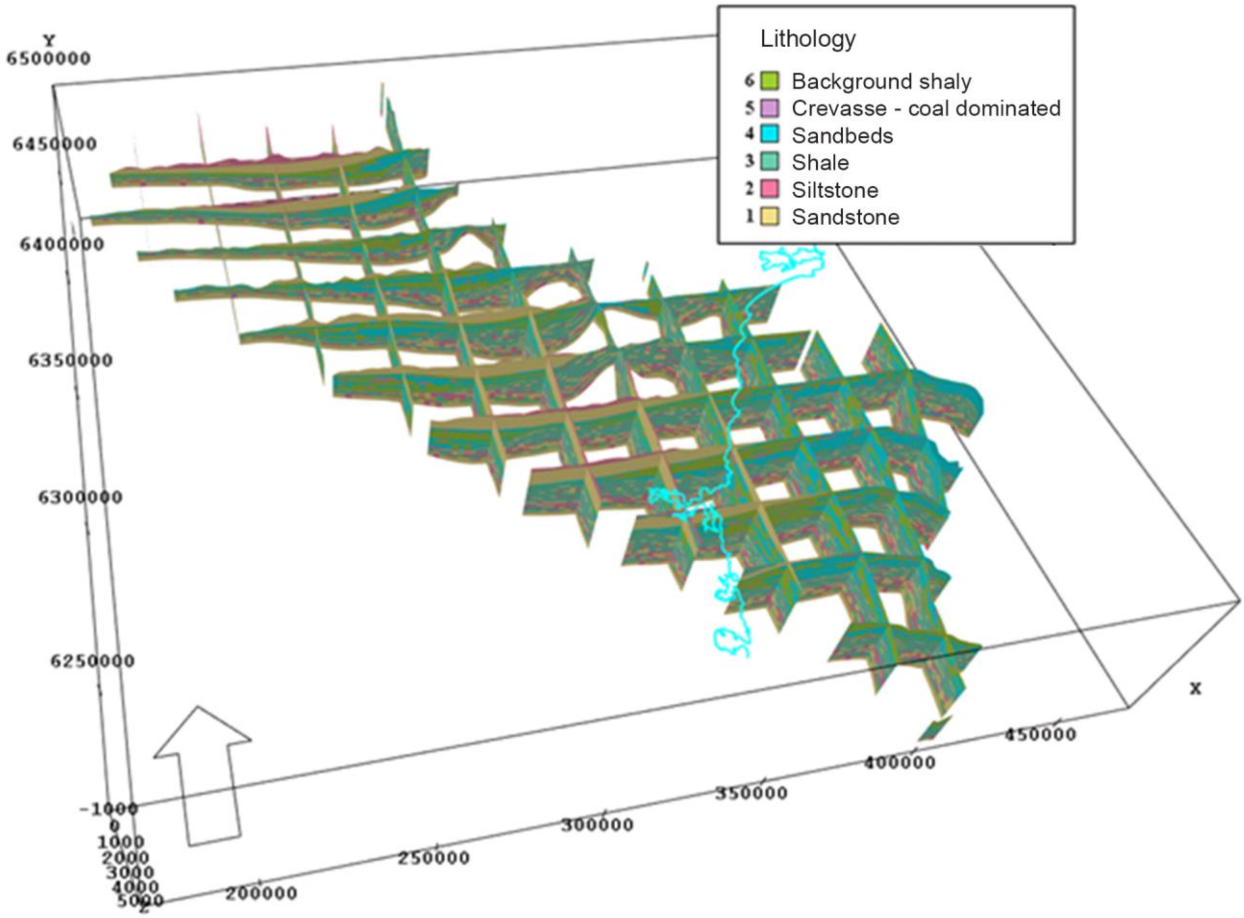


Figure 13 Three-dimensional perspective view of the regional lithology pattern in the geological model for the Hunter subregion

View from the south, showing a change in surface lithology from siltstone and sandstone outcrops in the upland areas of the subregion to shale and sand bed lithologies in more eroded areas. Mining is undertaken in areas where the siltstone and sandstone outcrops have been eroded.
Data: CSIRO (Dataset 9)

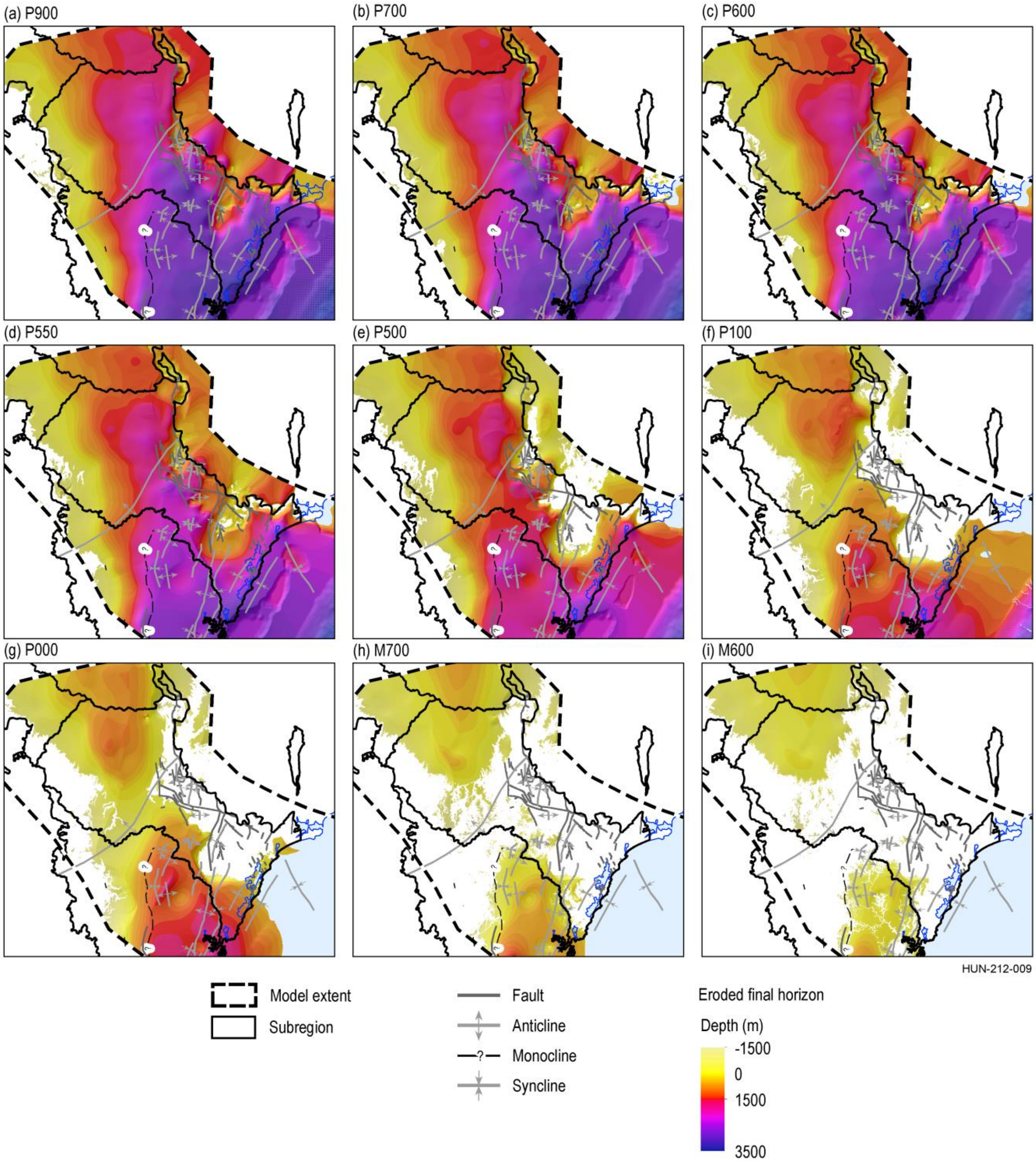


Figure 14 Depth structure maps extracted from the folded and eroded geological model for the Hunter subregion

Depth in m TVD ss = total vertical depth to the Australian Height Datum; negative values represent elevation above sea level. Faults from previous geological mapping are shown, but are not included in the Hunter geological model.
Data: CSIRO (Dataset 9)

2.1.2.3 Gaps

The geological model of the Hunter subregion was built between June 2014 and early February 2015, during which time data had to be acquired, processed, unified between the different coalfields and filtered to obtain data that could be used in the BA to underpin a regional-scale geological model. While a lot of different geological datasets exist in the Sydney Basin, to manage the data requirements and simplify the analyses in the time available, a decision was made to focus on petroleum well data that are deep enough to give access to different sedimentary units and are relatively homogeneous from one company dataset to another. Before developing the geological model, members of the project team met with geologists from Sydney University and NSW Trade and Investment in order to discuss their approach and obtain data. With more time to acquire and analyse their data and/or collaborate with them in developing the regional model, a refined geological model may have been possible. Areas for improvement include the following:

- The Hunter subregion geological model is focused on the Permo-Triassic strata and is characterised by a lack of structural constraints and the heterogeneity of the datasets. The Sydney Basin basement structure has been well characterised through the use of deep reflection seismic, magnetic and gravity data (Blevin et al., 2007; Danis et al., 2011), but the link between the Permo-Triassic sedimentary rocks and this deep structure needs to be more closely analysed.
- The incorporation of well data, which were not publicly available from the DIGS (Digital Imaging Geological System) database at the time when the Hunter geological datasets were being compiled (August 2014) could help to better constrain the geological framework.
- As explained in the introduction, other types of well data, such as coal and groundwater bores, could be included to add lithological and stratigraphic detail to the shallower levels of the model.
- Shallow seismic reflection data would improve the mapping of the Permo-Triassic horizon tops across the Hunter subregion.
- Depth interpretation of the raw seismic data is needed to improve the definition of geological structures in the Permo-Triassic strata. Interpretation reports were provided to the project by NSW Trade and Investment and reviewed by the BA team, but useful calibrated and shallow interpreted (in depth) seismic line data were not obtained. There would be value in reinterpreting the seismic reflection data, calibrating the wells and then converting the data from the time to the depth domain.
- The model could be updated by incorporating a stochastic distribution of the faults, as was done in the Gloucester Basin case study (Frery et al., 2018). A small displacement along a fault can lead to discontinuities in hydrogeological flow paths. These small-displacement faults are difficult to interpret, especially from onshore seismic data. A power law approach can be the best way to represent these structures in the model. Results from the groundwater modelling in the Gloucester subregion (Peeters et al., 2018) showed, however, that faults had little impact on model results.
- The lithology and the facies, defined from the general stratigraphic column, can be refined to include hydraulic properties and potential connectivity between horizons.
- A finer resolution model would permit better integration of the well data and geological complexity in defined areas.

Some of the foregoing deficiencies in the current geological model are compensated for in the groundwater modelling through simulating hydrological changes across a wide range of parameter values which reflect regional differences and account for the uncertainty in the geological model. The groundwater model emulators provide a means of incorporating better local-scale information, where it is available, to constrain the results from the regional groundwater model (see companion product 2.6.2 (groundwater numerical modelling) for the Hunter subregion (Herron et al., 2018). Thus the regional-scale geological model does not need to represent a lot of local detail to be fit for the regional-scale groundwater modelling undertaken for the bioregional assessment.

References

General material

Agnew D, Bocking M, Brown K, Ives M, Johnson D, Howes M, Preston B, Rigby R, Warbrooke P and Weber CR (1995) Sydney Basin - Newcastle Coalfield. In: Ward CR, Harrington HJ, Mallett CW, Beeston JW (eds) Geology of Australian coal basins. Geological Society of Australia Incorporated, Coal Group Special Publication No. 1. Geological Society of Australia, Coal Geology Group, Sydney, 197–212.

Blevin J, Hall L, Chapman J and Pryer L (2007) Sydney Basin Reservoir prediction study and GIS project MR705. Confidential report to the NSW Department of Primary Industries and Macquarie Energy, FrOG Tech Pty Ltd. Viewed 7 November 2014, http://documents.mx/documents/sydney-basin-reservoir-study.html.

Burra A and Esterle J (2012) Gas distribution and geology: a Hunter Valley example. Proceedings of the 38th Symposium on the Geology of the Sydney Basin – Advances in the study of the Sydney Basin. Pokolbin, NSW, 10–12 May, 2012.

Burra A, Esterle JS and Golding SD (2015) Use of temperature logs in coal seam gas reservoirs: Application to the Sydney Basin, Australia. International Journal of Coal Geology 143 (2015), 68–77.

Creech M (1994) Some aspects of coalbed methane in the Newcastle Coalfields. Advances in the study of the Sydney Basin. 28th Newcastle Symposium, Newcastle, NSW, 15–17 April, 1994, 110–117.

Caumon G, Collon-Drouaillet P, De Veslud CLC, Viseur S and Sausse J (2009) Surface-based 3D modeling of geological structures. Mathematical Geosciences 41(8), 927–945.

Danis C, O'Neill CO, Lackie M, Twigg L and Danis A (2011) Deep 3D structure of the Sydney Basin using gravity modelling. Australian Journal of Earth Sciences 58 (5), 517–542.

Emerson (2016) Roxar RMS website. Viewed 22 March 2016, http://www2.emersonprocess.com/en-us/brands/roxar/pages/roxar.aspx.

Faiz MM, Stalker L, Sherwood N, Saghafi A, Wold M, Barclay SA, Choudhury J, Barker W and Wang I (2003) Bio-enhancement of coal bed methane resources in the southern Sydney Basin. APPEA Journal 43 (1), 595–610.

Faiz MM, Saghafi A, Barclay SA, Stalker L, Sherwood NR and Whitford DJ (2007) Evaluating geological sequestration of CO_2 in bituminous coals: The southern Sydney Basin, Australia as a natural analogue. International Journal of Greenhouse Gas Control I, 223–235.

Frery E, Rohead-O'Brien H, Wilkes PG, McVicar TR, Van Niel TG, Li LT, Barron OV, Rachakonda PK, Zhang YQ, Dawes WR, Marvanek SP, Buettikofer H and Gresham MP (2018) Observations analysis and statistical analysis and interpolation for the Gloucester subregion. Product 2.1-2.2 for the Gloucester subregion from the Northern Sydney Basin Bioregional Assessment. Technical report, Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/NSB/GLO/2.1-2.2.

Herron NF, Peeters L, Crosbie R, Marvanek SP, Pagendam D, Ramage A, Rachakonda PK and Wilkins A (2018) Groundwater numerical modelling for the Hunter subregion. Product 2.6.2 for the Hunter 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/HUN/2.6.2.

McVicar TR, Pinetown KL, Hodgkinson JH, Barron OV, Rachakonda PK, Zhang YQ, Dawes WR, Macfarlane C, Holland KL, Marvanek SP, Wilkes PG, Li LT and Van Niel TG (2015) Context statement for the Hunter subregion. Product 1.1 for the Hunter subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 22 March 2016, http://data.bioregionalassessments.gov.au/product/NSB/HUN/1.1.

Oliveira F, Holmes E, Rumming K and Nicoll R (2014) Ca-IDTIMS tuff dating and stratigraphic correlation Sydney-Gunnedah Basin. Australian Earth Science Convention, 7th–10th July 2014, poster presentation.

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.

Pinetown K (2010) Delineation of coal seam gas domains in the Hunter Coalfield, Sydney Basin. Proceedings of 37th Symposium on the Geology of the Sydney Basin, Hunter Valley NSW, 6–7 May, 2010.

Pinetown KL (2014) Regional coal seam gas distribution and burial history of the Hunter Coalfield, Sydney Basin. Australian Journal of Earth Sciences 61 (3), Special Issue: Geological Advances in the Sydney Basin.

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.

Scheibner E (1999) The geological evolution of New South Wales – a brief review. Geological survey of New South Wales, Sydney. Viewed 03 November 2016, http://www.resourcesandenergy.nsw.gov.au/geoproducts/details?editionid=1159&productid=1078.

Stewart JR and Alder JD (1995) New South Wales petroleum potential – Sydney Basin. Department of Mineral Resources, Sydney.

Thomson S, Hatherly P, Hennings S and Sandford J (2008) A model for gas distribution in coals of the Lower Hunter, Sydney Basin. PESA Eastern Australasian Basins Symposium III, Sydney NSW, 14–17 September, 2008.

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.

Woodfull C, Munroe S, Grisn C, Buckingham S, Ham A, Etheridge M and Hanna P (2004) A structural synthesis of the Sydney Basin – working towards improving geological confidence and productivity.

Yoo EK, Tadros NZ and Bayly KW (2001) A compilation of the geology of the Western Coalfield. Report GS2001/204. Geological Survey of New South Wales, Sydney.

Well completion report list

Wells from the Hunter Deep Well Completion Reports V01 dataset

Advent Energy Ltd (2011) Well completion New Seaclem 1 PEP 11 – New South Wales. Advent Energy Ltd, Australia.

AMOCO Australia Petroleum Company (1992) Well completion Singleton 1 PEL 267 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1994) Well completion Bulga 1 PEL 267 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1995) Well completion Wollombi Brook 1 PEL 267 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1996) Well completion Big Adder Hill 1 PEL 4 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1996) Well completion Doolans Creek 1 PEL 4 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1996) Well completion East Dunlop 1 PEL 4 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1996) Well completion Goulburn River 1 PEL 4 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1996) Well completion Windy Hill 1 PEL 267 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1996) Well completion Wybong 1 PEL 4 – New South Wales. AMOCO Australia Petroleum Company, Australia.

Australian Gas Light Company (2009) Well completion Dartbrook 1 PEL 4 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2009) Well completion Turnermans 1 PEL 4 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2010) Well completion Monkey Place 1 PEL 267 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2010) Well completion Monkey Place 3 PEL 267 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2010) Well completion Windermere 1 PEL 267 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2010) Well completion Windermere 2 PEL 267 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2010) Well completion Windermere 3 PEL 267 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2011) Well completion Monkey Place 2 PEL 267 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2011) Well completion Monkey Place 4 PEL 267 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company (2011) Well completion Windermere 4 PEL 267 – New South Wales. Australian Gas Light Company, Australia.

Australian Gas Light Company and Australian Occidental Pty Ltd (1982) Well completion Bootleg 3 PEL 260 – New South Wales. Australian Gas Light Company and Australian Occidental Pty Ltd, Australia.

Australian Gas Light Company and Australian Occidental Pty Ltd (1983) Well completion Bootleg 4 PEL 260 – New South Wales. Australian Gas Light Company and Australian Occidental Pty Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1963) Well completion Mt Murwin 1 PEL 10 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1964) Well completion Sedgefield 1 PEL 103 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1965) Well completion Belford 1 PEL 103 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1965) Well completion Camberwell 1 PEL 103 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1966) Well completion Millfield 1 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1967) Well completion Martindale 1 and 1A PEL 103 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Command Petroleum Holdings NL (1990) Well completion Shearman 1 PEL 267 – Command Petroleum Holdings NL, Australia.

Dart Energy (2011) Well completion Fullerton 1 PEL 458 – New South Wales. Dart Energy, Australia.

Dart Energy (2011) Well completion Fullerton 2 PEL 458 – New South Wales. Dart Energy, Australia.

Dart Energy (2011) Well completion Fullerton 3 PEL 458 – New South Wales. Dart Energy, Australia.

Dart Energy (2011) Well completion Fullerton 4 PEL 458 – New South Wales. Dart Energy, Australia.

Eastern Star Gas (2007) Well completion Allambi 1 PEL 433 – New South Wales. Eastern Star Gas, Australia.

Eastern Star Gas (2007) Well completion Coolahville 1C PEL 433 – New South Wales. Eastern Star Gas, Australia.

ESSO (1969) Well completion Jerry Plains 1 PEL 103 – New South Wales. ESSO, Australia.

Macquarie Energy (2010) Well completion Catherine Hill Bay 1 PEL 461 – New South Wales. Macquarie Energy, Australia.

Maskell W (1977) Well completion Farley 1 – New South Wales. W. Maskell, Australia.

North West Oil and Minerals Company NL (1973) Well completion Longley 1 – New South Wales. North West Oil and Minerals Company NL.

Oil and Gas Investigations Ltd (2005) Well completion Loder 1 – New South Wales. Oil and Gas Investigations Ltd, Australia.

Pacific Power (1992) Well completion Hawkesbury Lisarow 1 PEL 279 – New South Wales. Pacific Power, Australia.

Pacific Power (1992) Well completion Hawkesbury Llanillo 1 PEL 278 – New South Wales. Pacific Power, Australia.

Pacific Power (1992) Well completion Hawkesbury Randwick Park 1 PEL 278 – New South Wales. Pacific Power, Australia.

Pacific Power (1994) Well completion Hawkesbury Munmorah 1, 2 and 3 PEL 285 – New South Wales. Pacific Power, Australia.

Planet Exploration Company (1963) Well completion East Maitland 1 PEL 88 – New South Wales. Planet Exploration Company, Australia.

Planet Gas (2012) Well completion Meads Crossing 1 PEL 468 – New South Wales. Planet Gas, Australia.

Planet Oil Company (1965) Well completion Woodbury 1 PEL 88 – New South Wales. Planet Oil Company, Australia.

Robertson Research Australia Pty Ltd (1974) Well completion Cape Three Points 1 PEL 191 and 198 – New South Wales. Robertson Research Australia Pty Ltd, Australia.

Santos Qnt Pty Ltd (2009) Well completion Oakdale 1 PEL 456 – New South Wales. Santos Qnt Pty Ltd, Australia.

Santos Qnt Pty Ltd (2010) Well completion Brawboy 1 PEL 456 – New South Wales. Santos Qnt Pty Ltd, Australia.

Santos Qnt Pty Ltd (2010) Well completion Brawboy 2 PEL 456 – New South Wales. Santos Qnt Pty Ltd, Australia.

Santos Qnt Pty Ltd (2010) Well completion Cuan 1 PEL 456 – New South Wales. Santos Qnt Pty Ltd, Australia.

Santos Qnt Pty Ltd (2010) Well completion Rouchel Rouchel 1 PEL 456 – New South Wales. Santos Qnt Pty Ltd, Australia.

Santos Qnt Pty Ltd (2010) Well completion Rouchel Rouchel 2 PEL 456 – New South Wales. Santos Qnt Pty Ltd, Australia.

Santos Qnt Pty Ltd (2011) Well completion Turill 1 PEL 456 – New South Wales. Santos Qnt Pty Ltd, Australia.

Stevens J (1961) Well completion Terrigal 1 PEL 242 – New South Wales. J. Stevens, Australia.

Sun Oil and Gas Company of California (1957) Well completion Farley 2 PPL 21 – New South Wales. Sun Oil and Gas Company of California, Australia.

Sydney Gas Ltd (2002) Well completion Knight 1 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2002) Well completion Pinegrove 1 PEL 4 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2004) Well completion Elizabeth Macarthur 1H and 1V PEL 2 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2005) Well completion Jilliby 1 PEL 5 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2005) Well completion Jilliby 1B PEL 5 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2005) Well completion Jilliby 2 PEL 5 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2008) Well completion Hunter Bulga 1 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2008) Well completion Hunter Bulga 2 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2009) Well completion Hunter Core Hole 1 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2009) Well completion Hunter Core Hole 3 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2009) Well completion Maison Dieu 1 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2009) Well completion Paynes Crossing 1 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2009) Well completion Rothanal 1 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2009) Well completion Roughit 1 PEL 267 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2010) Well completion Black Springs 1 PEL 4 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2010) Well completion Jilliby 13 PEL 5 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Gas Ltd (2010) Well completion Wappinguy 1 PEL 4 – New South Wales. Sydney Gas Ltd, Australia.

Sydney Oil Company Pty Ltd (1986) Well completion Camberwell 2 PEL 267 – New South Wales. Sydney Oil Company Pty Ltd, Australia.

Sydney Oil Company Pty Ltd (1986) Well completion Whybrow 2 PEL 275 – New South Wales. Sydney Oil Company Pty Ltd, Australia.

Unknown (1928) Well completion Belford Dome 1 – New South Wales. Unknown, Australia.

Wells from the South Sydney Deep Well Completion Reports V02 dataset

AMOCO Australia Petroleum Company (1992) Well completion Riverstone 1 PEL 260 – New South Wales. AMOCO Australia Petroleum Company, Australia.

AMOCO Australia Petroleum Company (1996) Well completion North Castlereagh 1 PEL 2 – New South Wales. AMOCO Australia Petroleum Company, Australia.

Australian Gas Light Company and Australian Occidental Pty Ltd (1983) Well completion Bootleg 2A PEL 260 – New South Wales. Australian Gas Light Company and Australian Occidental Pty Ltd.

Australian Oil and Gas Corporation Ltd (1957) Well completion Dural 1 PPL 3 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1958) Well completion Dural 3 PPL 3 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1961) Well completion Baulkham Hills 1 PPL 3 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1962) Well completion Kurrajong Heights 1 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1963) Well completion Kenthurst 1 PPL 3 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1964) Well completion Kulnura 1 PEL 102 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1964) Well completion Mellong 1 PEL 103 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1968) Well completion Berkshire Park 1 PEL 102 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1968) Well completion Higher MacDonald 1 PEL 102 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

Australian Oil and Gas Corporation Ltd (1968) Well completion Lower Portland 1 – New South Wales. Australian Oil and Gas Corporation Ltd, Australia.

ESSO (1970) Well completion Howes Swamp 1 PEL 103 – New South Wales. ESSO, Australia.

Metals Investment Holdings (1971) Well completion MacDonald 2 (St. Albans 1) MEL 220 – New South Wales. Metals Investment Holdings, Australia.

Metals Investment Holdings (1971) Well completion North Colah 1 – New South Wales. Metals Investment Holdings, Australia.

Metals Investment Holdings (1971) Well completion St. Albans 1 MEL 220 – New South Wales. Metals Investment Holdings, Australia.

Natural Gas and Oil Corporation Ltd (1937) Well completion Balmain 1 – New South Wales. Natural Gas and Oil Corporation Ltd, Australia.

North West Oil and Minerals Company NL (1973) Well completion Longley 1 – New South Wales. North West Oil and Minerals Company NL.

Pacific Power (1992) Well completion Hunter Coricudgy 1 PEL 278 – New South Wales. Pacific Power, Australia.

Pacific Power (1994) Well completion Hawkesbury Bunnerong 1 PEL 5 – New South Wales. Pacific Power, Australia.

Pacific Power (1995) Well completion Hawkesbury Everleigh 1 PEL 5 – New South Wales. Pacific Power, Australia.

Shell Development Australia (1967) Well completion Dural South 1 PEL 102 and 103 – New South Wales. Shell Development Australia, Australia.

Datasets

Dataset 1 DTIRIS NSW, Minerals Division Titles Branch (2015) Hunter Deep Well Completion Reports. Bioregional Assessment Source Dataset. Viewed 01 April 2016, https://data.bioregionalassessments.gov.au/dataset/f2df86d5-6749-48c7-a445-d60067109f08.

Dataset 2 CSIRO (2015) South Sydney Deep Well Completion Reports. Bioregional Assessment Source Dataset. Viewed 01 April 2016, https://data.bioregionalassessments.gov.au/dataset/dbeba812-8f42-4377-a178-608deaf82811.

Dataset 3 Bioregional Assessment Programme (2015) Location of Petroleum Wells North and South Sydney Basin. Bioregional Assessment Derived Dataset. Viewed 01 April 2016, https://data.bioregionalassessments.gov.au/dataset/d409881e-6a95-43bf-afc1-5f82bb9e588b.

Dataset 4 CSIRO (2015) HUN Deep Wells Biomarker. Bioregional Assessment Source Dataset. Viewed 01 April 2016, https://data.bioregionalassessments.gov.au/dataset/24dc9764-79bc-4887-9b47-0f1206f9b8da.

Dataset 5 Geoscience Australia (2012) Surface Geology of Australia, 1:1 000 000 scale, 2012 edition. Bioregional Assessment Source Dataset. Viewed 31 March 2015, http://data.bioregionalassessments.gov.au/dataset/8284767e-b5b1-4d8b-b8e6-b334fa972611.

Dataset 6 Geoscience Australia (2014) Bathymetry GA 2009 9sec v4. Bioregional Assessment Source Dataset. Viewed 12 November 2015, http://data.bioregionalassessments.gov.au/dataset/60fb8bf5-b97d-49c9-b7fb-e7d594d2c75b.

Dataset 7 Geoscience Australia (2010) Geoscience Australia, 3 second SRTM Digital Elevation Model (DEM) v01. Bioregional Assessment Source Dataset. Viewed 12 November 2015, http://data.bioregionalassessments.gov.au/dataset/12e0731d-96dd-49cc-aa21-ebfd65a3f67a.

Dataset 8 FROGTECH Pty Ltd (2014) Phanerozoic OZ SEEBASE v2 GIS. Bioregional Assessment Source Dataset. Viewed 22 March 2016, http://data.bioregionalassessments.gov.au/dataset/26e0fbd9-d8d0-4212-be52-ca317e27b3bd.

Dataset 9 Bioregional Assessment Programme (2015) HUN Geological Model Eroded Horizons v01. Bioregional Assessment Derived Dataset. Viewed 2 June 2016, http://data.bioregionalassessments.gov.au/dataset/0499bee7-a0c4-45e8-978b-e0ef0055fb0e.

2.1.3 Hydrogeology and groundwater quality

Summary

Datasets used in the groundwater modelling are identified. They include regolith depth, extent of Hunter alluvium, depth to watertable, recharge and hydraulic conductivity datasets.

Sources of data are provided, as well as the methods used to analyse and generate new datasets to inform the modelling. A detailed description of the data analysis and methods to create a recharge surface for the Hunter subregion is provided.

Depth to watertable data from Hunter subregion bores are generally poor, with many bores having only one or two measurements, as well as lack of supporting information and negligible quality assurance. Depth to watertable data are needed to constrain groundwater model results and to produce an interpolated depth to watertable surface for the subregion; however, the lack of confidence in the underpinning data results in increasing uncertainty in derived products.

This section describes some of the datasets that have been used to inform the groundwater modelling of the Hunter subregion. Some are used directly (this includes clipping to the required extent for modelling and/or extracting a specific attribute), whereas others have been derived from multiple data sources for modelling purposes. Not all datasets are reported here. Data used in calibration of groundwater models are reported in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018). The geological model is described in Section 2.1.2 of this product.

Table 6 lists the key datasets used to construct the groundwater model and where they are reported within the Hunter subregion suite of products. The datasets are classified as either 'source datasets' (i.e. pre-existing datasets sourced from outside the Bioregional Assessment Programme, but including data sourced from the Programme partner organisations) or 'derived datasets' that have been generated by the Programme for groundwater modelling purposes in the Hunter subregion. Details of source datasets and data processing to represent the baseline and additional coal resource developments in the modelling simulations are provided in Section 2.1.6 of this product.

No groundwater quality data are used in the groundwater modelling.

Table 6 Key datasets used for groundwater modelling for the Hunter subregion

Dataset	Source or Derived	Dataset	Details in
Digital elevation model	Derived	Bioregional Assessment Programme (Dataset 1)	Section 2.1.3.2.2
Vegetation height	Source	Caltech/JPL (Dataset 2)	Section 2.1.3.2.2
Geological model	Derived	Bioregional Assessment Programme (Dataset 3)	Section 2.1.2
Recharge	Derived	Bioregional Assessment Programme (Dataset 4)	Section 2.1.3.2.1 and Section 2.1.3.2.1
Regolith depth	Source	CSIRO (Dataset 5)	Section 2.1.3.1.1
Alluvium extent	Derived	Bioregional Assessment Programme (Dataset 6), extracted from Geoscience Australia (Dataset 7)	Section 2.1.3.1.1
Depth to watertable	Derived	Bioregional Assessment Programme (Dataset 8)	Section 2.1.3.1.3
Hydraulic conductivity	Derived	Bioregional Assessment Programme (Dataset 9)	Section 2.1.3.2.2
River network	Derived	Bioregional Assessment Programme (Dataset 10)	Product 2.6.2 Groundwater numerical modelling (Herron et al., 2018)
Groundwater extractions (non-mining)	Source	NSW Department of Primary Industries, NSW Office of Water (Dataset 11)	Product 2.6.2 Groundwater numerical modelling (Herron et al., 2018); Product 1.5 Current water account for the Hunter subregion (Zhang et al., 2016)
Potential evapotranspiration	Derived	Bioregional Assessment Programme (Dataset 12)	Product 2.6.2 Groundwater numerical modelling (Herron et al., 2018)

Section 2.1.3.1 provides details of observed (source) data that have been used for groundwater modelling. The statistical analysis and interpolation section (Section 2.1.3.2) describes the methods for deriving datasets for input into the groundwater model from existing data.

2.1.3.1 Observed data

2.1.3.1.1 Recharge

Groundwater recharge refers to surface water that moves to groundwater. It is not a water flux that is easy to measure and little observation data are available. Various methods are used to estimate recharge: some estimates are provided here for the Hunter subregion, but they are not strictly observations data.

The simplest method to estimate recharge is using a constant percentage of rainfall and to assume no other losses. Groundwater recharge is commonly *a priori* estimated at 2% of rainfall or less but with higher values in areas of higher regolith permeability (Mackie Environmental Research, 2006) as a first estimate. Assuming the 2% level applies uniformly across the subregion and using the subregion average rainfall of 793 mm, an estimate of the catchment average annual recharge of 15.9 mm is obtained.

The next level of complexity requires a spatially variable modelled estimate of recharge. A recharge surface has been generated for the Hunter subregion and Sydney Basin bioregion and is detailed in section 2.1.3.2. The recharge surface reflects the variability arising from lower rainfall conditions in the western parts of the catchment, compared to higher recharge in the sandy alluvial soils of the Hunter River and coastal dunes (see Figure 22). Estimates of mean annual recharge of 7.2 mm in the 7700 km^2 Goulburn River basin and 9.0 mm for the 13,616 km^2 of the subregion upstream of Greta (which includes the Goulburn River basin) were obtained from this gridded surface. Using a weighted difference by area, the mean annual recharge rate for the 5916 km^2 containing the regulated Hunter River alluvium in the subregion is 11.4 mm, or around 1.5% of rainfall.

2.1.3.1.2 Regolith depth and alluvium extent

The alluvium and other near-surface (not more than about 10 m below surface) strata are where exchanges between groundwater and surface water occur. Characteristics of the near-surface zone differ from the deeper stratigraphy: the alluvium is often a significant source of fresh groundwater; non-alluvial near-surface areas are typically more weathered and have higher hydraulic conductivities than the underlying rocks; and near-surface zones may be only partially saturated. Another advantage of having a clear estimate of the extent of the alluvium and its hydrogeology is that this zone often supports many GDEs, both those with above-ground expression as well as subsurface ecosystems. These characteristics mean that an accurate representation of the near-surface zone is advantageous in a groundwater model.

Regolith depth data over Australia can be found in Wilford et al. (2015; CSIRO, Dataset 5). This dataset maps the depth of the regolith over Australia at a 3-second (~90 m) resolution. Figure 15 shows regolith depth for the Hunter subregion. Mean regolith depth is less than 4 m, although is significantly deeper in alluvial areas (up to 20 m) and coastal sand beds (up to 40 m). This dataset informs the thickness of the topmost layers within the groundwater model (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018)).

The spatial extent of the alluvium and coastal sands in the Hunter subregion is shown in Figure 16 (Bioregional Assessment Programme, Dataset 6). These data are derived from the Surface Geology of Australia 2012 edition (Geoscience Australia, Dataset 7), which is a seamless national coverage of outcrop surficial geology at or around the 1:1,000,000 scale.

In the groundwater model the depth of the alluvium is assumed equal to the depth of the regolith; therefore, Figure 15 and Figure 16 define the three-dimensional extent of the alluvium in the groundwater model. This is described further in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018).

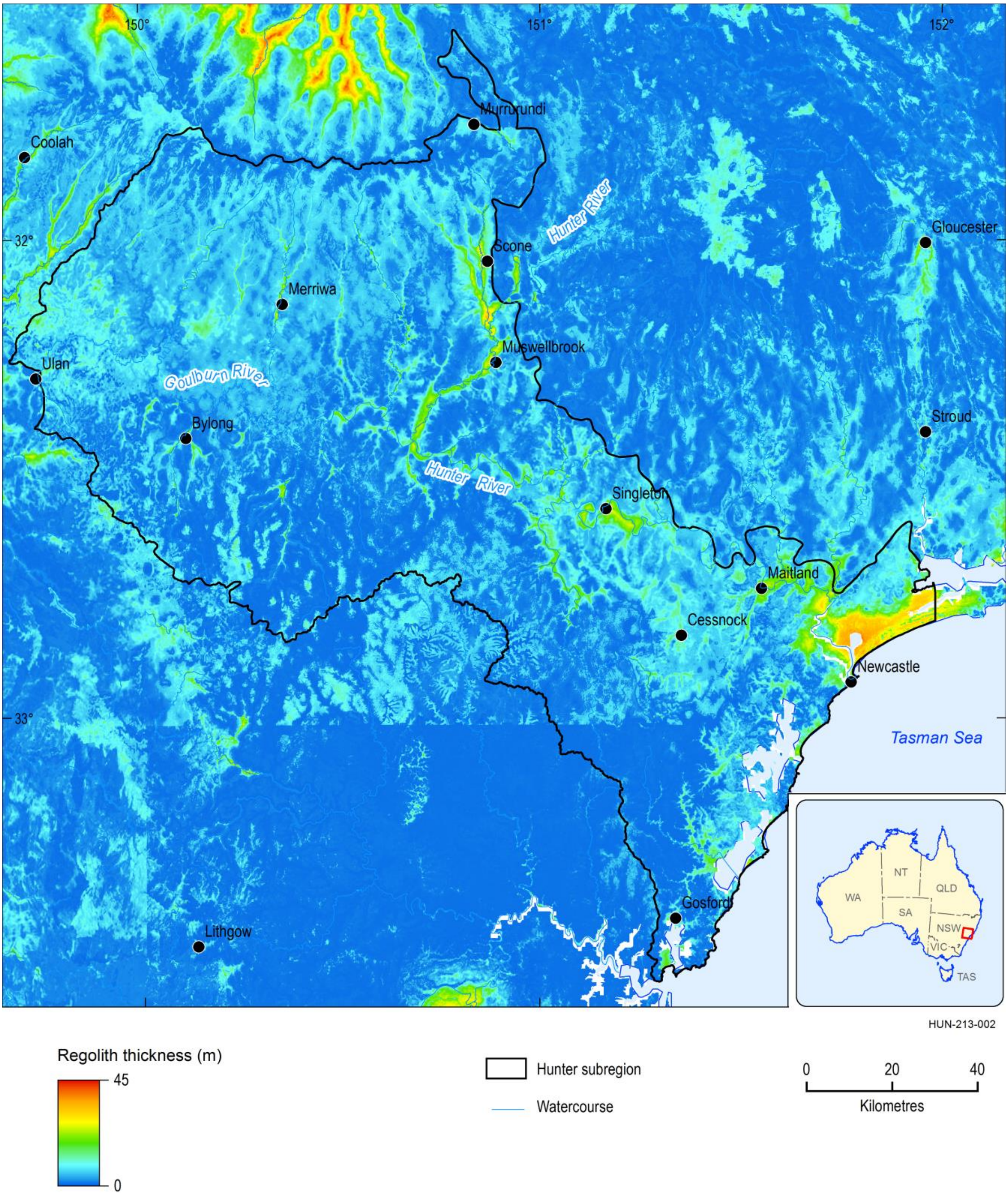


Figure 15 Depth of regolith over the Hunter subregion

Data: CSIRO (Dataset 5)

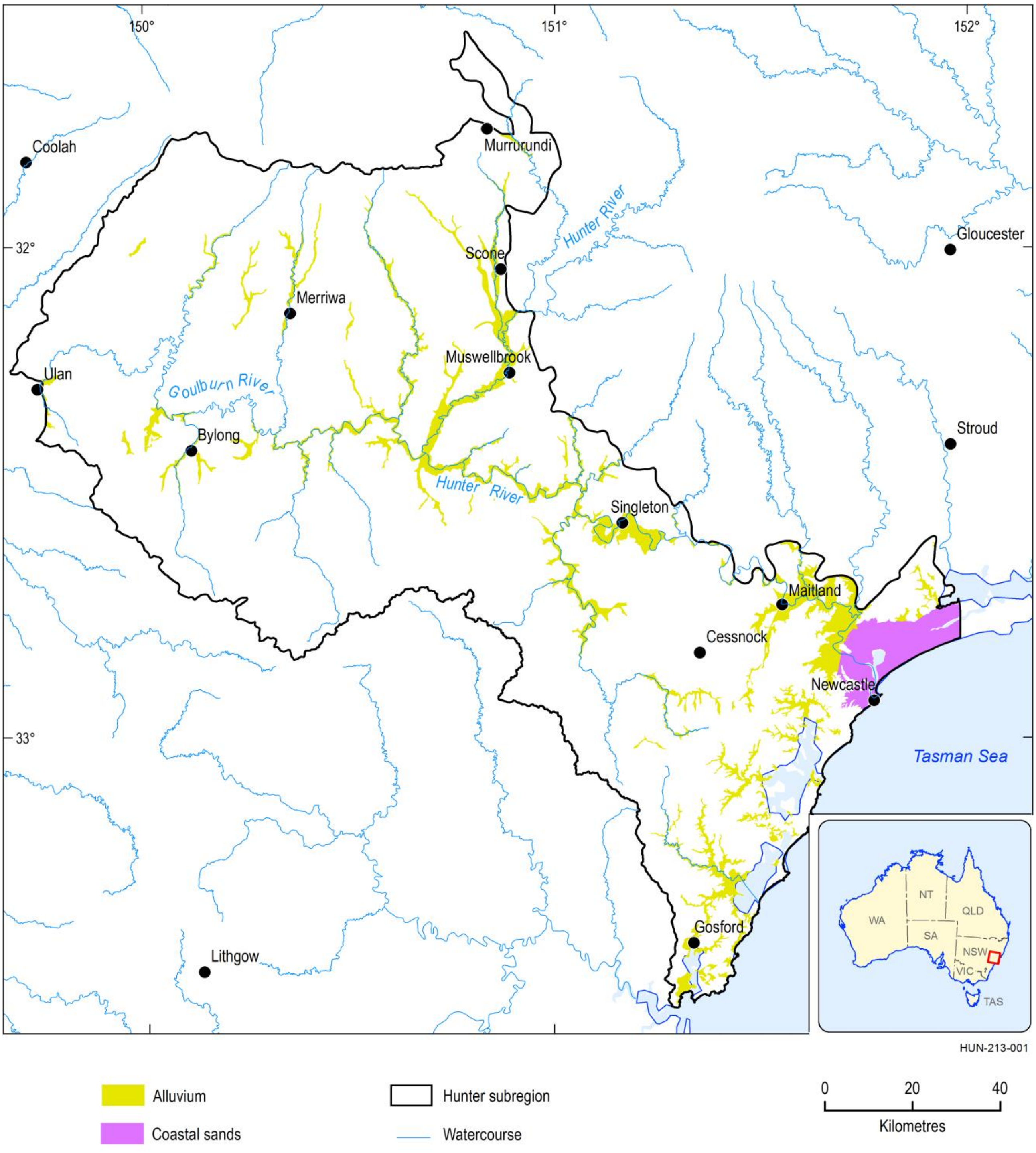


Figure 16 Spatial extent of the alluvium and coastal sands in the Hunter subregion

Note some areas of alluvium appear isolated from the stream network because not all streams are shown.
Data: Bioregional Assessment Programme (Dataset 6)

2.1.3.1.3 Observed depths to watertable

The Hydstra Groundwater Measurement (HYDMEAS) database (Bioregional Assessment Programme, Dataset 8) contains 6906 measurements of depth to watertable at 584 locations in the Hunter subregion. Measurements of watertable depth span the period 1902 to 2012, with depths ranging between –1 m (above ground surface) and 99 m (below ground surface). The NSW Office of Water (now DPI Water), who originally published these data, makes no claims as to the accuracy of the records. Note that depth to watertable is used here to include groundwater depth and depth to watertable because there is often insufficient information about the screening depths of bores within the database to differentiate between the two. A measurement of water level in a bore that is screened to a depth below the watertable will give a depth to groundwater; this is not necessarily the same as depth to watertable from an unscreened bore at the same location.

Figure 17 shows the frequency distribution of observations per bore. More than 25% of the bores (162) have only one measurement, while a further 55 bores have only two measurements. The median number of observations at a single point is 3. This dataset is used to constrain the parameters of groundwater model uncertainty analysis, however, given the poor quality of the dataset, it may not provide much constraint (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018)).

Bores with more frequent measurements are located around Muswellbrook, Singleton and Denman.

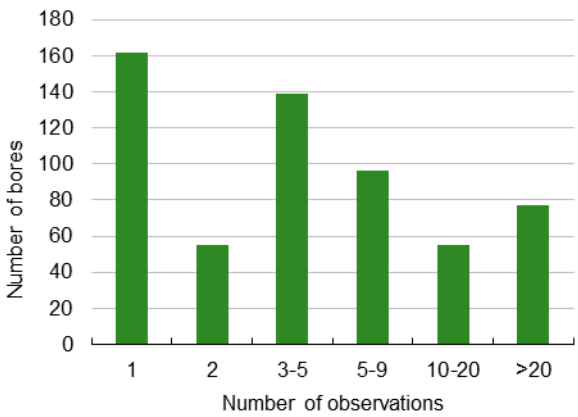


Figure 17 Observation points in the HYDMEAS database categorised by the number of observations recorded

Data: Bioregional Assessment Programme (Dataset 8)

Figure 18 shows time series of depth to watertable at these locations which, in spite of the relative lack of recent measurements, suggest a consistent pattern of varying depth to watertable along the Hunter River valley, with deeper groundwater levels at Muswellbrook (around 12 m depth), shallowing around Denman to between 4 and 5 m depth, and then deepening again around Singleton (around 8 m depth).

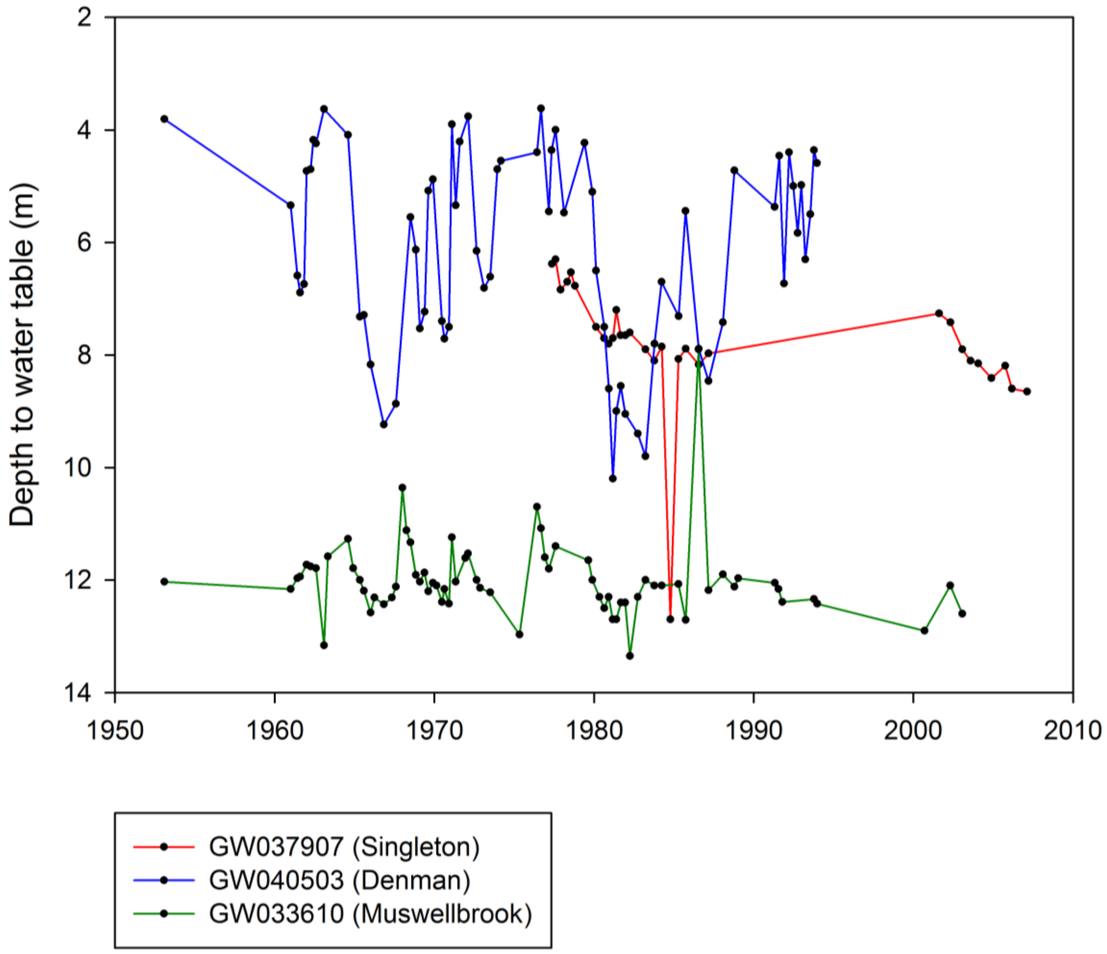


Figure 18 Observed depth to watertable at three locations within the Hunter subregion

Data: Bioregional Assessment Programme (Dataset 8)

Figure 19 shows mean depth to watertable for the 584 bores; however, as previously discussed, most of these mean depths are based on limited observations and take no account of when the measurements were taken.

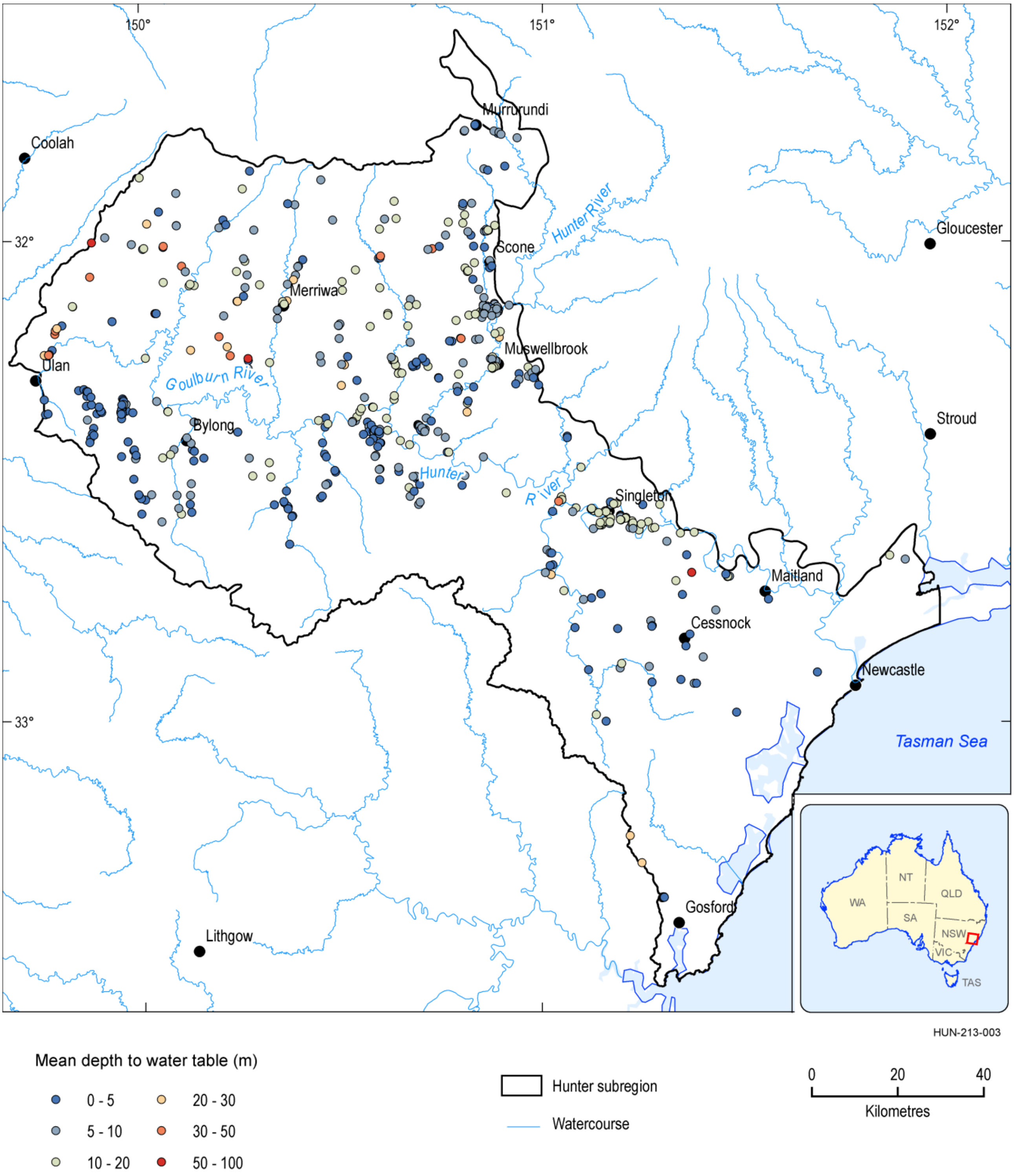


Figure 19 Mean depth to watertable (metres below ground surface) at groundwater bore locations across the Hunter subregion

Data: Bioregional Assessment Programme (Dataset 8)

2.1.3.2 Statistical analysis and interpolation

2.1.3.2.1 Recharge

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

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

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

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

$$R = \frac{100\ D}{[Cl^{-}]_{gw}} \qquad (1)$$

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

The recharge for the Hunter subregion and Sydney Basin bioregion were estimated together as they are both contained within the geological Sydney Basin. The results for the Sydney Basin bioregion are included here.

The chloride deposition over the geological Sydney Basin was extracted from the national dataset at a resolution of 0.05° (Leaney et al., 2011) (CSIRO, Dataset 13). This dataset was created from 297 field measurements of chloride deposition at point locations and then fitted to the model of Keywood et al. (1997). Figure 20a shows chloride deposition to be much greater near the coast compared to inland areas, which is due to decreasing concentrations of atmospheric salts with distance from the sea.

The chloride concentrations of groundwater were obtained from data collected by NSW Office of Water (now DPI Water) (NSW Office of Water, Dataset 14). There are 1393 points covering several decades of chloride data in the geological Sydney Basin (Figure 20a). A borehole may have one or more observations; where there were multiple observations for a borehole, the geometric mean was used to characterise the chloride concentration, otherwise the isolated value was used. At each location, the chloride data were assigned to a stratigraphic layer based on mapped surface geology (Geoscience Australia, Dataset 15) where better data did not exist. In most cases it was assumed that the bores were completed into the stratigraphic layer representing the surface geology, since there were only a few where the information existed to show otherwise (e.g. bores drilled through Wianamatta Shale to sample the Hawkesbury Sandstone).

In alluvial areas, the chloride signal reflects not only a contribution from rainfall, but also from streams and upward flow from deeper aquifers (Raiber et al., 2016). Consequently, the first assumption of the chloride mass balance method is not met and 529 data points from alluvial areas were excluded from the analysis. The remaining 864 measurements of groundwater chloride concentration were used to calculate point estimates of recharge. Figure 20b shows the spatial distribution of these 864 data points. They are not uniformly distributed across the Sydney Basin with better spatial coverage of recharge estimates in the Hunter subregion.

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

The assumption of steady-state conditions is difficult to meet in any area where there has been land use change. This can be mitigated by only using shallow bores as the water sampled would be younger. For an area that was cleared 200 years ago with an average recharge rate of 10 mm/year and a porosity of 0.02, the recharge post-clearing would have penetrated 100 m below the water table. If deep bores are used then there is the possibility of having a low bias to the recharge estimates. An attempt was made to only sample younger water by only including bores in the analysis that were screened in the same stratigraphic layer as the surface geology (e.g. bores sampled from the Hawkesbury Sandstone were excluded if they were overlain by the Wianamatta Shale).

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

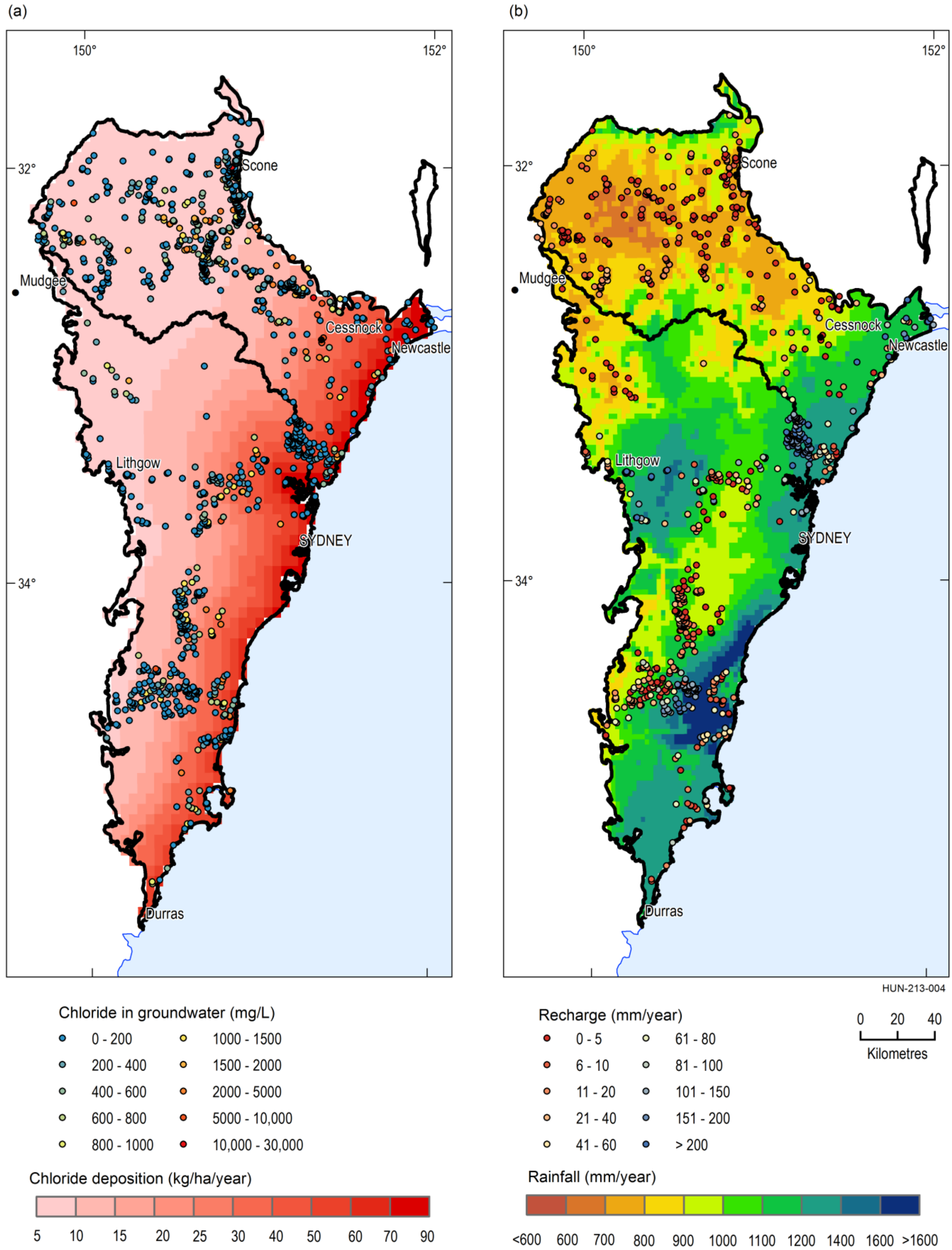


Figure 20 Inputs into the chloride mass balance method of estimating recharge

Left panel (a) showing the chloride deposition and the chloride concentration of the watertable aquifer and the right panel (b) showing the mean annual rainfall and the point estimates of recharge (excluding points on alluvium)
Data: CSIRO (Dataset 13), NSW Office of Water (Dataset 14), Bureau of Meteorology (Dataset 16), Bioregional Assessment Programme (Dataset 19)

To generate a continuous surface of recharge estimates for input into the groundwater model, the point estimates derived from the chloride mass balance method needed to be upscaled. Crosbie et al. (2010) found that mean annual rainfall, soil type and vegetation type are the key determinants of recharge. Crosbie et al. (2013) used these variables successfully to upscale point estimates to a continuous recharge surface. However, due to the paucity of point recharge estimates under different soil and vegetation types in the geological Sydney Basin, the mean annual rainfall (Bureau of Meteorology, Dataset 16) and eight different classes of surface geology have been used as covariates. The eight geological classes were based on layers defined in the Hunter subregion geological model (see Section 2.1.2.3) with the exception of the near-surface class, which has been split for the purposes of the recharge analysis into three different classes: Dunes (contains coastal dunes, dunes and sandplains), Volcanics (Liverpool Range Volcanics and similar) and Shales (Wianamatta Group and similar).

A log-linear relationship was adopted for estimating mean annual recharge from mean annual rainfall. This is similar to relationships developed previously from both field and modelled data (Crosbie et al., 2013; Crosbie et al., 2010). Use of a log-linear relationship can result in recharge rates at the higher end of the rainfall spectrum that are greater than rainfall (especially when extrapolated beyond the range of the field data). To prevent this, a global maximum recharge rate equal to half the rainfall was imposed, which is approximately the highest recharge estimated from the point scale chloride mass balance estimates. As the chloride mass balance method was not appropriate for alluvial areas, empirical relationships developed from historical field data to predict recharge using mean annual rainfall (Bureau of Meteorology, Dataset 16), soil clay content (Bioregional Assessment Programme, Dataset 17 and vegetation (ABARES, Dataset 18) were used (Wohling et al., 2012).

Figure 21 shows the log-linear relationship for estimating mean annual recharge from mean annual rainfall. This shows that for a given rainfall amount the Dunes, Volcanics and M600 (top of Hawkesbury Sandstone) classes have comparably more recharge than the other classes. The coal-bearing formations (P000) tend to have recharge that is similar to that of the aquitards (Wianamatta Group). Figure 22 shows the upscaled mean annual recharge with the highest recharge along the coast where rainfall is highest on the Dunes, alluvium and M700 (top of the Narrabeen Group); recharge is greatly reduced inland (particularly in the Goulburn river basin). The mean areal recharge across the entire Hunter subregion was estimated to be 23 mm/year. (For the Sydney Basin bioregion, the mean areal recharge was estimated to be 45 mm/year).

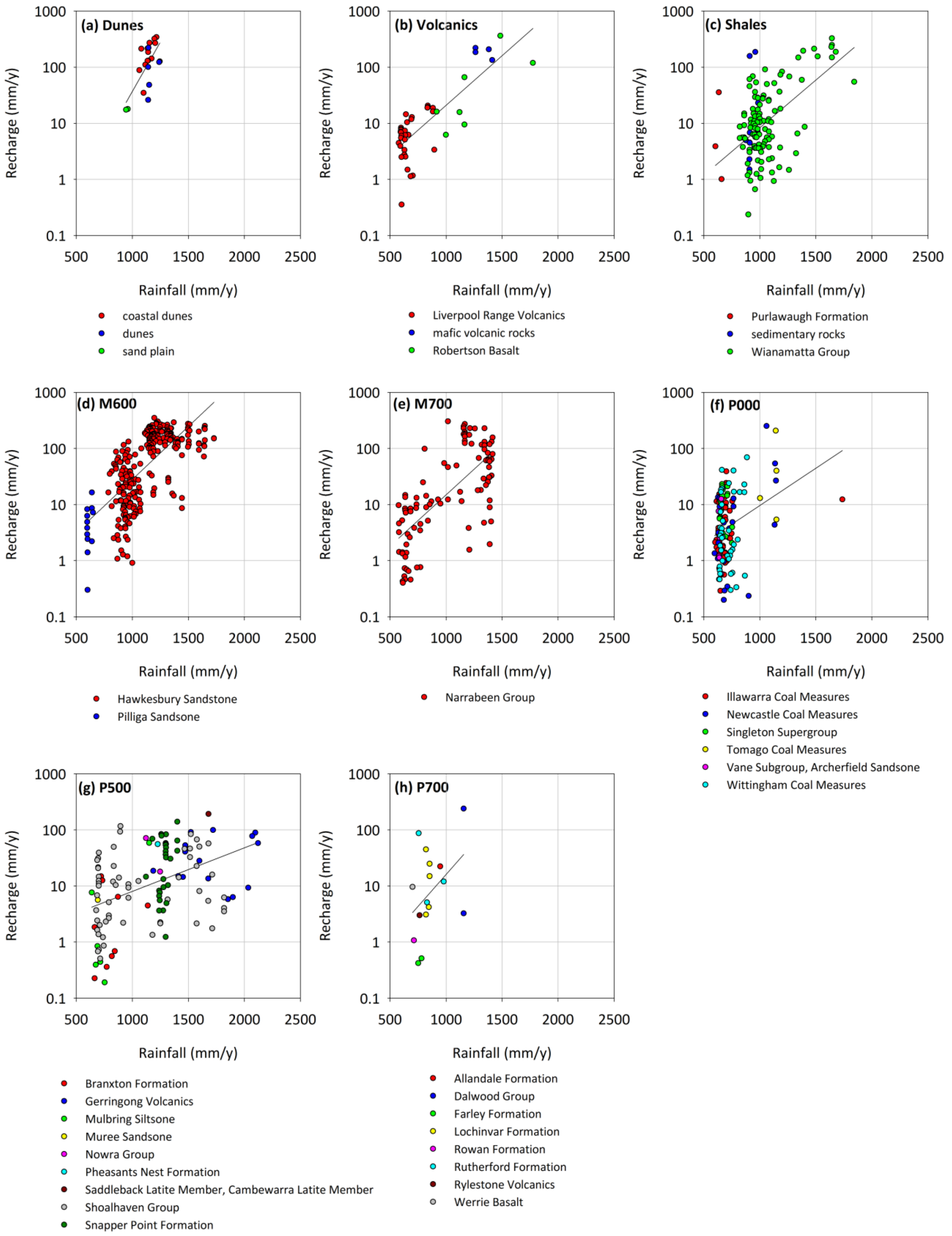


Figure 21 Relationship between mean annual rainfall and mean annual recharge for groupings of surface geology

The black line is the line of best fit through the data points. All of the regression lines are significant at a p-value of 0.01 except for P700 ($p=0.11$).

Data: Bioregional Assessment Programme (Dataset 19)

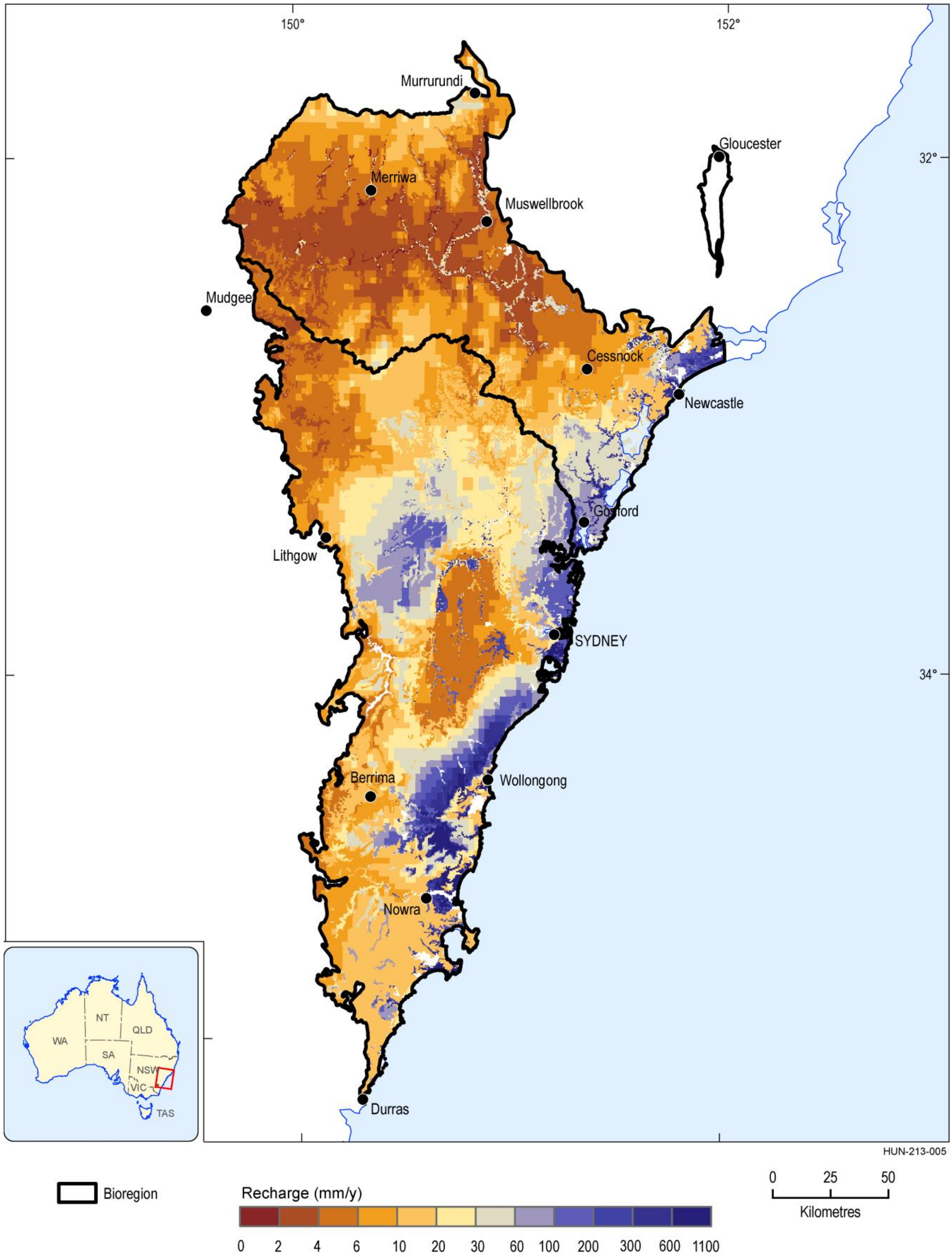


Figure 22 Upscaled estimates of mean annual recharge over the Sydney Basin

Data: Bioregional Assessment Programme (Dataset 4)

The deterministic estimate of recharge shown in Figure 22 was used as the base recharge in the numerical groundwater model. However, an estimate of the uncertainty around this deterministic estimate is necessary for carrying out the sensitivity and uncertainty analyses. The sources of uncertainty that can be quantified are the chloride deposition and the regression function. The chloride deposition shown in Figure 20 is the best estimate reported by Leaney et al. (2011), who also produced gridded estimates of the mean, standard deviation and skewness from 1000 equally well-calibrated replicates (Bioregional Assessment Programme, Dataset 9). These gridded datasets were used to stochastically generate ten alternate chloride deposition grids. Each of these ten deposition grids were used to generate the regression equations between mean annual rainfall and mean annual recharge using bootstrapping (Efron and Tibshirani, 1994) with replacement for ten replicates. This provided 100 replicate regression equations to use in up-scaling (Figure 23). [Bootstrapping is a statistical method that involves random sampling with replacement. In this case it has been used by leaving out some of the data points and replacing them with replicates of other data points and then re-calculating the regression equation. This allows us to estimate the uncertainty in the regression equations developed between rainfall and recharge.]

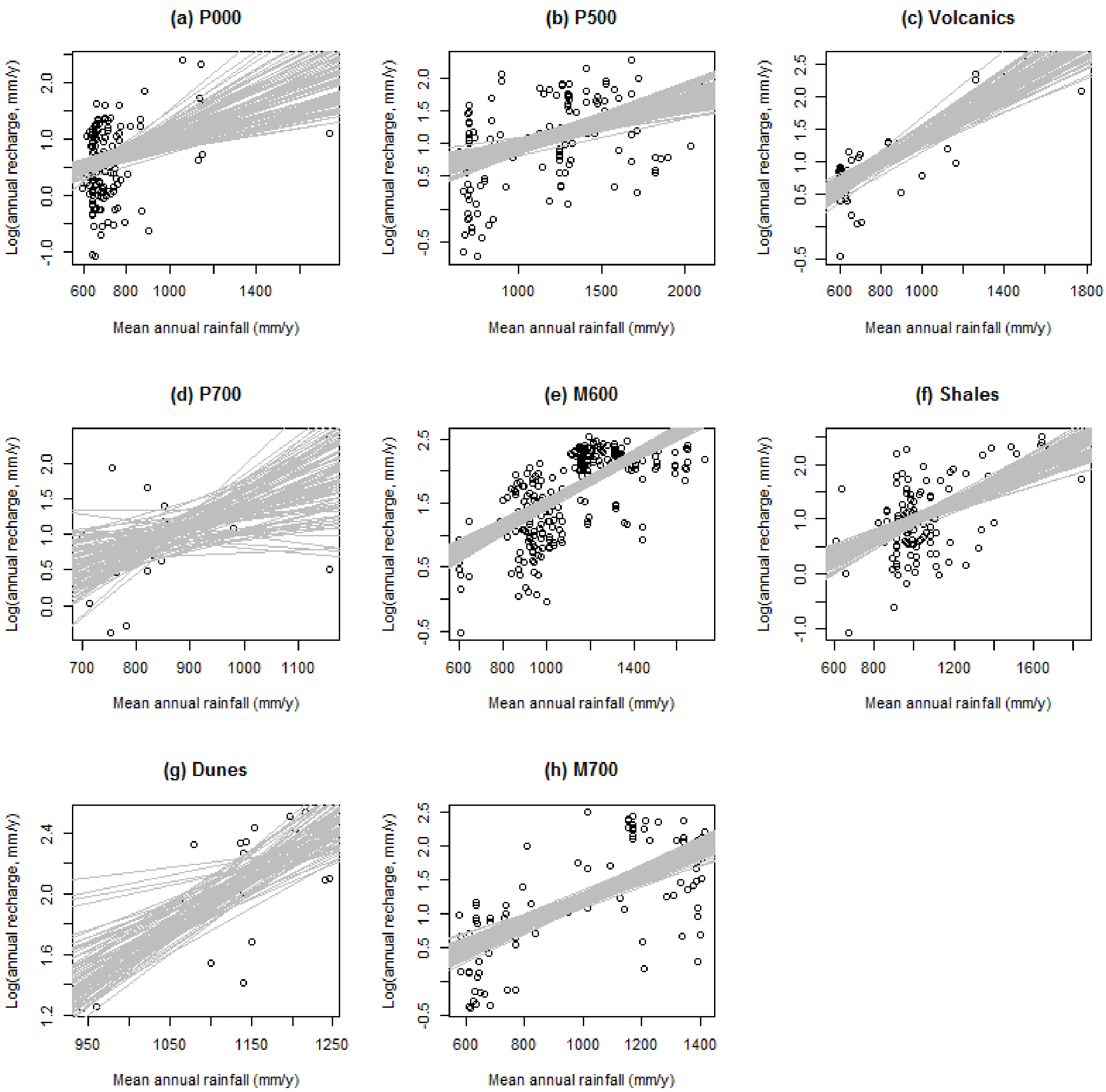


Figure 23 Relationship between mean annual rainfall and mean annual recharge considering the uncertainty in the chloride deposition and the regression equation for groupings of surface geology

Each line is 1 of 100 replicates of the regression equation between mean annual rainfall and mean annual recharge.
Data: Bureau of Meteorology (Dataset 16), Bioregional Assessment Programme (Dataset 4)

There is a higher uncertainty in the relationships developed for the below P700 class (i.e. below the Greta Coal Measures in the Hunter and Western coalfields) compared to the other classes (Figure 23) due to the lack of data and the spread in the point estimates of recharge. This is reflected in the upscaled estimates of recharge (Figure 24). The areally averaged recharge for the 50th percentile of the 100 replicates is 25 mm/year, with the 5th and 95th percentiles being 21 and 31 mm/year respectively for the Hunter subregion. (For the Sydney Basin bioregion the areally averaged recharge estimates are 35, 42 and 53 mm/year for the 5th, 50th and 95th percentiles respectively.)

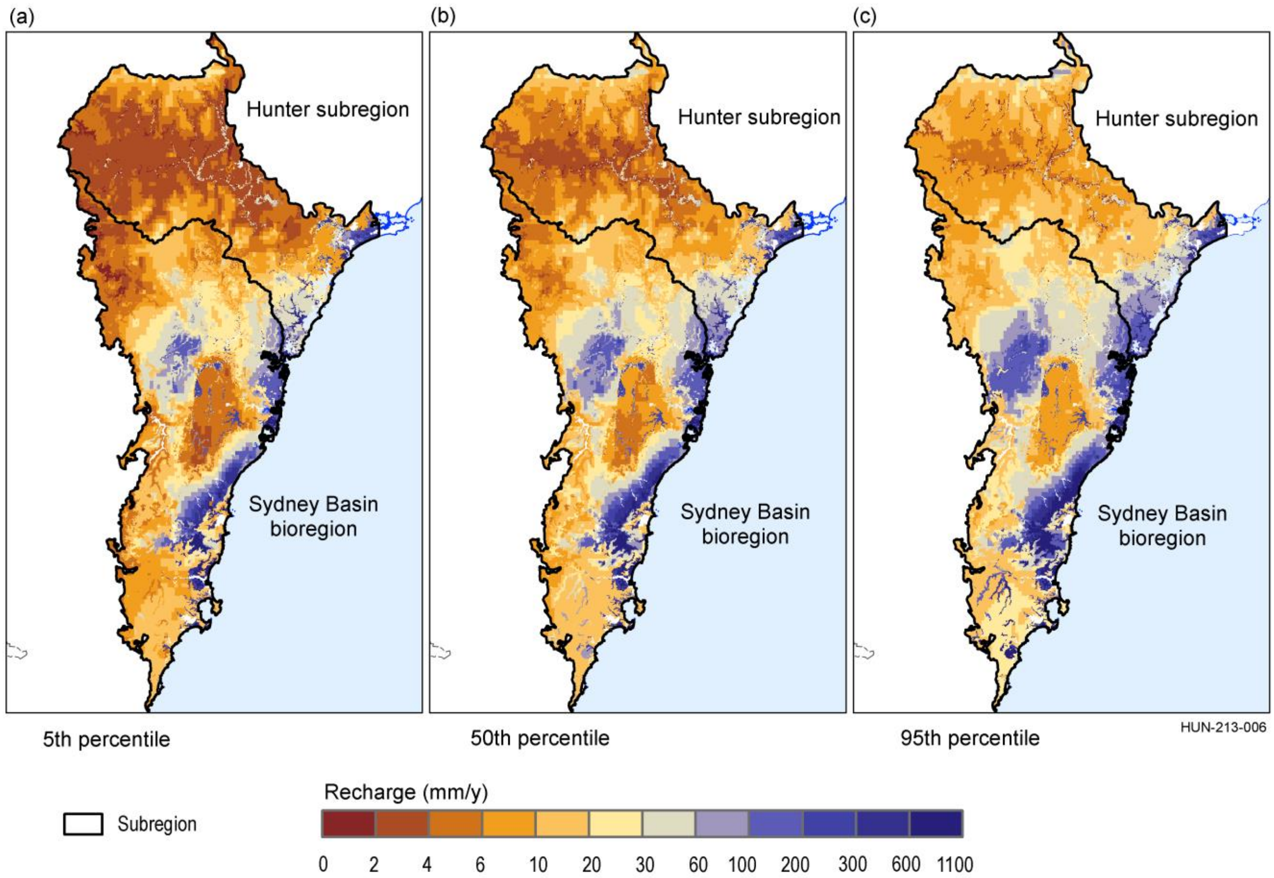


Figure 24 Uncertainty in the recharge estimation across the Hunter subregion and Sydney Basin bioregion displayed as the (a) 5th, (b) 50th and (c) 95th percentiles from 100 replicates

Data: Bioregional Assessment Programme (Dataset 4)

The limitations of the recharge estimation as applied here relate to the assumptions underpinning the methodology: by not accounting for the chloride that is lost from the system through surface runoff, recharge can be overestimated; whereas not accounting for the enhanced deposition on forested areas leads to underestimating recharge. The assumption of steady state conditions will be violated in areas that have not attained equilibrium following the clearing of native vegetation for agriculture, and will likely lead to an underestimation of recharge. No attempt was made to quantify the impacts of such forms of uncertainty.

2.1.3.2.2 Hydraulic conductivity

Hydraulic conductivities control the direction and speed of groundwater flow. Rock layers can be aquitards with low conductivity that retard flow between aquifers, which have higher conductivity. Hence rock conductivity characterises groundwater hydrological connectivity and flow directions.

It is notoriously difficult to appropriately assign a single conductivity to a hydrostratigraphic layer because rocks exhibit strong heterogeneity and anisotropy. Often in groundwater models, a horizontal conductivity and a vertical conductivity are assigned and these are varied by an order of magnitude or more in an uncertainty analysis to simulate the rock’s inherent heterogeneity.

Analyses of hydraulic conductivity measurements from the Hunter subregion were undertaken to determine whether they correlate with the stratigraphic layers of the geological model or the lithologies of the lithological model (Section 2.1.2). The groundwater model is built on these two models, so if any layers or lithologies were found to have a particular hydraulic conductivity, it would inform the parameterisation of the groundwater model. The analysis also informs the uncertainty analysis by placing realistic limits on the variation in hydraulic conductivity.

Hydraulic conductivities and porosities have been measured by mining companies throughout the Hunter subregion for the purpose of characterising their local hydrogeological conditions. The measurements are recorded in environmental impact statements for these mining companies. Five hundred and seventy-seven measurements were selected for analysis because they contained sufficient information to determine their spatial location (including depth), and the hydrostratigraphic unit sampled. They have been compiled into a dataset for the groundwater modelling for the Hunter subregion (Bioregional Assessment Programme, Dataset 9), which includes references to the 21 source documents. The data are highly variable.

Most of the 577 measurements pertain to coal fields and coal-bearing strata, and a significant number are on coal. This introduces some unavoidable bias into the analysis presented below. Measurements are broadly of two types: downhole, where conductivity is measured in the field; and lab, where a rock core is extracted and tested. About 55% of measurements were conducted in the field using various methods, while 20% were performed in the lab. The remaining 25% did not specify the experimental method.

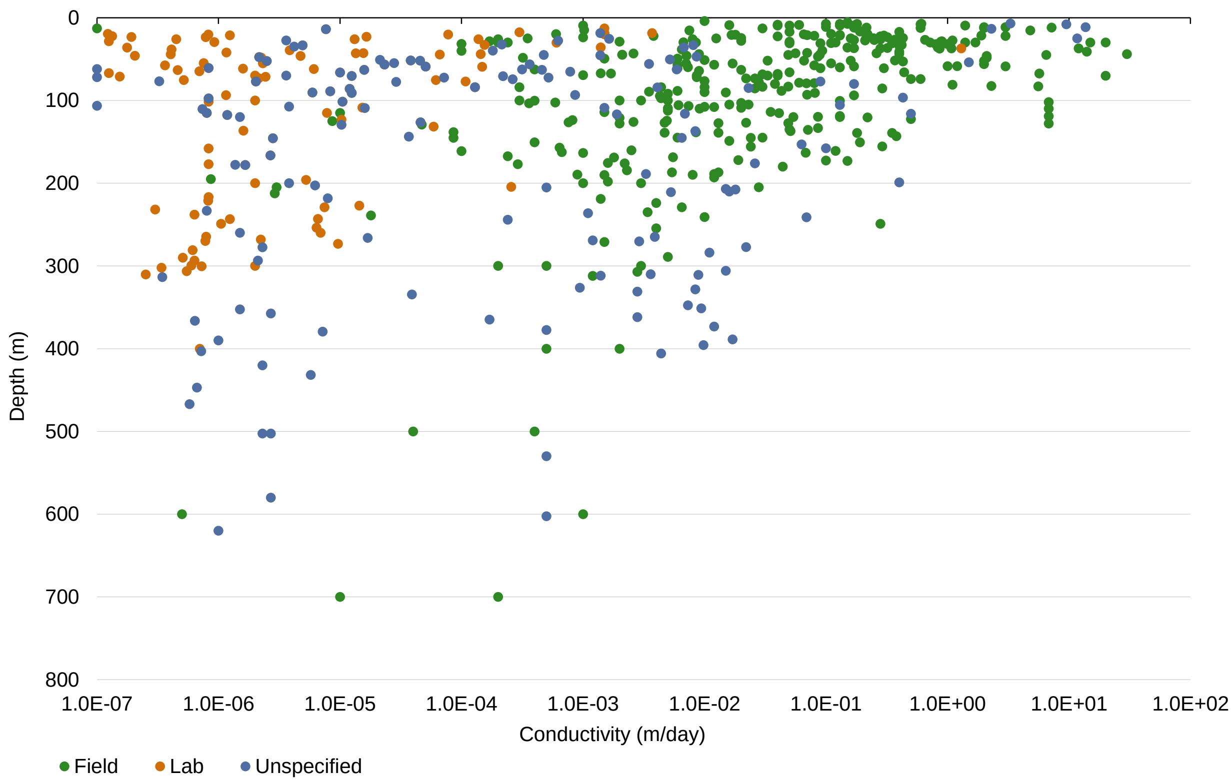


Figure 25 Hydraulic conductivity differentiated by measurement type and correlated with depth

Multiple regression analyses revealed no strong correlation with lithology (Figure 26), Hunter geological model (Section 2.1.2) stratigraphic layers (Figure 27) or geographic area (Figure 28). The measured conductivities for each stratigraphic layer in Figure 27 generally vary by 7 to 8 orders of magnitude, although when the very low conductivities from the lab-based measurements are excluded the range of variability is more like 5 to 6 orders of magnitude. Either way the data show very high intra-layer variability at a regional scale, which means a tightly constrained set of hydraulic conductivity values cannot be specified for each layer.

A similar conclusion is reached when the measurements are classified by lithology (Figure 26). The wide variability in hydraulic conductivity measurements within all lithology classes indicates there is no basis for differentiating between lithologies by hydraulic conductivity at the scale represented by the measurements. A correlation might exist if the hydraulic conductivities for a lithology or stratigraphic layer were biased towards the right (high conductivity) or to the left (low conductivity) in Figure 26 and Figure 27.

The lack of correlation is due in part to the coarse resolution of the regional geological and lithological models, and the challenges presented in attempting to define distinct lithological and stratigraphic characteristics across vast areas from point measurements. The variation in hydraulic properties which might give rise to a particular sequence of aquitards and aquifers at a local scale cannot be assumed to extend over the wider subregion. While there may be distinct geographical differences between sites (e.g. conductivities at one mine site generally being lower than at another mine site, even when the measurements are apparently taken from the same geological layer and lithology), these represent local-scale effects and are largely irrelevant to regional-scale representation of hydrogeology for which variations in hydraulic conductivity over large scales govern groundwater flow. The Hunter groundwater model cannot make direct use of the point-scale hydraulic conductivity data except where it shows a good correlation with regional-scale features, which our analyses indicate it does not. However, such local-scale information can be incorporated into the model emulators. Incorporating local-scale information constrains model predictions in the area where the information is relevant, and this process is demonstrated in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018).

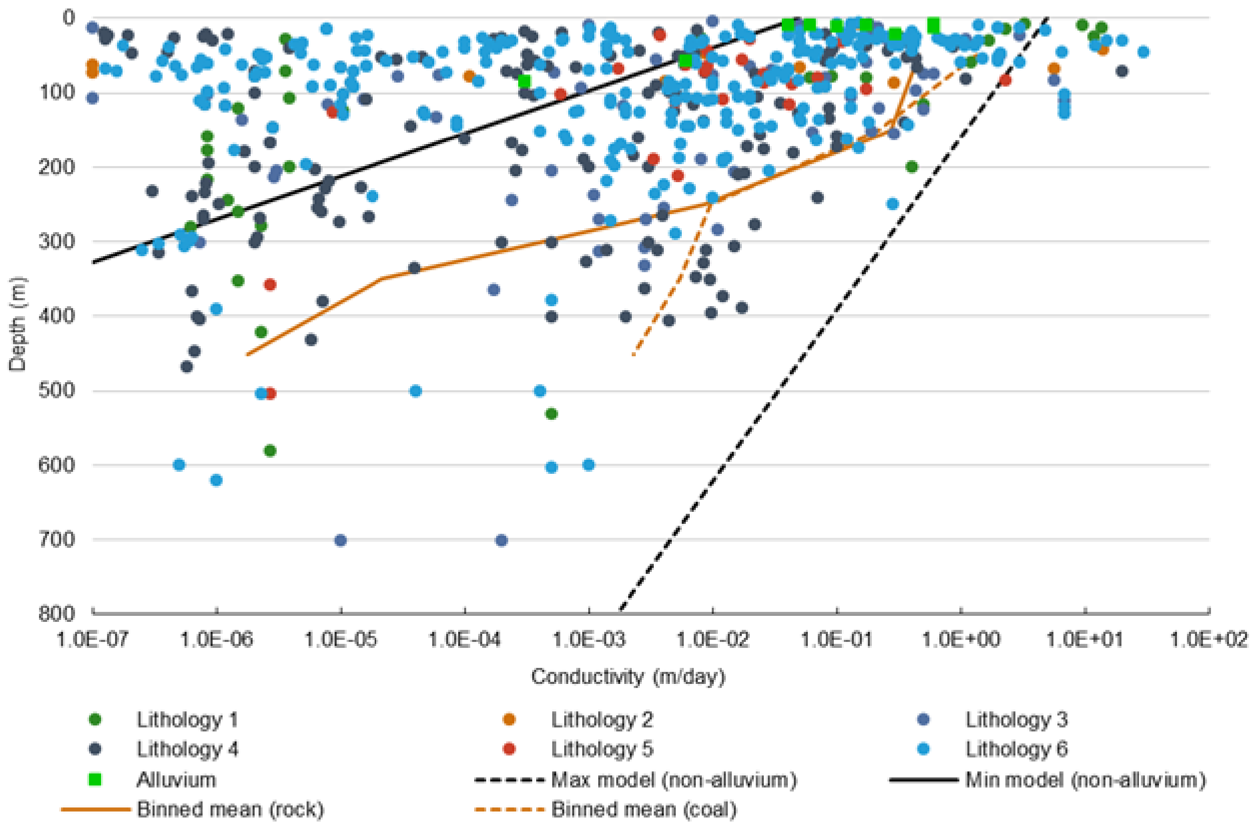
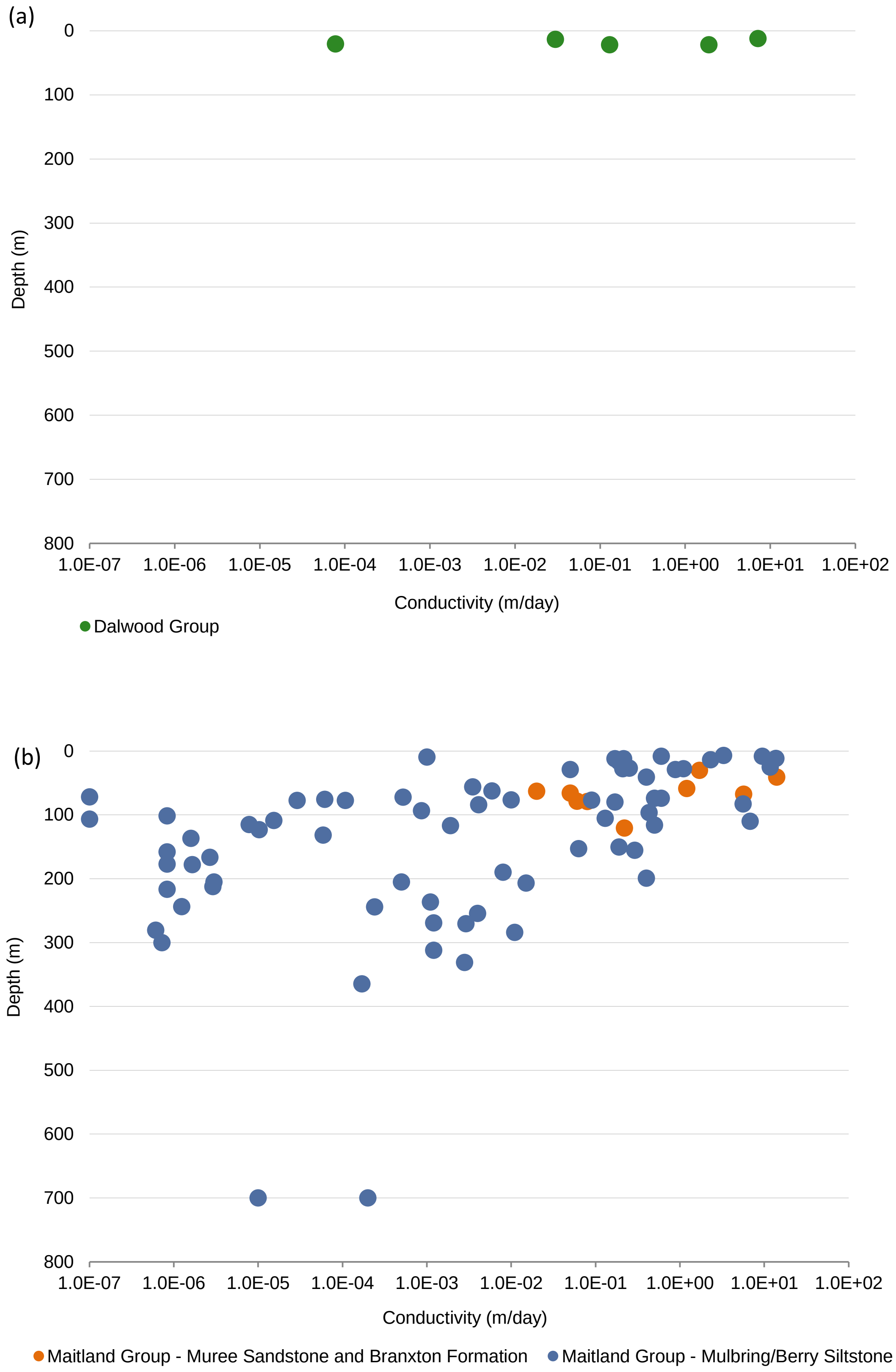
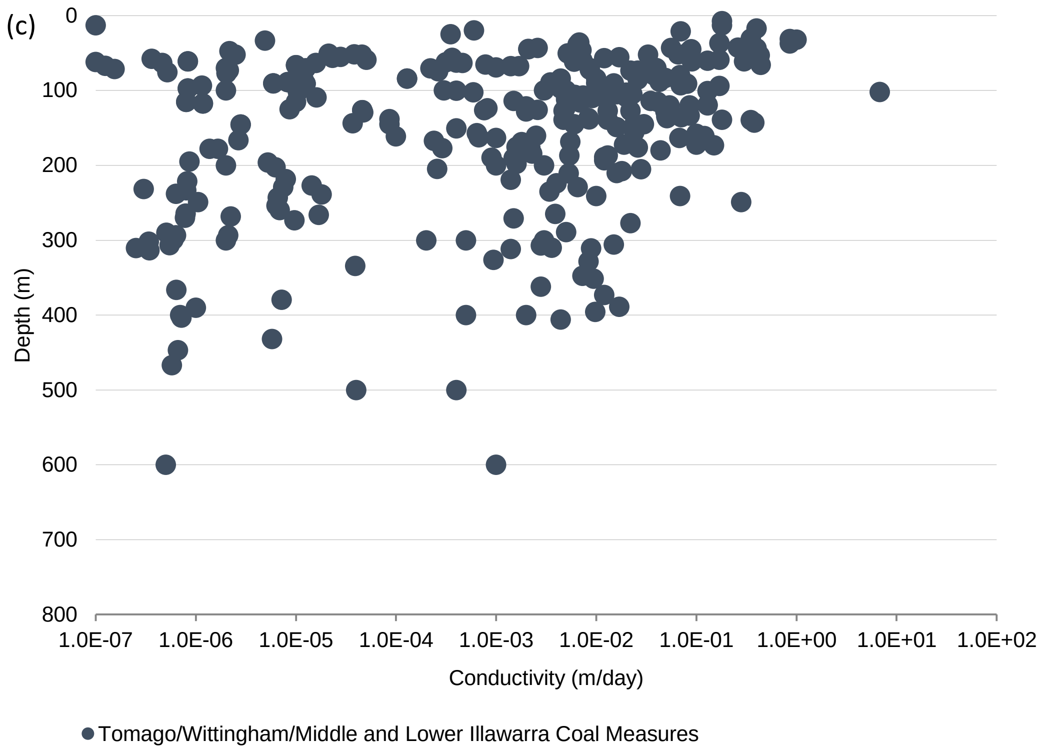
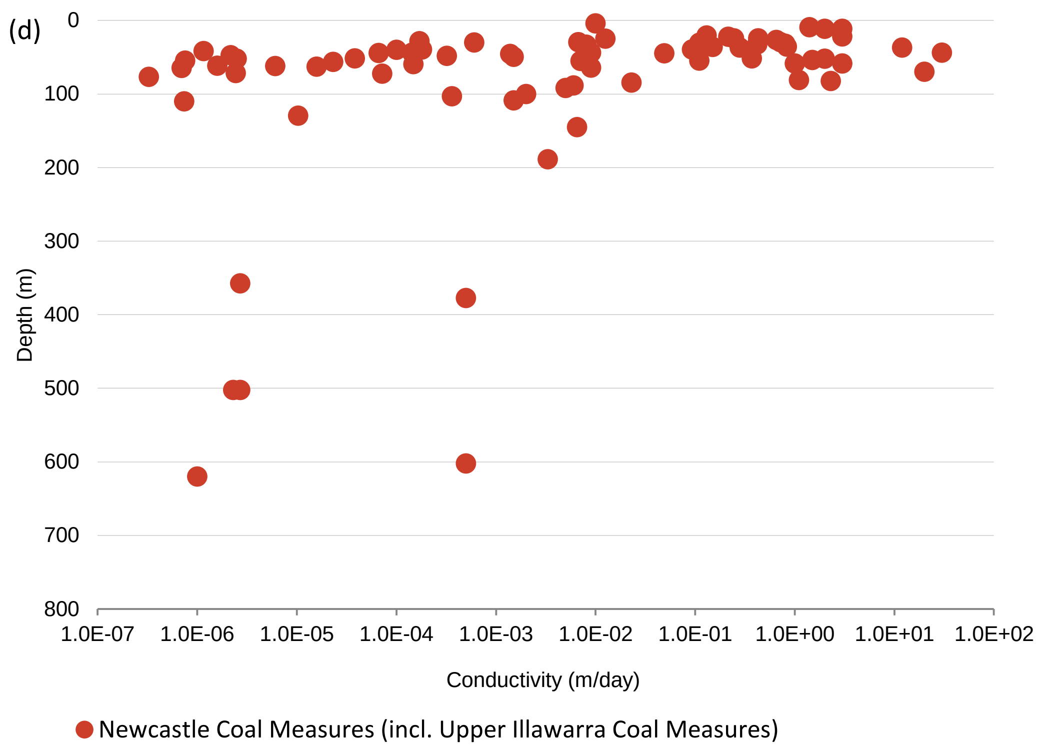


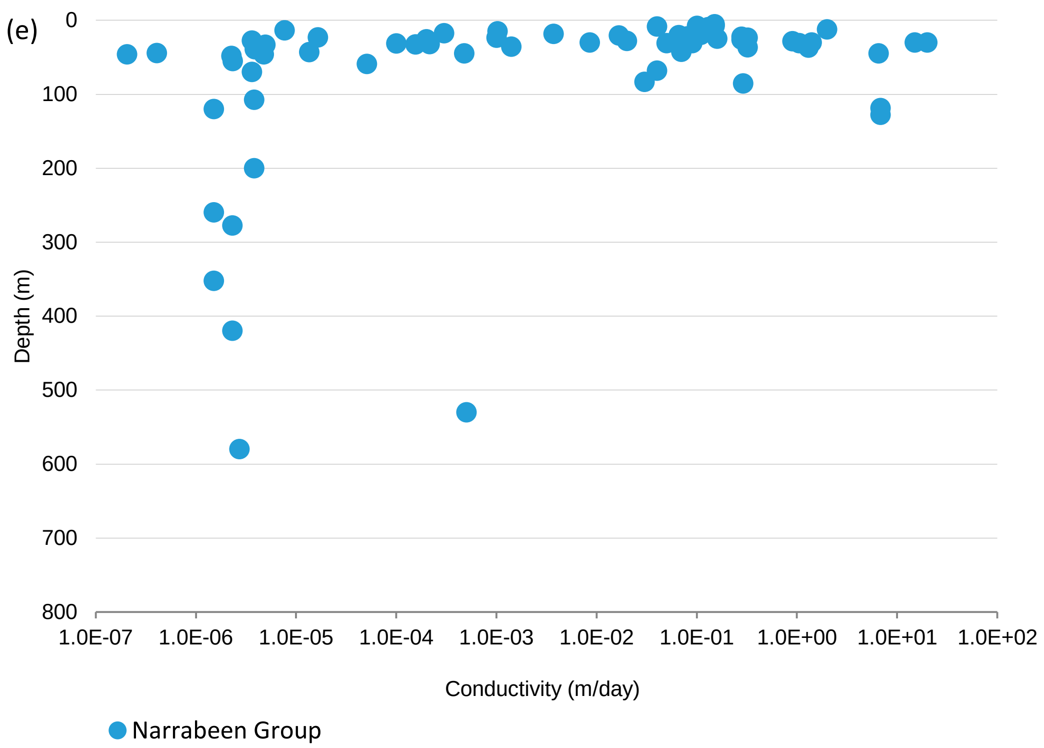
Figure 26 Hydraulic conductivity differentiated by lithology class and correlated with depth

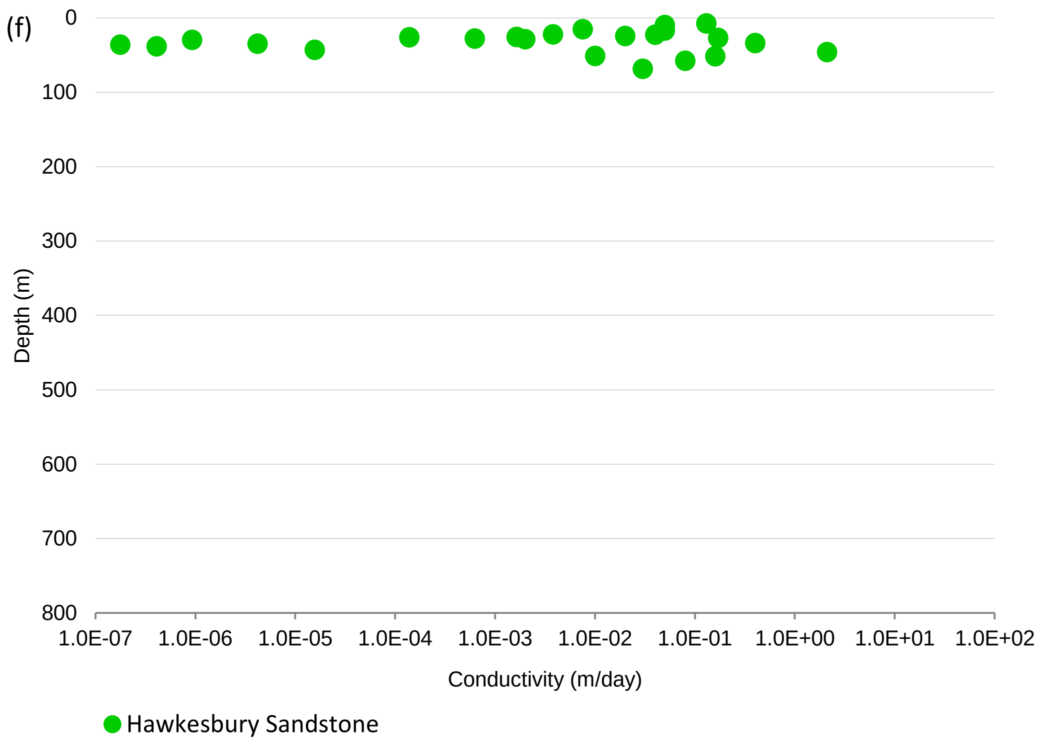
Lithologies are defined in Section 2.1.2 and are: 1, mostly sandstone; 2, mostly siltstone; 3, mostly shale; 4, sandbeds in the fluviatile system; 5, fine sands, silts, and coal; 6, mixture of shale, siltstone and mudstone. The Min and Max model are used by the Hunter groundwater model in the uncertainty analysis (Herron et al., 2018). The Binned mean line shows the arithmetic mean of the conductivity measurements, binned to 100 m depth intervals.
Data: Bioregional Assessment Programme (Dataset 9)


(a)
0
100
200
300
400
500
600
700
800
Depth (m)
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Conductivity (m/day)
Dalwood Group
(b)
0
100
200
300
400
500
600
700
800
Depth (m)
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Conductivity (m/day)
Maitland Group - Muree Sandstone and Branxton Formation
Maitland Group - Mulbring/Berry Siltstone


(c)
Depth (m)
0
100
200
300
400
500
600
700
800
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Conductivity (m/day)
Tomago/Wittingham/Middle and Lower Illawarra Coal Measures


(d)
Depth (m)
0
100
200
300
400
500
600
700
800
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Conductivity (m/day)
Newcastle Coal Measures (incl. Upper Illawarra Coal Measures)


(e)
0
100
200
300
400
500
600
700
800
Depth (m)
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Conductivity (m/day)
Narrabeen Group


(f)
0
100
200
300
400
500
600
700
800
Depth (m)
1.0E-07
1.0E-06
1.0E-05
1.0E-04
1.0E-03
1.0E-02
1.0E-01
1.0E+00
1.0E+01
1.0E+02
Conductivity (m/day)
Hawkesbury Sandstone

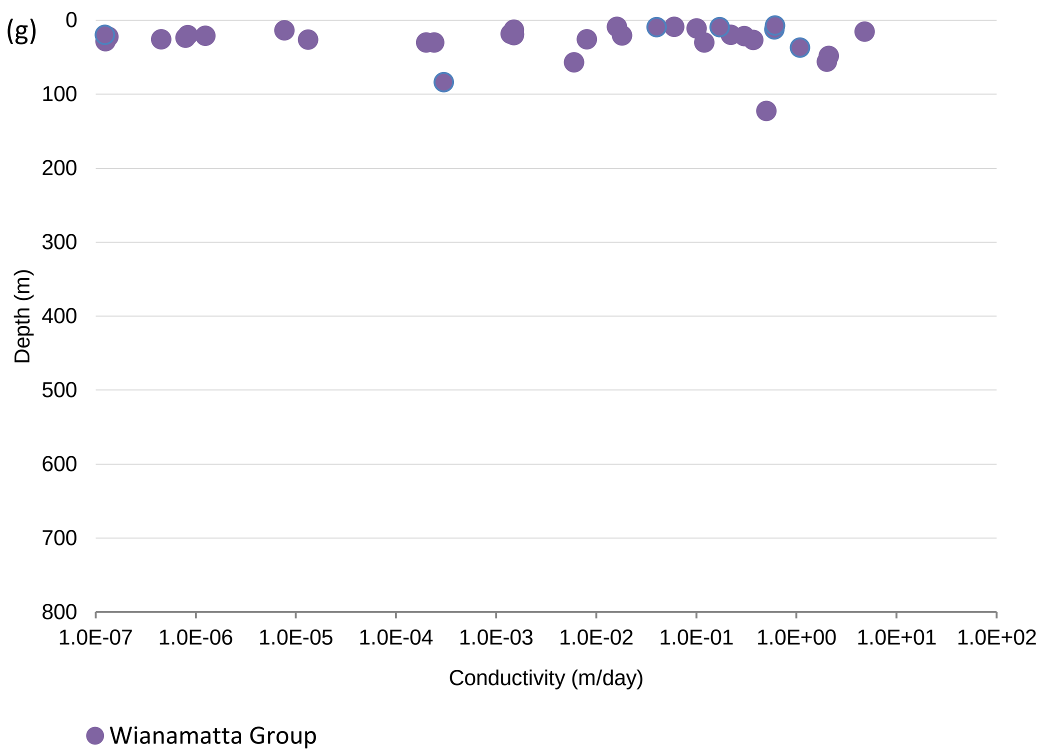


Figure 27 Hydraulic conductivity differentiated by stratigraphy, and correlated with depth for Hunter groundwater model layers (a) 0 (bottom), (b) 2 and 3, (c) 4, (d) 5, (e) 6, (f) 7 and (g) 8, 9 and 10

Layer 1 is not shown because there were no data for this layer. While Layer 0 is the lowest stratigraphic layer in the sequence, the measurements correspond to shallow depths, where this layer outcrops at the surface.
Data: Bioregional Assessment Programme (Dataset 9)

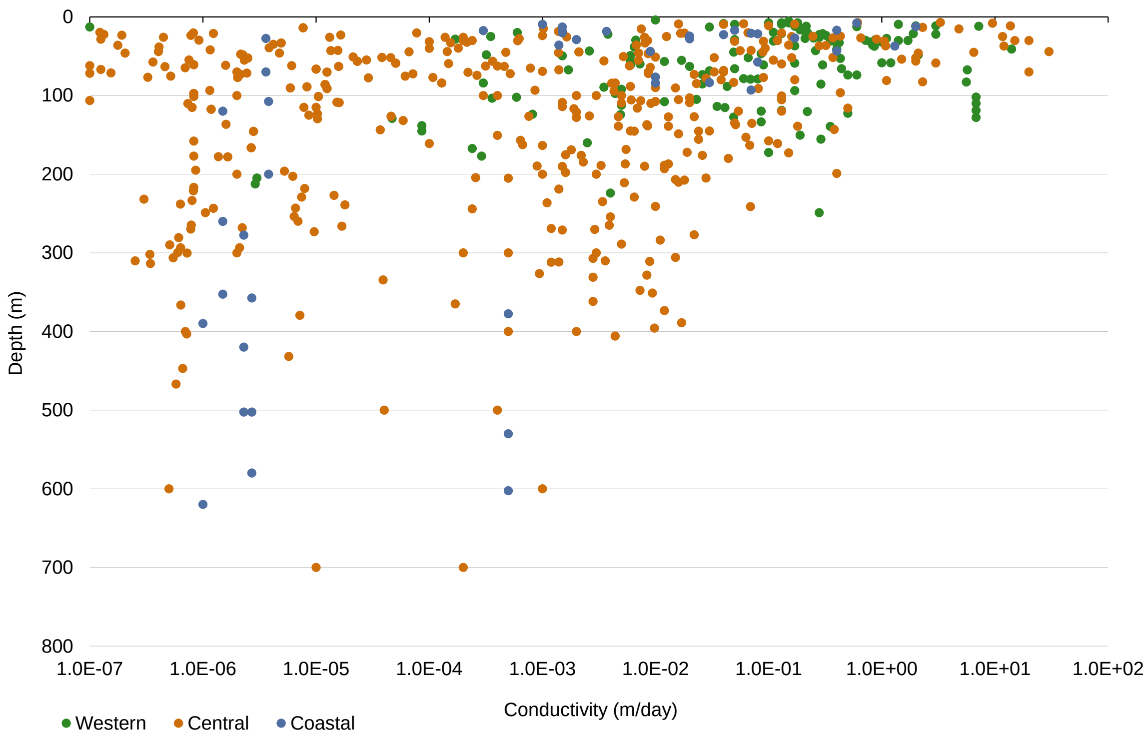


Figure 28 Hydraulic conductivity differentiated by geographic area, and correlated with depth

The various plots show there may be a weak correlation between hydraulic conductivity and depth. In particular, the field-based measurements show a trend of decreasing conductivity with depth (Figure 25), based predominantly on measurements in the Maitland Group stratigraphic units (Figure 27b) and the Tomago, Wittingham and Middle and Lower Illawarra coal measures (Figure 27c). When the data are plotted on a linear scale (Figure 29), it is evident that measurements from the deeper lithologies and stratigraphic layers have hydraulic conductivities less than 0.5 m/day, but there is a lot of variability below this value. The hydraulic conductivity measurements greater than 0.5 m/day are almost all within the top 100 m. As discussed previously, the large degree of scatter is due to the different test types, different formations being sampled and the inherent heterogeneity of rocks and sediments.

While the correlation is weak, Figure 26, Figure 27 and Figure 29 suggest that representing hydraulic conductivity as a function of depth in the Hunter groundwater model is more accurate than adopting a constant hydraulic conductivity throughout. The bold lines (Max model and Min model lines) shown in Figure 26 correspond to the maximum and minimum hydraulic conductivity values used in the groundwater model uncertainty analysis, which are discussed further in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018).

The binned-mean line in Figure 26 shows the arithmetic mean, which is biased to the higher hydraulic conductivity measurements, for each 100 m depth increment. It is used to inform the parameterisation of the Hunter groundwater model, as flow at the large scale is governed by preferential pathways of high conductivity. A small region of low conductivity is almost irrelevant at the large scale. This pattern can be observed in Figure 25, which distinguishes the measurements by testing type. The downhole field tests typically yield higher conductivities than lab methods because: (1) a successful coring requires reasonably coherent rock with few fractures, while downhole measurements may be sampling a highly fractured region (Rovey and Cherkauer, 1995); and (2), the groundwater flows through preferential pathways of high conductivity. The depth-decay functions presented in the figures above (‘Max model’ and ‘Min model’) more accurately capture measurements at larger scales than at the scale of cores. This is discussed further in Herron et al. (2018).

Figure 28 distinguishes the conductivity measurements by geographical area. Most data come from the ‘Central’ area (Hunter Coalfield), so the depth decay function used most accurately captures the hydraulic conductivities in that region. The data are more limited for the other two areas and the quantitative form of the depth decay is less clear, especially in the ‘Western’ area (Western Coalfield) where measurement depths are concentrated within the top 150 m with relatively few measurements at greater depths. Nevertheless, the ‘Max model’ and ‘Min model’ conductivities used in the uncertainty analysis bound the plausible range of conductivities in all regions. Similar depth relationships have been used in the Hunter subregion previously. For example, correlations with depth reported in AGE (2012) and AGE (2014) lie between the maximum and minimum shown in Figure 26, and Figure 13 in companion submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016). Parsons Brinckerhoff (2015) shows a relationship with depth for hydraulic conductivity data from the Hunter, Gloucester and Sydney regions.

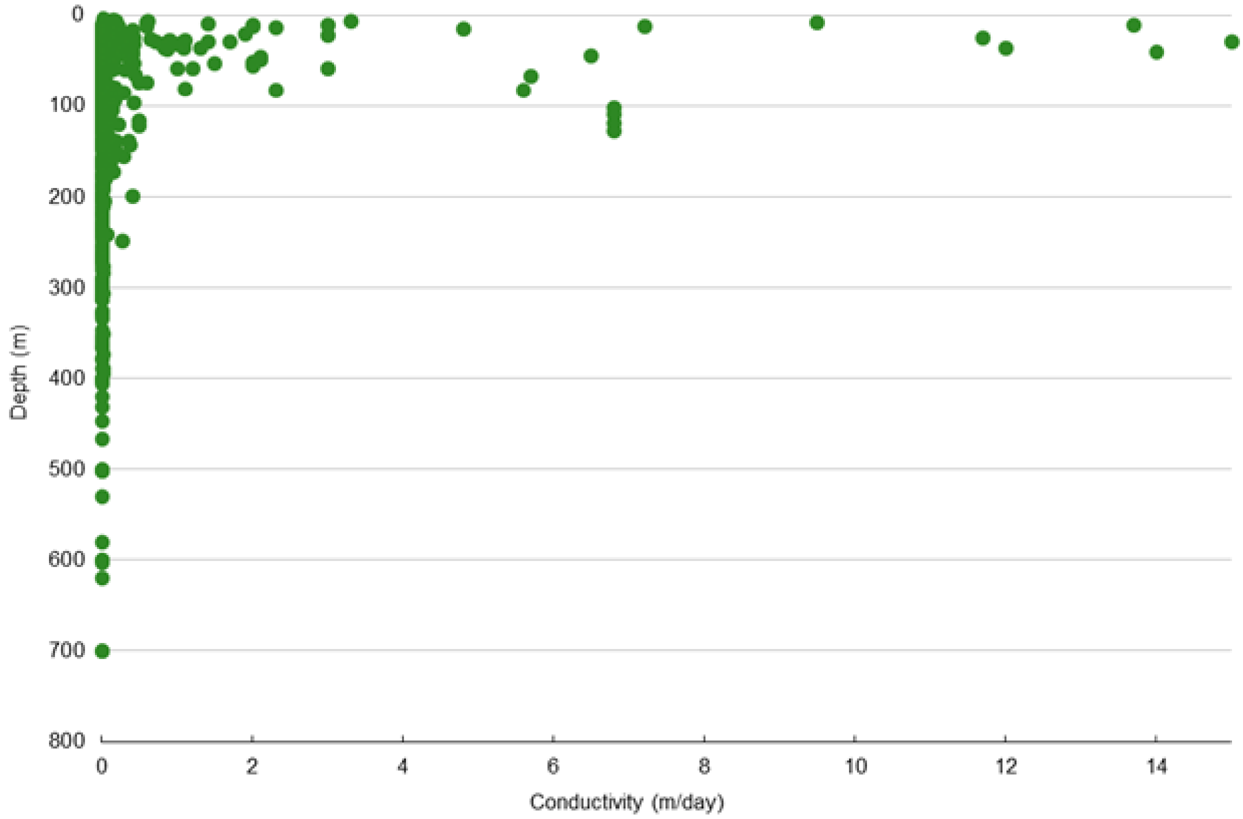


Figure 29 Hydraulic conductivity (on a linear scale) and its relation with depth

Data: Bioregional Assessment Programme (Dataset 9)

When measurements were classified into alluvium, coal-bearing and rock groupings, the units containing coal are found to be typically up to three orders of magnitude more conductive than the rock that does not contain coal (Figure 30). However, as coal seams are not explicitly represented in the Hunter groundwater model, this distinction is not incorporated into the model.

The alluvium plays an important role in surface water – groundwater interactions. Nine of the 577 measurements pertained to alluvium, and these had mean conductivity of 0.25 m/day (Figure 30). This informs the parameterisation of the Hunter groundwater model.

Comparatively few measurements of porosity were available from the environmental impact statements. The porosity data obtained are shown in Figure 31, along with maximum and minimum values used in the Hunter groundwater uncertainty analysis.

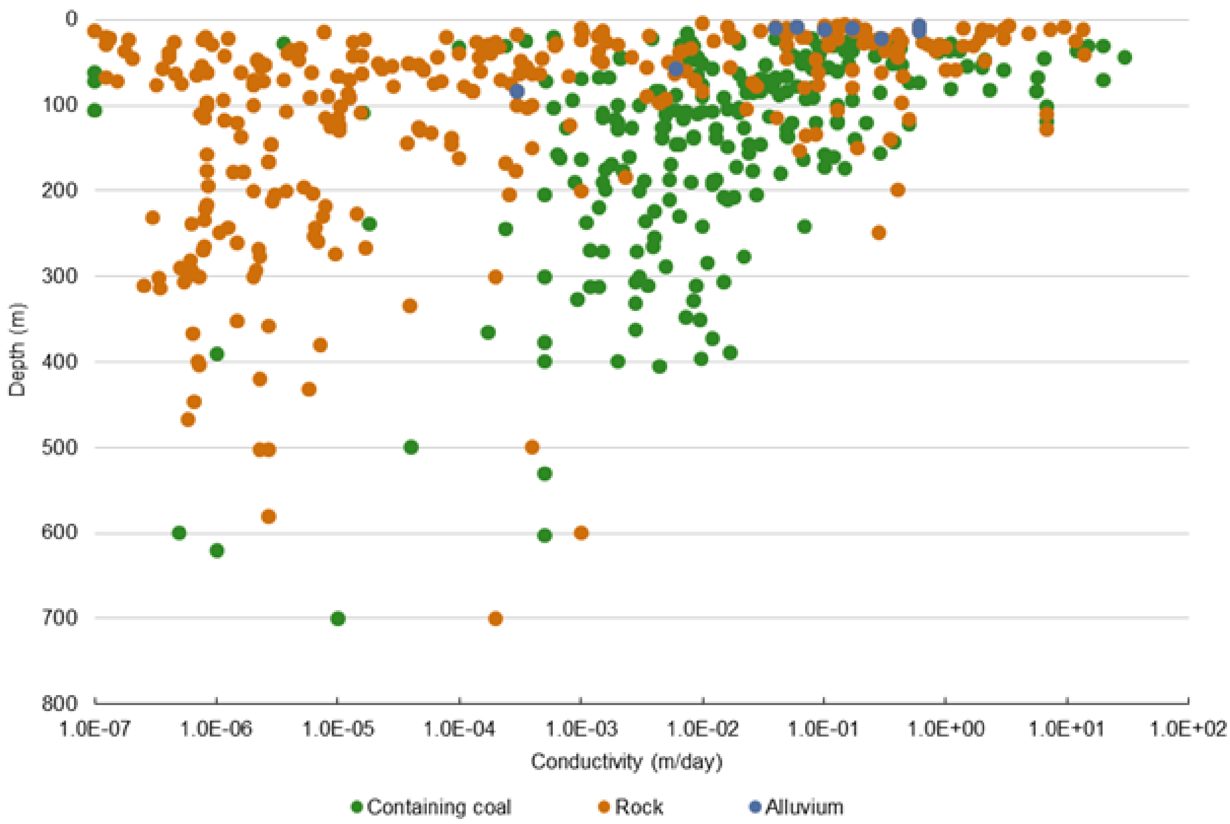


Figure 30 Hydraulic conductivity for coal, rock and alluvium, and correlated with depth

Data: Bioregional Assessment Programme (Dataset 9)

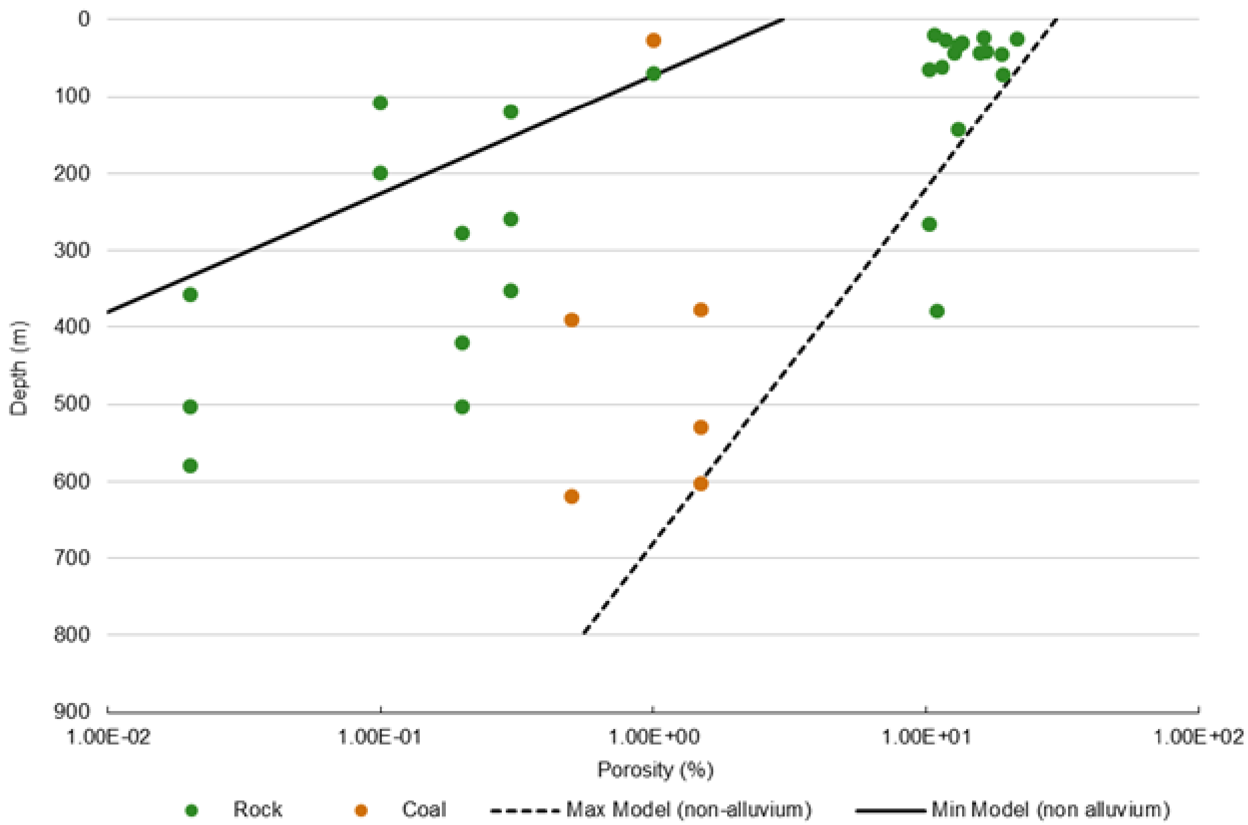


Figure 31 Porosity correlated with depth

Data: Bioregional Assessment Programme (Dataset 9)

2.1.3.3 Gaps

Groundwater data are often patchy and poorly documented, particularly for regional applications. This has been identified in the Hunter subregion, particularly for depth to watertable and recharge.

The uncertainty analysis (Section 2.6.2.8 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018)) will help to quantify the magnitude of the uncertainty arising from poor observation data. The capacity to constrain groundwater model outputs with better localised data is expected to be limited. More information on data gaps will be provided in this product, since the modelling and analysis help identify the most significant data gaps and can inform recommendations for the future.

References

AGE (2012) Report on Drayton South Coal Project Groundwater Impact Assessment, Project No. G1544, October 2012 (Appendix C of the Drayton South Coal Project Gateway Application).

AGE (2014) Mount Thorley Operations 2014 Groundwater Assessment, Project No. G1468F, May 2014 (Appendix I of the Mount Thorley Continuation Project Environmental Impact Statement).

Anderson VG (1945) Some effects of atmospheric evaporation and transpiration on the composition of natural water in Australia (continued). 4. Underground waters in riverless areas. Journal and Proceedings of the Australian Chemical Institute 12, 83–98.

Crosbie RS, Jolly ID, Leaney FW and Petheram C (2010) Can the dataset of field based recharge estimates in Australia be used to predict recharge in data-poor areas? Hydrology and Earth System Sciences 14(10), 2023–2038. DOI: 10.5194/hess-14-2023-2010.

Crosbie R, Pickett T, Mpelasoka F, Hodgson G, Charles S and Barron O (2013) An assessment of the climate change impacts on groundwater recharge at a continental scale using a probabilistic approach with an ensemble of GCMs. Climatic Change 117, 41–53. DOI: 10.1007/s10584-012-0558-6.

Crosbie R, Peeters L and Carey H (2016) Groundwater modelling. Submethodology M07 from the Bioregional Assessment Technical Programme. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/submethodology/M07.

Efron B and Tibshirani RJ (1994) An introduction to the bootstrap. CRC press, Boca Raton, Florida.

Herron NF, Peeters L, Crosbie R, Marvanek SP, Pagendam D, Ramage A, Rachakonda PK and Wilkins A (2018) Groundwater numerical modelling for the Hunter subregion. Product 2.6.2 for the Hunter 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/HUN/2.6.2.

Keywood MD, Chivas AR, Fifield LK, Cresswell RG and Ayres GP (1997) The accession of chloride to the western half of the Australian continent. Australian Journal of Soil Research 35, 1177–1189.

Leaney F, Crosbie R, O'Grady A, Jolly I, Gow L, Davies P, Wilford J and Kilgour P (2011) Recharge and discharge estimation in data poor areas: Scientific reference guide. CSIRO: Water for a Healthy Country National Research Flagship.

Mackie Environmental Research (2006) Anvil Hill Project: groundwater management studies. Centennial Hunter Pty Limited, Sydney. Viewed 01 December 2014, https://majorprojects.affinitylive.com/public/15987e1d6effbca80892d85cb7626029/Environmental%20Assessment-Appendix08-Groundwater.pdf.

Parsons Brinckerhoff (2015) Updated conceptual hydrogeological model of the Gloucester Basin, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. Parsons Brinckerhoff Australia Pty Limited, Sydney. Viewed 19 October 2016, https://www.agl.com.au/-/media/AGL/About-AGL/Documents/How-We-Source-Energy/Gloucester-Document-Repository/Water-Reports/20151117_Updated-Conceptual-Hydrogeological-Model-of-the-Gloucester-Basin.pdf.

Raiber M, Cui T, Pagendam D, Rassam D, Gilfedder M, Crosbie R, Marvanek S and Hartcher M (2016) Observations analysis, statistical analysis and interpolation for the Clarence-Moreton bioregion. Product 2.1-2.2 from the Clarence-Moreton Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/product/CLM/CLM/2.1-2.2.

Rovey CW and Cherkauer DS (1995) Scale Dependency of Hydraulic Conductivity Measurements. Ground Water 33(5), 769–780.

Wilford J, Searle R, Thomas M and Grundy M (2015) Soil and landscape grid national soil attribute maps - depth of regolith (3" resolution) release 2. v5. CSIRO. Data collection. Viewed 19 April 2016, http://doi.org/10.4225/08/55C9472F05295.

Wohling DL, Leaney FW and Crosbie RS (2012) Deep drainage estimates using multiple linear regression with percent clay content and rainfall. Hydrology and Earth System Sciences 16(2), 563–572. DOI: 10.5194/hess-16-563-2012.

Wood WW (1999) Use and misuse of the chloride-mass balance method in estimating ground water recharge. Ground Water 37(1), 2–3.

Zhang YQ, Rachakonda PK, Herron NF, Peña-Arancibia JL and Marvanek SP (2016) Current water accounts and water quality for the Hunter subregion. Product 1.5 for the Hunter subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 14 November 2016, http://data.bioregionalassessments.gov.au/product/NSB/HUN/1.5.

Datasets

Dataset 1 Bioregional Assessment Programme (2014) HUN GW modelling DEM v01. Bioregional Assessment Derived Dataset. Viewed 19 August 2016, http://data.bioregionalassessments.gov.au/dataset/f0927e8a-cc41-419b-ae68-660d5d5fa47b.

Dataset 2 Caltech/JPL (2014) Vegetation height for Australia (Simard). Bioregional Assessment Source Dataset. Viewed 12 February 2016, http://data.bioregionalassessments.gov.au/dataset/09f0ceb4-d401-410c-bd4f-dfbc5276ef8b.

Dataset 3 Bioregional Assessment Programme (2016) HUN Geological Model Eroded Horizons v01. Bioregional Assessment Derived Dataset. Viewed 19 August 2016, http://data.bioregionalassessments.gov.au/dataset/0499bee7-a0c4-45e8-978b-e0ef0055fb0e.

Dataset 4 Bioregional Assessment Programme (2015) SYD Dryland Diffuse Groundwater Recharge v01. Bioregional Assessment Derived Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/c73b2181-b2eb-4272-939c-98823f4e7ce1.

Dataset 5 CSIRO (2015) AUS Soil and Landscape Grid National Soil Attribute Maps - Depth of Regolith (3" resolution) - Release 2. Bioregional Assessment Source Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/c28597e8-8cfc-4b4f-8777-c9934051cce2.

Dataset 6 Bioregional Assessment Programme (2015) HUN Alluvium (1:1m Geology). Bioregional Assessment Derived Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/c2706e2f-8800-440d-ad60-d0f2790b32e3.

Dataset 7 Geoscience Australia (2012) Surface Geology of Australia, 1:1 000 000 scale, 2012 edition. Bioregional Assessment Source Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/8284767e-b5b1-4d8b-b8e6-b334fa972611.

Dataset 8 Bioregional Assessment Programme (2015) GIS analysis of HYDMEAS - Hydstra Groundwater Measurement Update - NSW Office of Water- Nov2013 v01. Bioregional Assessment Derived Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/d414c703-aabd-43af-81e0-30aab4d9dfb1.

Dataset 9 Bioregional Assessment Programme (2017) HUN Hydraulic Properties v03. Bioregional Assessment Derived Dataset. Viewed 30 March 2017, http://data.bioregionalassessments.gov.au/dataset/dae8cca5-0b9d-46c7-b50c-9cfc4ccd079b.

Dataset 10 Bioregional Assessment Programme (2014) GEODATA TOPO 250K Series 3, File Geodatabase format (.gdb). Bioregional Assessment Derived Dataset. Viewed 14 November 2016, http://data.bioregionalassessments.gov.au/dataset/96ebf889-f726-4967-9964-714fb57d679b.

Dataset 11 NSW Department of Primary Industries, NSW Office of Water (2015) Groundwater Entitlement Hunter NSW Office of Water 20150324. Bioregional Assessment Source Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/19697f0a-4513-42a4-a7ce-4e00f48a715a.

Dataset 12 Bioregional Assessment Programme (2016) HUN gridded daily PET from 1973-2102 v01. Bioregional Assessment Derived Dataset. Viewed 19 August 2016, http://data.bioregionalassessments.gov.au/dataset/ad969062-dd2f-436b-b4a0-de57b2c120d5.

Dataset 13 CSIRO (2014) Australian 0.05º gridded chloride deposition v2. Bioregional Assessment Source Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/c1649bd7-227f-41ff-9964-b55479bef640.

Dataset 14 NSW Office of Water (2013) NSW Office of Water Groundwater Quality extract 28_nov_2013. Bioregional Assessment Source Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/74da836a-7b97-4278-9034-c9a259a34fbb.

Dataset 15 Geoscience Australia (2012) Surface Geology of Australia, 1:2 500 000 scale, 2012 edition. Bioregional Assessment Source Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/4a91fff8-ed51-4994-b358-066497e25c8c.

Dataset 16 Bureau of Meteorology (2008) Australian Average Rainfall Data from 1961 to 1990. Bioregional Assessment Source Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/fd91f2d4-2cc8-4d5d-9f67-8fe8af1e2676.

Dataset 17 Bioregional Assessment Programme (2016) SYD Soil - Average Clay Content Top 2m v01. Viewed 14 October 2016. http://data.bioregionalassessments.gov.au/dataset/95fc3145-5249-4bd4-bfd2-a812c39d68f9.

Dataset 18 Australian Bureau of Agricultural and Resource Economics Bureau of Rural Sciences (ABARE-BRS) (2012) Catchment-scale Land Use Management (CLUM). Bioregional Assessment Source Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/88995758-2993-405e-bd0b-a2001a6539e6.

Dataset 19 Bioregional Assessment Programme (2015) SYD Point Recharge Estimates from Chloride Mass Balance v01. Bioregional Assessment Derived Dataset. Viewed 13 April 2016, http://data.bioregionalassessments.gov.au/dataset/2de56d51-44d0-4217-a98a-10ae1dedcf8b.

2.1.4 Surface water hydrology and water quality

Summary

This product summarises key datasets that are used in surface water modelling of the Hunter subregion. Streamflow data from 14 gauging stations are used to calibrate the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L), and 34 for calibrating the AWRA-R river model.

To represent the geometry of a river, 34 surveyed cross-sections were obtained and associated river lengths were computed from geographic data. At 22 additional locations, where surface water simulations are required but no information on cross-sections were available, a method was developed that related catchment area and mean annual streamflow to an idealised trapezoidal cross-section. At another seven locations, cross-sections from nearby gauging stations were used.

To simulate irrigation demand in the river model, irrigated areas and crop types for river reaches were obtained from land use data.

Surface water modelling results are generated at model nodes. The hydrological changes along the links (reaches) between them must be interpolated from the results at the model nodes. The mapping of links to nodes is presented. It is essential for defining the surface water zone of potential hydrological change from additional coal resource developments. For some links, interpolations are not recommended.

Many datasets have been used to inform the surface water modelling of the Hunter subregion. Some are used directly, while others have been derived from other existing data. Not all the datasets are reported here. Table 7 lists the key datasets for surface water modelling (AWRA-R and AWRA-L), whether they have been derived from existing data for surface water modelling purposes in the Hunter subregion and where they are reported within the Hunter subregion suite of products.

As stated in companion product 2.3 (conceptual modelling) for the Hunter subregion (Dawes et al., 2018), no surface water quality data are used directly in the numerical modelling for surface water, nor were water quality data used indirectly to inform other model inputs. The AWRA-R model represents mine site discharges of mine water as part of the Hunter River Salinity Trading Scheme, but only in terms of volumes and timing of discharges as determined by discharge windows (related to exceedance of defined flow rate thresholds) and permissible discharge volumes used to manage salinity in the Hunter River. Thus no water quality data are considered in this section.

Table 7 Key datasets for surface water modelling for the Hunter subregion

Dataset	Source or derived	Section or product
Streamflow	Source (Bioregional Assessment Program, Dataset 1)	2.1.4.1.1
River cross-sections at gauging stations	Source (CSIRO, Dataset 2)	2.1.4.1.2
River cross-sections at simulation nodes	Derived (Bioregional Assessment Programme, Dataset 3)	2.1.4.2.1
River reach lengths	Derived from river network data (CSIRO, Dataset 4, Dataset 5)	2.1.4.2.2
Irrigation area extents and crop types	Derived (CSIRO Land and Water, Dataset 9) from land use (Department of Agriculture: Australian Bureau of Agricultural and Resource Economics, Dataset 8)	2.1.4.2.3
Hunter River Salinity Trading Scheme discharges	Derived from observed daily streamflow data (Bioregional Assessment Programme, Dataset 1) and observed mine discharge data (EPA, Dataset 10)	2.1.4.2.4
River extractions	Derived from IQQM modelling data (NSW Department of Primary Industries (Office of Water), Dataset 11)	2.6.1.4.2 in Surface water numerical modelling
Dam releases, reservoir storage and allocations	Derived from IQQM modelling (NSW Department of Primary Industries (Office of Water), Dataset 11) and reservoir storage from observed data (CSIRO Land and Water, Dataset 12)	2.6.1.4.2 in Surface water numerical modelling
Catchment boundaries	Derived from digital elevation models (DEM) (CSIRO Land and Water, Dataset 7) and stream gauging stations (CSIRO Land and Water, Dataset 13)	2.6.1.4.2 in Surface water numerical modelling

Section 2.1.4.1 provides details of observed data that have been used for surface water modelling. The statistical analysis and interpolation section (Section 2.1.4.2) describes the methods for deriving datasets for input into the AWRA-R river model from existing data. This section also presents the method for interpolating and extrapolating results generated at model nodes to links (river reaches) in the link-node structure.

2.1.4.1 Observed data

2.1.4.1.1 Stage and streamflow data

There are 43 streamflow gauging stations (Bioregional Assessment Programme, Dataset 1) in the subregion: 39 are located in the Hunter river basin and have gauge IDs with the prefix 210---, and four are located in the Macquarie-Tuggerah lakes basin and have gauge IDs prefixed by 211--- (Figure 32). There are 34 and 14 gauging stations used for AWRA-R and AWRA-L surface water model calibrations, respectively. The site details and data used for surface water modelling are summarised in Table 8.

Table 8 Gauge information for streamflow data for the Hunter subregion

AWRA-R = Australian Water Resources Assessment river model
AWRA-L = Australian Water Resources Assessment landscape model

Gauge ID	River name	Gauge name	Catchment area (km^2)	Latitude	Longitude	Gauge opened	Gauge closed	AWRA module
210001	Hunter	Singleton	16,400	–32.562°	151.170°	3 Jan 1913	No	AWRA-R
210002	Hunter	Muswellbrook Br	4,220	–32.258°	150.888°	2 Jan 1913	No	AWRA-R
210004	Wollombi Brook	Warkworth	1,848	–32.572°	151.045°	10 Feb 1908	No	AWRA-R
210006	Goulburn	Coggan	3,340	–32.345°	150.102°	1 Jan 1913	No	AWRA-R
210011	Williams	Tillegra	194	–32.320°	151.687°	20 Feb1931	No	AWRA-L
210014	Rouchel Brook	Rouchel Brook (The Vale)	395	–32.153°	151.048°	7 Dec 1934	No	AWRA-R AWRA-L
210015	Hunter	Glenbawn	1,295	–32.113°	150.990°	1 Dec 1940	No	AWRA-R
210016	Goulburn	Kerrabee	4,950	–32.418°	150.318°	15 Dec 1940	No	AWRA-R
210017	Moonan Brook	Moonan Brook	103	–31.943°	151.280°	18 Dec 1940	No	AWRA-L
210022	Allyn	Halton	205	–32.308°	151.512°	12 Dec 1940	No	AWRA-L
210028	Wollombi Brook	Wollombi Brook at Bulga	1,672	–32.651°	151.020°	27 Dec 1949	No	AWRA-R
210031	Goulburn	Sandy Hollow	6,810	–32.347°	150.573°	24 Dec 1954	No	AWRA-R
210040	Wybong Ck	Wybong	676	–32.270°	150.635°	16 Dec 1955	No	AWRA-R AWRA-L
210042	Foy Brook	Ravensworth	170	–32.398°	151.047°	24 Dec 1956	No	AWRA-R
210044	Glennies Ck	Middle Falbrook (Fal Dam Site)	466	–32.452°	151.148°	27 Jan 1956	No	AWRA-R
210048	Wollombi Brook	Paynes Crossing	1,064	–32.860°	151.058°	2 Dec 1940	No	AWRA-L
210052	Pages	Gundy Recorder	1,050	–32.012°	150.997°	26 De 1958	No	AWRA-R AWRA-L
210055	Hunter	Denman	4,530	–32.382°	150.710°	5 Feb 1959	No	AWRA-R
210056	Hunter	Aberdeen	3,090	–32.160°	150.882°	18 De 1959	No	AWRA-R
210059	Bayswater Ck	D/S Liddell (Site 2)	88	–32.403°	151.022°	3 Dec 1973	No	AWRA-R
210060	Baerami Ck	Baerami	384	–32.445°	150.452°	15 Dec 1980	1 Jan 1992	AWRA-R
210061	Pages	Blandford (Bickham)	302	–31.812°	150.925°	21 Dec 1960	No	AWRA-R
210064	Hunter	Greta	17,320	–32.667°	151.400°	6 Dec 1968	No	AWRA-R
210080	West Brook	U/S Glendon Brook	80	–32.473°	151.282°	30 Dec 1969	No	AWRA-R AWRA-L
210082	Wollar Ck	U/S Goulburn	274	–32.340°	149.952°	1 Dec 1980	1 Jan 1997	AWRA-R

Gauge ID	River name	Gauge name	Catchment area (km^2)	Latitude	Longitude	Gauge opened	Gauge closed	AWRA module
210083	Hunter	Liddell	13,400	−32.490°	150.922°	6 Dec 1969	No	AWRA-R
210084	Glennies Ck	The Rocks No.2	227	−32.365°	151.238°	6 Dec 1969	No	AWRA-R
210087	Doyles Ck	Doyles Ck	202	−32.513°	150.798°	2 Jan 1987	No	AWRA-R
210088	Dart Brook	Dart Brook at Aberdeen No. 2	799	−32.174°	150.868°	21 Dec 1970	No	AWRA-R
210089	Black Creek	Black Creek at Rothbury	220	−32.717°	151.326°	31 Dec 1972	No	AWRA-R
210093	Kingdon Ponds Ck	Nr. Parkville	177	−31.958°	150.855°	3 Dec 1972	No	AWRA-R AWRA-L
210120	Apple Tree Ck	Dural Gap	29	−32.562°	150.847°	14 Dec 1984	1 Jan 1998	AWRA-R
210123	Fal Brook	U/S Glennies Ck Dam	106	−32.288°	151.265°	27 Dec 1989	No	AWRA-L
210124	Dart Brook	Yarrandi Br	233	−32.013°	150.782°	10 Dec 1994	No	AWRA-R
210127	Hunter	U/S Glennies Ck	13,855	−32.502°	151.060°	25 Dec 1993	No	AWRA-R
210128	Hunter	Mason Dieu	14,394	−32.533°	151.048°	27 Dec 1993	No	AWRA-R
210131	Black Ck	D/S Anvil Ck	155	−32.052°	151.033°	29 Dec 1993	No	AWRA-R
210134	Hunter	Long Point	16310	−32.562°	151.137°	29 Dec 1993	No	AWRA-R
210135	Wollombi Brook	D/S Brickmans Br	1088	−32.850°	151.058°	18 Dec 1995	No	AWRA-R
211008	Jigadee Ck	Avondale	55	−33.067°	151.467°	19 Dec 1969	No	AWRA-L
211009	Wyong	Gracemere	236	−33.272°	151.360°	26 Dec 1972	No	AWRA-L
211010	Jilliby Ck	U/S Wyong R (Durren La)	92	−33.248°	151.390°	21 Dec 1972	No	AWRA-L
211013	Ourimbah Ck	U/S Weir	83	−33.348°	151.343°	14 Dec 1976	No	AWRA-L

Data: Bioregional Assessment Programme (Dataset 1)

Figure 32 Location of stream gauges in the Hunter subregion (listed in Table 8)

Data: Bioregional Assessment Programme (Dataset 1, Dataset 15), Bureau of Meteorology (Dataset 14)

The daily streamflow values in the time series are aggregated from instantaneous observations of streamflow that have been converted from observed stage height using a rating curve. Thus the quality of the streamflow records depend on the quality of the rating curves.

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 (Viney et al., 2011; Zhang et al., 2013) (Table 9). 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.

Streamflow data flagged as good, fair, poor or 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 dataset as –9999.

Table 9 Quality codes for the NSW gauges for the Hunter 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: Bioregional Assessment Programme (Dataset 1)

Figure 33 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 eight catchments accounts for more than 30%.

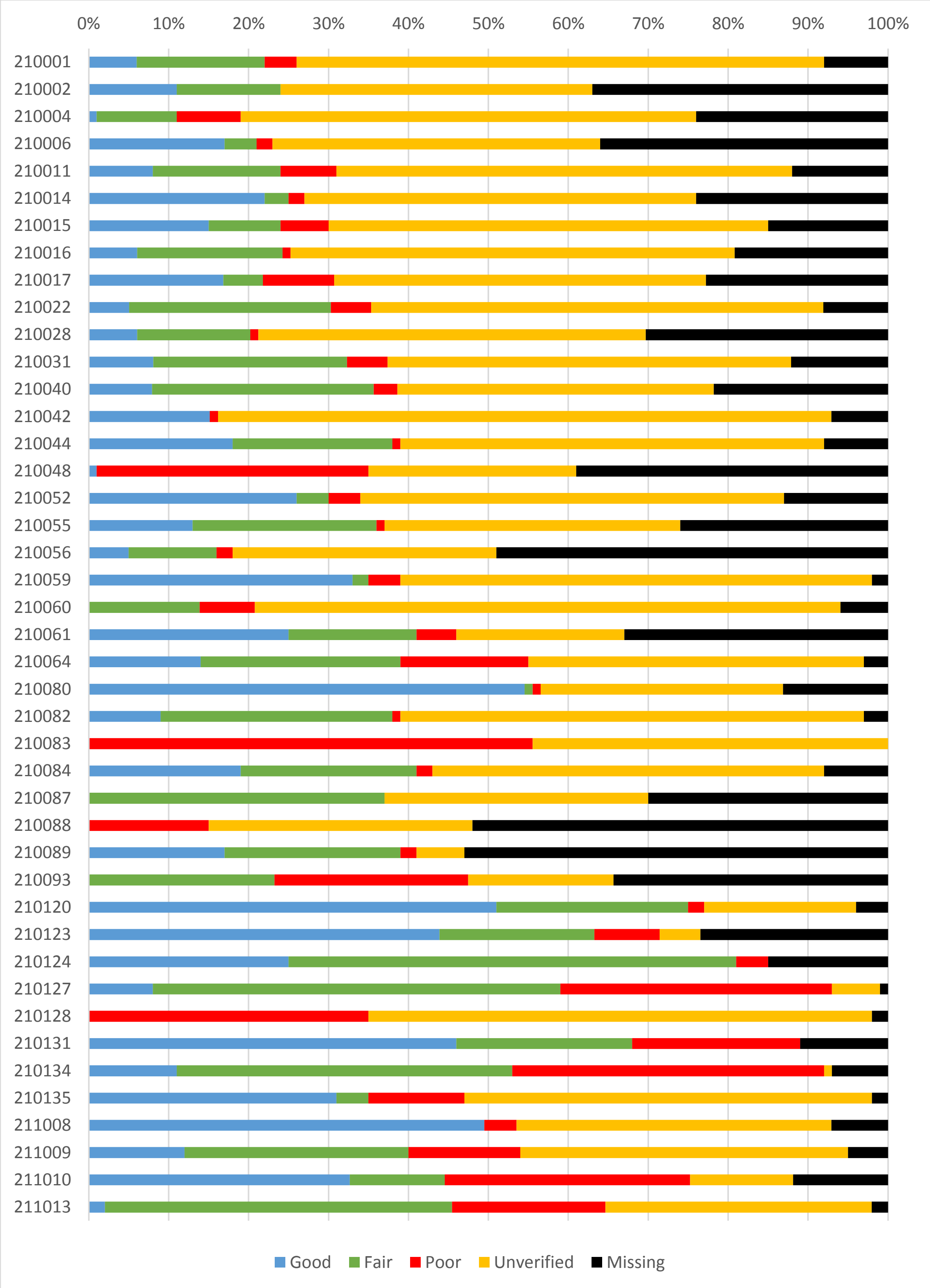


Figure 33 Percentage of streamflow data in each quality code class by gauging station

Data: Bioregional Assessment Programme (Dataset 1)

The stage and streamflow data are used as provided in the calibration of surface water models reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

2.1.4.1.2 River cross-sections

Information on stream cross-sections are used in AWRA-R to represent the geometry of a river reach. A river reach is defined for modelling purposes as the runoff contributing area between two streamflow gauges or simulation nodes. This definition expands on the more traditional definition of a reach, which includes only the segment of river between two streamflow gauges or simulation nodes. Reach geometry – as defined by the upstream and downstream cross-sections – is used in AWRA-R to compute instream actual evapotranspiration and rainfall fluxes, instream capacity and losses to groundwater (Lerat et al., 2013; Dutta et al., 2014). The cross-sections for 34 streamflow gauges used in AWRA-R (Table 8) were obtained from CSIRO (Dataset 2). These, plus the 22 headwater derived cross-sections (see Section 2.1.4.2.1), defined the calibration node-link network (CSIRO Land and Water, Dataset 7), where a link is defined as the element that routes water through the system.

DPI Water collects cross-section data every few years. In AWRA-R, only the latest or most detailed (for example, the one with more distance measurements) was used, hence potential changes in cross-section due to scour and re-deposition of sediment after peak flows are not reflected in the model (McMillan et al., 2010). In addition, distances between gauges vary from a few to tens of kilometres, which may result in an underestimation or overestimation of the river width and depth when averaging the river instream capacity from the upstream and downstream cross-sections. Model calibration will partially compensate proportional biases arising from this underestimation.

2.1.4.2 Statistical analysis and interpolation

2.1.4.2.1 River cross-sections at simulation nodes

In Australia, cross-section data are generally available at streamflow gauges only. River model simulations are required to assess the impacts of coal resource development on streamflow at several locations where cross-section data are lacking. Obtaining channel cross-sections requires detailed surveys which are time-consuming and carried out under stringent guidelines (Stewardson et al., 2005). Regional hydraulic geometry models can be obtained using proxies (catchment area, mean annual streamflow) that are more readily available. Using data from about 400 stations in Queensland, Tennakoon and Marsh (2007) developed functional relationships of modest explanatory value (with a coefficient of determination $r^2 \approx 0.3$) between cross-section width and mean channel depth with catchment area and mean annual streamflow. A similar approach was used here to produce stream cross-sections in headwater catchments where there is no upstream gauge (so that the averaging method described in Section 2.1.4.1.2 is not applicable), by assuming that cross-sections at nearby gauging stations (or at gauging stations draining a comparable catchment area, or at gauging stations with comparable mean annual streamflow) provided a reasonable estimate of bottom channel width (Bioregional Assessment Programme, Dataset 3). The information on bottom channel width (L) was then converted into a Cippoletti weir (Figure 34) with a height (H) able to accommodate AWRA-L maximum streamflow.

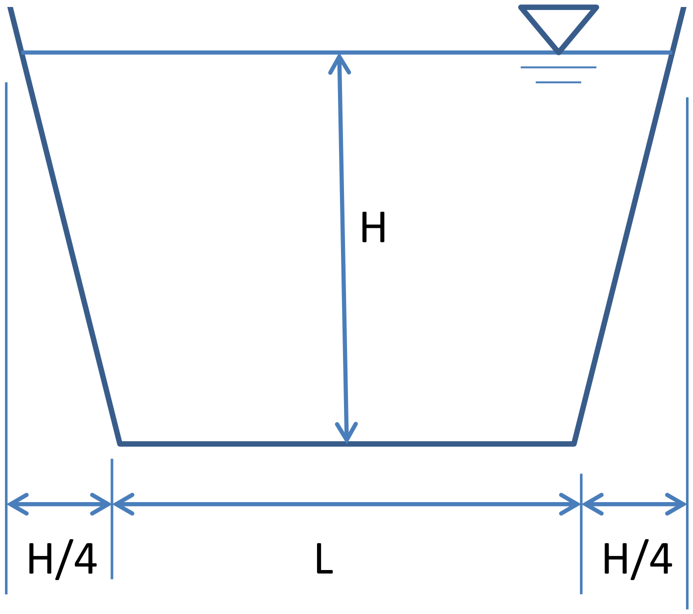


Figure 34 Cross-section of a Cippoletti (trapezoidal) weir

H=height, L=bottom channel width

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

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

where C_d is the coefficient of discharge (assumed as 0.62; Daugherty and Franzini, 1965), *g* is gravity acceleration (9.81 ms^{-2}). C_d considers roughness of the channel (e.g. Manning's *n*) and other variables that govern flow and channel cross-sectional area relationship and it can be adjusted to match maximum flow height for a nearby catchment. This process may be simplistic and there are no suitable data to evaluate the approach. Methods exist that use DEMs to estimate cross-sections (Patro et al., 2009), but they require high resolution data currently not available for the geographic domain (see Teng et al., 2015). The Cippoletti weir cross-sections do not incorporate overbank geometry, which means that this assumption may be reasonable in the headwater catchments for which the cross-sections have been derived, as they tend to drain rapidly (due to the steeper down-valley gradients) only after intense rainfall events, which will very unlikely overtop the stream bank. Again systematic errors arising may be partially compensated through calibration. Furthermore, as the Bioregional Assessment Programme is reporting on the relative difference of hydrological response variables between baseline and the coal resource development pathway (CRDP), any errors introduced by the above assumptions will partially cancel out. Table 10 shows the characteristics of the 22 derived cross-sections.

Table 10 Characteristics and dimensions (used in the Cippoletti weir) of derived cross-sections used in AWRA-R modelling for the Hunter subregion

AWRA-R = Australian Water Resources Assessment river model

Node ID	Water course	Catchment area (km^2)	Longitude	Latitude	Length (m)	Height (m)
4	Black Creek	11.42	-32.867°	151.361°	3	3
7	Loders Creek	76.2	-32.611°	151.126°	8	6
8	Doctor's Creek	13.08	-32.605°	151.097°	3	3
9	Loders Creek	38.35	-32.648°	151.114°	6	4
11	Unnamed	14.64	-32.568°	151.089°	3	2
13	Redbank Creek	13.08	-32.559°	151.026°	3	2
15	North Wambo Creek	48.49	-32.592°	150.995°	4	3
19	Wollomby Brook	97.3	-32.909°	151.282°	8	4
22	Main Creek	20.92	-32.459°	151.112°	5	2
26	Betty's Creek	17.6	-32.458°	151.072°	4	2
27	Swamp Creek	24.52	-32.455°	151.067°	5	2
29	Bayswater Creek	6.98	-32.405°	151.027°	4	2
32	Saltwater Creek	54.17	-32.466°	150.889°	6	4
35	Saddlers Creek	96.31	-32.441°	150.777°	10	4
42	Bylong River	704.13	-32.350°	150.094°	5	4
43	Bylong River	665.39	-32.384°	150.130°	5	4
44	Bylong River	302.52	-32.418°	150.118°	5	4
45	Goulburn River	1981.02	-32.217°	150.073°	20	8
47	Wilpinjong Creek	191.71	-32.314°	149.919°	4	3
50	Goulburn River	317.38	-32.204°	149.829°	6	3
52	Dry Creek	24.62	-32.299°	150.806°	5	3
55	Unnamed	18.36	-32.220°	150.888°	4	3

Data: Bioregional Assessments Programme (Dataset 3)

For seven nodes that were between or close to existing gauges, the cross-section of the closer gauge or gauge with similar catchment area was chosen to define its cross-section. Table 11 shows the characteristics and cross-section used in these locations. These were added to the calibration node-link network, defining the simulation node-link network (CSIRO, Dataset 5). Again, distances between gauges vary from a few to tens of kilometres, which may result in over- or underestimation of the river channel geometry when choosing the upstream or downstream cross-sections. Model calibration will partially compensate proportional biases arising from this underestimation.

Table 11 Characteristics of derived cross-sections used in AWRA-R modelling for the Hunter subregion

AWRA-R = Australian Water Resources Assessment river model

Node ID	River name	Catchment area (km^2)	Longitude	Latitude	Cross-section from gauge
6	Wollar Ck	529.89	–32.261°	149.976°	210006
10	Goulburn	617.79	–32.258°	149.967°	210006
15	Goulburn	1578.36	–32.432°	150.673°	210031
20	Wollombi Brook	1336.72	–32.708°	151.053°	210028
23	Wollombi Brook	1877.16	–32.551°	151.055°	210134
27	Fal Brook	514.05	–32.502°	151.074°	210044
56	Hunter	4338.19	–32.276°	150.857°	210002

Data: Bioregional Assessments Programme (Dataset 3)

2.1.4.2.2 River reach lengths

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

River reach lengths are quantified for all rivers in the reach, including main channel and tributary channels (if these exist) (CSIRO, Dataset 4). River reach lengths are obtained from the River Styles spatial layer for NSW, which was obtained through digitisation of high resolution aerial or satellite imagery with field validation from many different sources (NSW Department of Primary Industries (Office of Water), Dataset 6). Visual assessment showed that these data were more accurate than drainage networks derived from DEM data, particularly in meandering sections of the river. The dataset was clipped using catchment boundaries defined by the AWRA-R modelling domain (see Section 2.6.1.3 in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018); CSIRO Land and Water, Dataset 7) and each river reach length was manually selected using GIS software and lengths computed. These lengths are planar and are different from real lengths, particularly in steep areas.

2.1.4.2.3 Irrigation areas and crop types

The AWRA-R river model needs details of irrigated areas and crop types in each river reach in which irrigation is present in order to determine areal extent and crop factors of the most common crop types (Dutta et al., 2015).

Areas and crop types are obtained from the Catchment scale Land Use Management (CLUM) (described in Section 2.1.1; Department of Agriculture: Australian Bureau of Agricultural and Resource Economics and Sciences, Dataset 8). The dataset was clipped using catchment boundaries defined by the AWRA-R modelling domain (see Section 2.6.1.3 in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018); CSIRO Land and Water, Dataset 7) and the information summarised by reach in order to determine crop types and associated crop factors (CSIRO Land and Water, Dataset 9). Irrigation areas are determined using the first level classification in the CLUM dataset which describes the main land use type. Crop types were determined from the third level classification, which provides detailed information on crop types. A summary of areas and crop types per river reach is shown in Table 12.

Table 12 Crop types and areas used for modelling in each AWRA-R reach for the Hunter subregion

AWRA-R = Australian Water Resources Assessment river model

Gauge ID	Crop type	Irrigated area (ha)	Total irrigated area (ha)	Percentage of total irrigated area
210001	4.2.0 Grazing irrigated modified pastures	1602.45	1691	94.7%
	4.4.2 Irrigated oleaginous fruits	62.60		3.7%
	4.4.3 Irrigated tree nuts	8.80		0.5%
	4.5.4 Irrigated seasonal vegetables & herbs	17.44		1.0%
210002	4.2.0 Grazing irrigated modified pastures	431.12	431	100.0%
210044	4.2.0 Grazing irrigated modified pastures	99.71	100	100.0%
210055	4.2.0 Grazing irrigated modified pastures	1192.56	1193	100.0%
210064	4.2.0 Grazing irrigated modified pastures	2996.88	3505	85.5%
	4.4.1 Irrigated tree fruits	2.81		0.1%
	4.4.2 Irrigated oleaginous fruits	37.37		1.1%
	4.4.3 Irrigated tree nuts	10.28		0.3%
	4.4.4 Irrigated vine fruits	383.25		10.9%
	4.5.4 Irrigated seasonal vegetables & herbs	73.96		2.1%
210083	4.2.0 Grazing irrigated modified pastures	2165.51	3336	64.9%
	4.4.2 Irrigated oleaginous fruits	16.47		0.5%
	4.4.4 Irrigated vine fruits	1153.65		34.6%
210127	4.2.0 Grazing irrigated modified pastures	547.87	592	92.5%
	4.4.2 Irrigated oleaginous fruits	5.20		0.9%
	4.4.4 Irrigated vine fruits	39.21		6.6%
210128	4.2.0 Grazing irrigated modified pastures	333.85	334	100.0%
210134	4.2.0 Grazing irrigated modified pastures	534.74	539	99.1%
	4.4.2 Irrigated oleaginous fruits	3.60		0.7%
	4.4.3 Irrigated tree nuts	1.02		0.2%

Data: CSIRO Land and Water (Dataset 9)

2.1.4.2.4 Hunter River Salinity Trading Scheme discharges

The purpose of the Hunter River Salinity Trading Scheme (HRSTS) is to manage river salinity to ensure suitable outcomes for agriculture, mining, electricity generation, town water supply and other uses by using a system of salt credits (NSW Environment Protection Authority, 2003). Mines discharge saline water collected in mine pits and shafts to continue with their operations, and electricity generators discharge water used for cooling that is more saline due to evaporation leading to more concentration of natural salt. The scheme has been devised so that participants in the scheme (mines and electricity generators) can only discharge saline water when conditions in the receiving stream are such that the mixing is below a certain threshold (measured in electrical conductivity units or EC). Three sectors in the river are considered: upper, middle and lower, delimited by three gauging stations (Table 14). In addition, in each sector three streamflow thresholds determine how scheme participants can release saline water. During low-flow conditions, no discharges are allowed. During high-flow conditions, limited discharge is allowed and controlled by the salt credit system in which members of the scheme coordinate discharges to abide by the HRSTS. During flood conditions, unlimited discharges are allowed as long as the salt concentration does not go above 900 EC (NSW Environment Protection Authority, 2003).

Discharge data (NSW Environment Protection Authority, Dataset 10) from scheme participants were analysed to determine timing and discharge volumes under the different flow conditions (Bioregional Assessment Programme, Dataset 1) for the above mentioned sectors. The NSW Environment Protection Authority (EPA) dataset provided observed discharge volumes and EC data for eleven sites, including two sites in the upper sector (mining), four sites for the middle sector (three mining and one electricity generation), and five sites for the lower sector (four mining and one electricity generation), which have gauging stations nearby with observed daily streamflow data. The water discharge records for the three sectors were for the years 2006 to 2012. The lower sector had 217 discharge records from 2007 to 2012, whereas the middle sector had 345 records for the period from 2006 to 2012. The upper sector only had 12 discharge records for the years 2008 to 2012. Details for each site considered in the analysis are presented in Table 13.

Table 13 Details for sites in the Hunter River Salinity Trading Scheme (HRSTS) with discharge records

Site	EPA licence number	Discharge records	Sector	Start date	End date
Bengalla Mine	6538	8	Upper	8 Feb 2008	12 Feb 2008
Mt Arthur Coal	11457	4	Upper	5 Mar 2012	8 Mar 2012
Hunter Valley Operations	640	112	Middle	7 Feb 2008	24 Mar 2012
Bayswater Power Station	779	134	Middle	6 Jun 2006	9 Mar 2012
Liddell Coal Operations	2094	42	Middle	22 Aug 2007	8 Mar 2012
Ravensworth Operations	2652	57	Middle	24 Dec 2007	28 Nov 2011
Wambo Coal	529	31	Lower	1 Apr 2009	5 Mar 2012
Bulga Coal	563	81	Lower	9 Dec 2007	10 Jun 2012
Warkworth Coal Mine	1376	56	Lower	22 Aug 2007	10 Sep 2012
Mount Thorley Operations	1976	44	Lower	2 Sep 2008	15 Mar 2012
Redbank Power Station	11262	5	Lower	2 Sep 2008	7 Mar 2012

Data: NSW Environment Protection Authority (Dataset 10)

Water quality is not considered in the surface water modelling for the bioregional assessment of the Hunter subregion, however discharge from participants in the scheme may impact water quantity and thus hydrological response variables. Thus, simple rules for mine and electricity generation water discharge were devised and implemented in AWRA-R. The following assumptions were made in the estimation:

- Discharge is allowed above a defined threshold, equal to the high-flow conditions specified by the HRSTS in each sector of the river (Table 14).
- The scheme would not expand in the future.
- Participants in the scheme will use a similar proportion of their dewatering entitlement in the future.
- Discharge is related to climate, since opportunities to discharge are increased by wetter conditions, and saline water impounded in storages or mine pits may increase in volume during wetter conditions prompting its release.
- Salinity is not the purpose of current modelling, but it is assumed that water quality is acceptable.

Although there were only up to six years of discharge data, a pattern between discharge and rainfall was examined. As pointed out previously, it was hypothesised that mines and electricity generators would need to do more dewatering in a wetter climate and there would also be more opportunities for discharging. Conversely, less dewatering would be needed in a drier climate alongside less opportunities for discharge. Therefore, wet and dry years were identified by using the mean annual long-term rainfall from 1973 to 2014. Years above average (wet) were 2007, 2008, 2010 and 2011, whereas 2009 and 2012 were below average (dry) years. Figure 35 shows discharge volumes for all individual discharges in each HRSTS sector were grouped into wet and dry years and combined to produce a daily discharge. Note that under these criteria there were only three discharge events in the upper sector during dry years. Although water discharge is somewhat lower during dry years, the differences are not important when compared to high-flow conditions. Consequently, discharge volumes (see below) in the model were not varied to reflect wet and dry years.

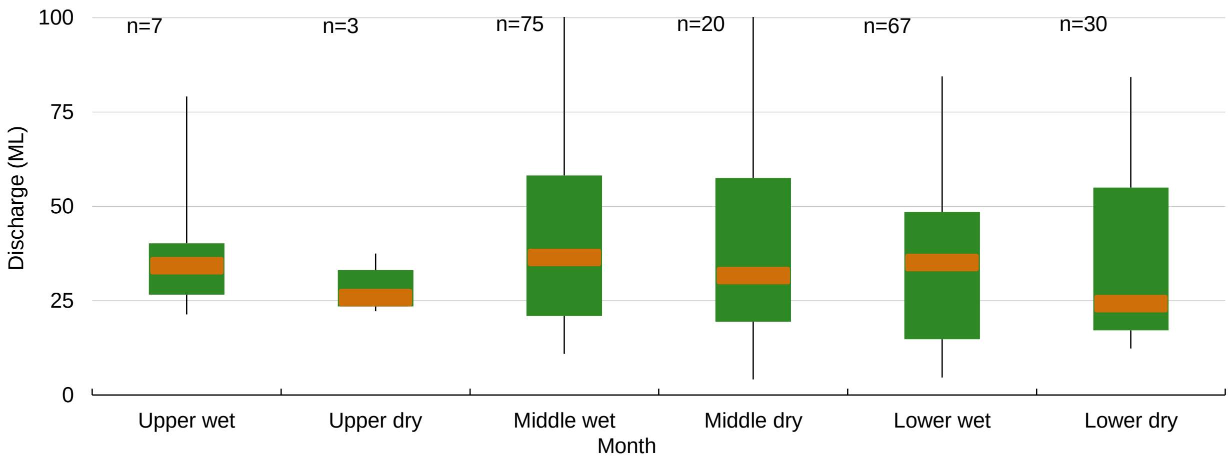


Figure 35 Box plots of water discharge for each sector during dry and wet years

Orange identifies the median value; green boxes define the interquartile ranges; whiskers indicate the 10th and 90th percentiles of discharges. Individual scheme participant discharges are combined in each sector for dry and wet years to produce a daily discharge.
HRSTS = Hunter River Salinity Trading Scheme; n is the number of discharge events in each sector for dry and wet years
Data: NSW Environment Protection Authority (Dataset 10)

The NSW EPA data were used to estimate annual releases to obtain a mean annual release by river sector. Also individual releases were used to estimate a ratio of discharge to streamflow volume (Table 14). In the model, it is assumed that scheme participants can discharge water up to a volume determined by the mean annual release. The amount discharged once the streamflow threshold is exceeded is determined by the fixed ratio of water, which depends on the streamflow volume. Discharge is computed daily, which is the temporal resolution of observed streamflow data and modelling time-step (see Section 2.6.1.3 in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018)). In dry years when the streamflow threshold may not be exceeded very often, scheme participants may not be able to discharge all their mean annual volume. It is assumed that the water that cannot be discharged is reused or otherwise disposed of. In wet years, when there are more opportunities for discharge, scheme participants will often discharge the full mean annual water discharge volume.

Table 14 Gauges, streamflow thresholds and mean annual discharge volumes and discharge/streamflow ratio used in the simplified discharge scheme for the Hunter subregion

Gauge ID	Name	Streamflow threshold (ML/d)	Mean annual discharge volume (ML/y)	Discharge to streamflow ratio
210055	Hunter R at Denman	1000	750	0.006
210127	Hunter R upstream Glennies Ck	1800	1000	0.009
210001	Hunter R at Singleton	2000	100	0.009

Data: Bioregional Assessment Programme (Dataset 1), NSW Environment Protection Authority (Dataset 10)

2.1.4.2.5 Node-link interpolation

The AWRA-R model generates outputs at model nodes. In order to characterise the changes in stream hydrology from additional coal resource development throughout the Hunter River modelling domain, results from the model nodes must be interpolated or extrapolated to reaches (links) in the river network for which results are not specifically computed. Companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) details the approach. In general, results at a model node are assumed to apply to some length of reach upstream and downstream of the node, so far as there is no significant change in the hydrology along the reach. Where a change in flow could occur, such as from a tributary inflow or hydrological changes caused by mining, it is not appropriate to interpolate from the model nodes beyond this point of difference.

The interpolation (link to node mapping) is informed by analysis of Google Earth imagery and GIS layers of mine footprints, stream network and subcatchment areas. Figure 36 shows the link to node mapping for the modelled link-node networks of the Hunter River and Wyong River (not to scale): red lines delineate distinct reaches, each of which is associated with a number in a circle, corresponding to a model node, or to a cross in a circle, indicating that an interpolation cannot be made. Non-model reaches (dashed blue lines) have been added to identify inflows to model links where results from a model node are no longer applicable; and non-model nodes (open blue circles) have been included to identify points along a reach where some other change in hydrology, such as a coal mine or tidal influence, renders the interpolation inaccurate. Table 15 lists the non-model nodes and provides details of their location.

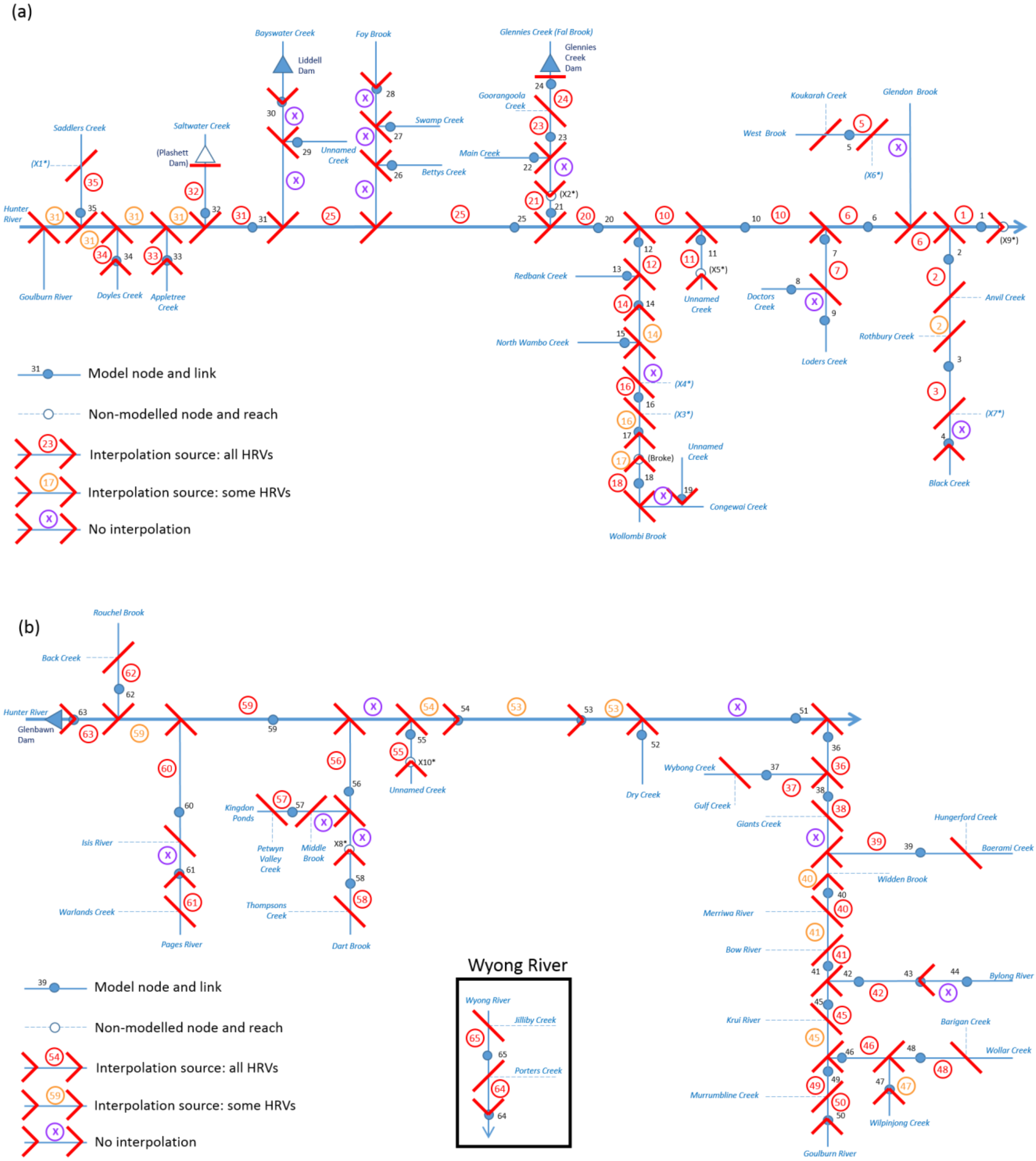


Figure 36 Link-node mapping for (a) the lower Hunter River and (b) upper Hunter, Goulburn and Wyong River modelled river networks

HRV = hydrological response variable

Not all tributary inflows are deemed to cause a noticeable hydrological change to the receiving stream. Small inflows into much larger streams, such as from Unnamed Creek at node 11 into the Hunter River, do not affect the interpolation along the receiving reach – that is, results from node 10 are assumed applicable both upstream and downstream of the inflow point; whereas larger inflows can cause a sufficiently large hydrological change such that results from an upstream node can be applied only to the reach upstream of the junction and results from the downstream node applied only to the reach downstream of the junction. This is illustrated where

Wollombi Brook joins the Hunter River, with the Hunter River reach upstream of the junction mapped to node 20 and the reach downstream of the junction mapped to node 10.

Table 15 Location details of non-model nodes used to inform the Hunter River link-node mapping

Non-model node	Details of location
X1*	An unnamed stream entering Saddlers Creek from the right at a location –32.4263° latitude, 150.7973° longitude, 2.8 km due north-east of the junction of Saddlers Creek and Hunter River
X2*	A location –32.5000° latitude, 151.0789° longitude on Fal Brook 1.45 km from the junction of Fal Brook and Hunter River in roughly a 62 degree heading
X3*	An unnamed stream entering Wollombi Brook from the right at a location 2.0 km east of Cockfighters Bridge (node 16)
X4*	An unnamed stream entering Wollombi Brook from the right at a location 1.9 km north of Cockfighters Bridge (node 16)
X5*	A location –32.5729° latitude, 151.0730° longitude on the unnamed creek containing node 11 where the creek crosses under the transmission lines about 1.9 km west-south-west of the junction of the unnamed creek and Hunter River
X6*	Unnamed Creek entering West Brook from the right at –32.5145° latitude, 151.2731° longitude, approximately 4.6 km south of node 5
X7*	Unnamed Creek entering Black Creek from the right at –32.7454° latitude, 151.3561° longitude, approximately 3.9 km south-east of node 3
X8*	A location on Dart Brook at the road bridge at –32.0469° latitude, 150.8177° longitude, approximately 5.0 km south-east of node 58
X9*	A location –32.6950° latitude, 151.5689° longitude on the Hunter River where the rail line crosses the river
X10*	A location on the unnamed creek containing node 55 at a road crossing at –32.2089° latitude, 150.8707° longitude

At the most downstream point of the link-node network, results from node 1 (stream gauge 210064 on Hunter River at Greta) can be extrapolated to the tidal limit of the Hunter River. This is represented in Figure 36 (a) by non-model node (X9*) and corresponds to the point on the Hunter River where the rail line crosses the river.

Extrapolation upstream of a headwater model node is considered appropriate where there is no coal resource development in the headwater catchment and only as far as the first substantial tributary inflow. An example of this is upstream of node 39 on Baerami Creek. Where there is a coal resource development, such as Ulan mine which is upstream of node 50 on the Goulburn River, no extrapolation is possible.

The interpolation and extrapolation of model results from nodes to stream reaches is used to inform where the receptor impact models (see companion product 2.7 for the Hunter subregion (as listed in Table 2)) can be applied to enable an analysis of risk and impact upon the subregion's landscape classes and assets (see companion product 3-4 for the Hunter subregion (as listed in Table 2)).

2.1.4.3 Gaps

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

The data obtained from the NSW Environment Protection Authority in relation to discharges under the Hunter River Salinity Trading Scheme (HRSTS) covered the period from 2006 to 2012 (the HRSTS was established in 1995). Given the short duration of record, the set of rules implemented in the model to simulate discharge may not adequately represent the real pattern of discharges. Mine discharge management is complex – for example, participants can come up with alternative ways of using or disposing of water produced as a result of their operations; salinity credits can be traded between scheme participants – and the rules developed from the six years of data can only be a simplistic representation of what really happens. The implementation of HRSTS discharges is not expected to impact on predictions of the differences in hydrological response variables due to the ACRD because the salinity credits are set within the scheme, the same rule set is applied to baseline and CRDP, and high rainfall and dam releases, and not mining operations, are the key determinants of discharge windows.

The mapping of links to nodes for interpolation and extrapolation of model results to other parts of the river network shows that there are reaches in the stream network where interpolating results from model nodes is not recommended. The incorporation of additional, strategically placed model nodes within the link-node network would largely address this for non-headwater reaches, but the simulations would need to be re-done to generate outputs at these nodes. The distance upstream to where results can be extrapolated to is limited. Thus streamflow changes beyond the link-node extent are a knowledge gap. Not all streams in the stream network were included in the link-node network.

More information on data gaps will be provided in Section 2.6.1.3 and Section 2.6.1.4 of companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018), because the modelling and analysis contributes to identifying main gaps. Likewise, recommendations for monitoring will be reported in later products.

References

Daugherty R and Franzini J (1965) Fluid mechanics with engineering applications. McGraw-Hill, New York.

Dutta et al. (2015) AWRA-R v5.0 technical report. CSIRO Land and Water, Australia.

Dawes WR, Herron NF, Macfarlane C, Rachakonda PK, Henderson BL, Ford JH, Wilkes PG, Marvanek SP, Ramage A (2018) Conceptual modelling for the Hunter subregion. Product 2.3 for the Hunter 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/HUN/2.3.

Dutta D, Vaze J, Kim S, Hughes J, Teng J, Yang A, Crosbie R and Frost A (2014) AWRA-LGR Description and Integration: Current System and Future Plans, CSIRO: Water for a Healthy Country National Research Flagship, Australia.

Lerat J, Dutta D, Kim S, Hughes J, Vaze J and Dawes W (2013) Refinement and extension of the AWRA-R model, CSIRO: Water for a Healthy Country National Research Flagship, Australia, 64 pp. Viewed 17 December 2015, https://publications.csiro.au/rpr/download?pid=csiro:EP136859&dsid=DS6.

McMillan H, Freer J, Pappenberger F, Krueger T and Clark M (2010) Impacts of uncertain river flow data on rainfall-runoff model calibration and discharge predictions. Hydrological Processes 24(10), 1270–1284. DOI: 10.1029/2011WR010643.

NSW Environment Protection Authority (2003) Hunter River Salinity Trading Scheme: Working together to protect river quality and sustain economic development. Department of Environment and Conservation NSW. Viewed 3 February 2016, https://www.epa.nsw.gov.au/resources/licensing/hrsts/hrsts.pdf.

Patro S, Chatterjee C, Singh R and Raghuwanshi NS (2009) Hydrodynamic modeling of a large flood-prone river system in India with limited data. Hydrological Processes 23, 2774–2791. DOI: 10.1002/hyp.7375.

Stewardson M, DeRose R and Harman C (2005) Regional models of stream channel metrics, Technical report. Cooperative Research Centre for Catchment Hydrology, Melbourne University, Australia. Viewed 17 December 2015, http://www.ewater.org.au/archive/crcch/archive/pubs/pdfs/technical200516.pdf.

Teng J, Vaze J, Dutta D, and Marvanek S (2015) Rapid inundation modelling in large floodplains using LiDAR DEM. Water Resources Management 29, 2619–2636. DOI: 10.1007/s11269-015-0960-8.

Tennakoon S and Marsh N (2007) Regional hydraulic geometry models for Queensland streams. Australian rivers: making a difference. Proceedings of the 5th Australian Stream Management Conference, Charles Sturt University, Thurgoona, New South Wales. Viewed 17 December 2015, https://www.csu.edu.au/__data/assets/pdf_file/0010/748477/Tennakoon_Sunil_390.pdf.

Viney N (2016) Surface water modelling. Submethodology M06 from the Bioregional Assessment Technical Programme. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/submethodology/M06.

Viney NR, McMahon TA and Chiew FHS (2011) Guidelines for presentation of the Bureau of Meteorology national streamflow database. CSIRO Water for a Healthy Country Flagship, Australia.

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, Australia.

Zhang YQ, Peña-Arancibia J, Viney N, Herron NF, Peeters L, Yang A, Wang W, Marvanek SP, Rachakonda PK, Ramage A, Kim S and Vaze J (2018) Surface water numerical modelling for the Hunter subregion. Product 2.6.1 for the Hunter 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/HUN/2.6.1.

Datasets

Dataset 1 Bioregional Assessment Programme (2014) Hunter Surface Water data v2 20140724. Bioregional Assessment Derived Dataset. Viewed 24 September 2015, http://data.bioregionalassessments.gov.au/dataset/1934f57d-c6d6-43d1-abcd-1cf957f3e7e2.

Dataset 2 CSIRO (2016) HUN AWRA-R Gauge Station Cross Sections v01. Bioregional Assessment Source Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/93fbc2b9-463c-42f6-8817-cb45a54ee28e.

Dataset 3 Bioregional Assessment Programme (2016) HUN AWRA-R Simulation Node Cross Sections v01. Bioregional Assessment Derived Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/1fd9e5fe-eec1-4a34-8b4c-6d95a54998df.

Dataset 4 CSIRO (2016) HUN AWRA-R River Reaches Calibration v01. Bioregional Assessment Source Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/43f10e76-4541-433a-8b3c-deed9655ce05.

Dataset 5 CSIRO (2016) HUN AWRA-R River Reaches Simulation v01. Bioregional Assessment Source Dataset. Viewed 18 February 2016, http://data.bioregionalassessments.gov.au/dataset/43f10e76-4541-433a-8b3c-deed9655ce05.

Dataset 6 NSW Department of Primary Industries (Office of Water) (2012) Riverstyles Spatial Layer for New South Wales. Bioregional Assessment Source Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/06fb694b-d2f1-4338-ab65-a707c02f11d7.

Dataset 7 CSIRO (2016) HUN AWRA-R calibration catchments v01. Bioregional Assessment Derived Dataset. Viewed 17 February 2016, http://data.bioregionalassessments.gov.au/dataset/d419aae0-1cb3-48a8-82de-941398a80e3a.

Dataset 8 Department of Agriculture: Australian Bureau of Agricultural and Resource Economics and Sciences (2014) Catchment Scale Land Use of Australia - 2014. Bioregional Assessment Source Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/6f72f73c-8a61-4ae9-b8b5-3f67ec918826.

Dataset 9 CSIRO Land and Water (2016) HUN AWRA-R Irrigation Area Extents and Crop Types v01. Bioregional Assessment Derived Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/90013748-6247-47ad-bddb-07a9c2d857cd.

Dataset 10 New South Wales, Environment Protection Authority (2012) Hunter River Salinity Scheme Discharge NSW EPA 2006-2012 20150821. Bioregional Assessment Source Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/1647c153-5120-4c64-a5e8-6a1b4b0b4e4b.

Dataset 11 NSW Department of Primary Industries (Office of Water) (2015) Model Simulation Regulated Rivers NSW Office of Water HUN 20150615. Bioregional Assessment Source Dataset. Viewed 18 January 2016, http://data.bioregionalassessments.gov.au/dataset/d6e8c6f0-08bf-4ca6-bbef-6ae0d79c34ce.

Dataset 12 CSIRO Land and Water (2016) HUN AWRA-R Observed storage volumes Glenbawn Dam and Glennies Creek Dam. Bioregional Assessment Source Dataset. Viewed 17 February 2016, http://data.bioregionalassessments.gov.au/dataset/9c2dccdb-ef46-48c7-bfe1-946ab57645e5.

Dataset 13 CSIRO Land and Water (2016) HUN AWRA-R calibration nodes v01. Bioregional Assessment Derived Dataset. Viewed 17 February 2016, http://data.bioregionalassessments.gov.au/dataset/f2da394a-3d08-4cf4-8c24-bf7751ea06a1.

Dataset 14 Bureau of Meteorology (2013) National Surface Water sites Hydstra. Bioregional Assessment Source Dataset. Viewed 15 August 2016, http://data.bioregionalassessments.gov.au/dataset/f7edc5e5-93ee-4527-bed5-a118b4017623.

Dataset 15 Bioregional Assessment Programme (2013) Selected streamflow gauges within and near the Hunter subregion. Bioregional Assessment Derived Dataset. Viewed 15 August 2016, http://data.bioregionalassessments.gov.au/dataset/e83b0500-6254-47e1-b103-5e6b5961fe6f.

2.1.5 Surface water – groundwater interactions

Summary

No observed datasets that specifically represent surface water – groundwater interactions in the Hunter subregion have been used in the hydrological modelling of the Hunter subregion.

A number of methods for estimating the groundwater contribution to streamflow are used to explore the variability in the baseflow index in the Hunter subregion. The estimates vary widely, from around 15 to 66% of streamflow, depending on the method and assumptions made.

Results of this analysis have been used to constrain groundwater modelling results, reported in companion product 2.6.2 (groundwater numerical modelling) for the Hunter subregion (Herron et al., 2018).

2.1.5.1 Observed data

Regional-scale coverage of surface water – groundwater flux data are generally lacking, although there are local studies that have attempted to quantify these fluxes (Heritage Computing Pty Ltd, 2012; Worley Parsons, 2009). For regional-scale modelling, local-scale data can be useful for defining the variability in surface water – groundwater connections across the subregion and putting some upper and lower bounds on the groundwater contribution to streamflow (expressed as a proportion of total streamflow, or baseflow index; see also Kellett et al., 1989). In the EPA (2013) salinity assessment of the Hunter River basin, it was concluded that 'the detailed interaction between groundwater and surface water in many parts of the Hunter River catchment still requires further research'.

No observed datasets that specifically represent surface water – groundwater interactions have been used as inputs into the hydrological modelling of the Hunter subregion because this is a variable calculated by the model, nor have they been used to constrain model results. Instead a range of common approaches to estimating the groundwater contribution to streamflow are used to determine possible ranges, including extrapolation from local-scale information reported in a mine environmental impact statement (EIS; Section 2.1.5.2).

2.1.5.2 Statistical analysis and interpolation

2.1.5.2.1 Groundwater contributions to stream flow

A simple method to estimate the proportion of streamflow that is derived from groundwater is to assume that all recharge contributes to streamflow. As previously stated in Section 2.1.3.1, in the absence of other data, groundwater recharge is commonly estimated as 2% of rainfall (Mackie Environmental Research, 2006). For a mean annual rainfall of 793 mm for the subregion, an estimate of 16 mm of subregion mean annual recharge is obtained.

For steady-state conditions, and assuming all groundwater recharge discharges to the stream as baseflow, a crude estimate of the contribution from groundwater to streamflow can be made. The mean annual streamflow recorded in the Hunter River at Greta (gauge 210064) between 1968 and 2015 was 709.5 GL/year, equivalent to a depth of 41.0 mm across the 17,320 km^2 contributing area (DPI, 2015). For 16 mm of recharge, this equates to a maximum baseflow contribution from groundwater of about 39%, with the remainder of Hunter River flow coming from surface and shallow subsurface runoff. The gauging station at Greta is used for this estimate because it is the most downstream gauge on the Hunter River that is not tidally influenced and represents the lower limit of the Hunter subregion river model.

Using the subregion estimate of mean annual recharge of 9.0 mm from the recharge surface reported in Section 2.1.3.2, this simple ratio approach to estimating the baseflow contribution to Hunter River flow at Greta (gauge 210064) yields a maximum baseflow contribution of 28%.

It is a simplification to assume that all diffuse recharge becomes river discharge even in a closed basin where evaporation and pumping occur (i.e. no other losses), however, this does provide an upper estimate for baseflow. It needs to be supported by other measures such as environmental tracers and computer models of mines near rivers. For example, in a groundwater modelling study at the North Wambo Underground Mine, fitted diffuse recharge was 1.2% of rainfall and alluvial discharge to the river accounted for two-thirds of all losses (Heritage Computing Pty Ltd, 2012). This could be used as a first estimate to partition aquifer discharge between baseflow and evaporation losses, reducing the previous maximum estimates of baseflow to 25.8 and 18.5%.

As previously described, the stream and alluvial aquifer are considered to be closely coupled and are managed conjunctively. Fluxes are expected in both directions under mean climatic conditions. In the case of modelling the North Wambo Underground Mine, the transient water balance estimated that from 2003 to 2009 the river leaked 12.1 ML/day into the alluvium and the alluvium returned 17.4 ML/day to the river. This is a net baseflow discharge of 5.3 ML/day, which based on the model area of 304 km^2 equates to an annual depth of 6.4 mm.

It is difficult to make accurate generalisations of baseflow discharge for the subregion based on spatially averaged, or small-scale spatially explicit, models of recharge alone. If the total discharge values from the North Wambo model are representative of the subregion more generally this would equate to a gross discharge 20.9 mm (i.e. a baseflow index of 51.0%) or, taking account of the 12.1 ML/day that leaked from the river, a net baseflow contribution from groundwater of 15.3%.

To place this in context, estimates of baseflow index using digital filtering (Lyne and Hollick, 1979) vary from 40 to 66% for eight rivers in the Hunter river basin, and 44 to 49% for two rivers in the Macquarie Tuggerah Lakes basin (see Figure 44 in companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). These estimates based solely on daily flow values do not account for leakage and return flow between the river and alluvium.

No other analyses were undertaken to inform the surface water and groundwater modelling. The foregoing estimates of baseflow contributions show that it is hard to specify this term for modelling purposes, but suggest an upper limit for the groundwater contribution to streamflow of 66%.

The modelling framework that has been developed represents surface water – groundwater interactions through using outputs from the groundwater model as inputs into the river model (see companion product 2.6.2 (groundwater numerical modelling) for the Hunter subregion (Herron et al., 2018)). For the purposes of constraining the modelled surface water – groundwater fluxes, it has been assumed that on average groundwater contributions to streamflow will not exceed 70% of the mean streamflow record (Herron et al., 2018). This proportion was deliberately chosen to be higher than the various estimates of baseflow that have been made for the Hunter subregion.

2.1.5.3 Gaps

A range of different methods are available to estimate the baseflow component of streams, as it is not something that is easy to measure directly. Estimates of baseflow can help to constrain the groundwater model, but the estimates themselves can be highly variable. Local scale estimates of groundwater contributions to streamflow are sometimes reported in mine environmental impact statements, but these were not actively sought during the project. Local-scale data are of little value for parameterising the regional-scale groundwater model, but may be of use in constraining model results locally by training the groundwater model emulators on the local data. While a high baseflow index was adopted to constrain groundwater model results across the Hunter subregion (see companion product 2.6.2 for the Hunter subregion (Herron et al., 2018)), training of the model emulators on local information may lead to local improvements in model predictions.

Lack of surface water – groundwater interactions data are not a major gap for modelling purposes, as the focus of the modelling is on evaluating the difference between two futures using a probabilistic approach, not on building a deterministic model calibrated to historical data. The groundwater model generates baseflow volumes for input into the river model. This is the major interaction between surface water and groundwater.

References

DPI (2015) HYSTATF V91 Flow Statistics Report, Hunter River at Greta. NSW Department of Primary Industries, Office of Water, Sydney. Viewed 01 September 2015, http://realtimedata.water.nsw.gov.au/water.stm.

EPA (2013) Hunter Catchment Salinity Assessment: Final Report. Report prepared by Office of Environment and Heritage for the NSW Environmental Protection Agency, Sydney, Australia, 60 pp.

Heritage Computing Pty Ltd (2012) North Wambo underground mine modification. Appendix B: groundwater assessment. Report prepared for Wambo Coal Pty Ltd, HC2012/13.

Herron NF, Peeters L, Crosbie R, Marvanek SP, Pagendam D, Ramage A, Rachakonda PK and Wilkins A (2018) Groundwater numerical modelling for the Hunter subregion. Product 2.6.2 for the Hunter 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/HUN/2.6.2.

Kellett JR, Williams BG and Ward JK (1989) Hydrogeochemistry of the upper Hunter River valley, New South Wales. Bureau of Mineral Resources, Sydney. Viewed 01 August 2014, http://www.ga.gov.au/corporate_data/25/Bull_221.pdf.

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, pp. 89-93.

Mackie Environmental Research (2006) Anvil Hill Project: groundwater management studies. Centennial Hunter Pty Limited, Sydney. Viewed 01 December 2014, https://majorprojects.affinitylive.com/public/15987e1d6effbca80892d85cb7626029/Environmental%20Assessment-Appendix08-Groundwater.pdf.

McVicar TR, Pinetown KL, Hodgkinson JH, Barron OV, Rachakonda PK, Zhang YQ, Dawes WR, Macfarlane C, Holland KL, Marvanek SP, Wilkes PG, Li LT and Van Niel TG (2015) Context statement for the Hunter subregion. Product 1.1 for the Hunter subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. Viewed 03 August 2016, http://data.bioregionalassessments.gov.au/product/NSB/HUN/1.1.

Worley Parsons (2009) Bickham Mine Project, Scone, Assessment of Water Resource Management Issues. Report prepared for Upper Hunter Progress Association, Sydney, Australia, 19 pp.

2.1.6 Water management for coal resource developments

Summary

The surface water and groundwater numerical models require data on impacted areas, depths of mine workings, water extractions and discharge rules to quantify the hydrological impacts of mine developments. These data have been sourced primarily from mining company documents and state agency datasets. Details of the source data and the methods used to generate datasets for input into the models are presented in this section.

The objective of groundwater and surface water modelling in bioregional assessments is to quantify the cumulative impacts of coal resource developments on regional hydrology. In Section 2.3.5 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018), four causal pathway groups are identified that potentially link hydrological changes from mining developments to water-dependent assets in the wider region. These causal pathway groups are subsurface depressurisation and dewatering, subsurface physical flow paths, surface water drainage and operational water management. The models require information on the location and magnitude of hydrological changes at each mine site to quantify the changes on and off the site via these causal pathways.

The Australian Water Resources Assessment (AWRA) landscape water balance model (AWRA-L) requires a time series of the mine site footprint area for each mining operation, where the footprint includes all disturbed surface areas – including the open-cut pits, areas above longwall panels, roads, spoil dumps, water storages and infrastructure – as well as undisturbed areas from which runoff is captured by water storages. Except for the footprint areas above longwall mine panels, the model assumes all runoff generated from the footprint area is retained on site. For the mine footprints above longwall mines, the model assumes that there is some interception of runoff as a consequence of subsidence (see companion product 2.6.1 (surface water numerical modelling) for the Hunter subregion (Zhang et al., 2018)).

While a mine's footprint is known to vary over the life of the mine, a constant footprint was used in the groundwater modelling, broadly corresponding to the maximum footprint. Variations in time are represented through a changing annual flow rate, rather than a time-varying footprint. Each mine complex may have many individual mine workings. Mine workings are individual pits, or clusters of pits, or groups of longwall panels that mine the same seam, or a bord-and-pillar area, defined by availability of geometry and flow rate data. Given the coarse resolution of the regional-scale groundwater model (minimum pixel area of ~500 m), the finer details of individual roadways, chain pillars, bords, etc. are not represented in the model. In most areas, even individual longwall panels are not resolved. The depth of the footprint is the lowest depth of excavation for the mine workings, which could be the bottom of the open-cut pit, the deepest longwall panel, or the deepest bord-and-pillar section. Details on representation of mine footprints in the groundwater model can be found in Section 2.6.2.5 of companion product 2.6.2 for the Hunter subregion (Herron et al., 2018).

The river model (AWRA-R) requires data on extractions from the river for both mining and non-mining uses. It also represents licensed discharges to the stream. Section 2.1.4 details data and methods for representing licensed extractions and discharge rules in the river in the model.

Key sources of mine water management information are the mining companies and state agencies. In particular, mining companies prepare a range of reports as part of the mining approvals process and subsequent management, monitoring and reporting processes. These include annual environmental management reports, annual reviews, briefing papers, conditions of approval, Director-General's or Secretary's environmental assessment reports, environmental impact statements (EIS), groundwater monitoring program reports, mine plan reviews, mining operations plans, subsidence management plans and water management plans. These reports can be obtained from either or both of the mining company and the NSW Planning and Environment's Major Projects Assessments websites. These reports were searched for information to inform both surface water and groundwater modelling.

This section provides details of the data used in the numerical models to represent mine water management, including the sources of data, quality and quantity of data and the steps undertaken to derive datasets for input into the models. Table 16 lists the relevant datasets, identifies which model uses them, the relevant causal pathway group and the relevant section of this product. Water management plans referred to as sources of information for representing mine water management in the numerical models are listed in the references list at the end of this section.

A number of additional coal resource developments were not modelled by the groundwater and/or surface water models (see Section 2.3.4 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018)). Therefore details relevant to modelling these mines are not included in this section. The potential impacts from these developments will be considered qualitatively in companion product 3-4 for the Hunter subregion (as listed in Table 2).

Table 16 Datasets used to represent mine water management in hydrological modelling for the Hunter subregion

Dataset	Model	Causal pathway group	Section
Surface water mine footprints	Surface water – AWRA-L	Surface water drainage	2.1.6.1.1
Groundwater mine footprints	Groundwater	Subsurface depressurisation and dewatering; Subsurface physical flow paths	2.1.6.1.1
Groundwater flow rates (mine water make)	Groundwater	Subsurface depressurisation and dewatering	2.1.6.1.2
River and alluvial water source extractions	Surface water – AWRA-R	Operational water management	2.1.4.2.3
Mine discharges to rivers	Surface water – AWRA-R	Operational water management	2.1.4.2.4

2.1.6.1 Data sources

2.1.6.1.1 Mine footprints

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

Several sources of data were used to delineate footprint areas for groundwater and surface water modelling. Groundwater and surface water footprints are not the same. The maximum footprint for groundwater modelling is the union of the areas at the ground surface disturbed by open-cut mining and overlying underground extraction areas. The surface water footprint includes, in addition to the mine working area, other disturbed areas at the surface associated with site facilities, spoil dumps, roads and areas where runoff is intercepted and retained on site as part of a site's mine water management plan.

To inform the modelling for the baseline coal resource development (baseline), historical footprint information was obtained from mine environmental impact statements (EIS) and similar reports, NSW Department of Trade and Investment (DTI), and by digitising the identifiable areas of open-cut mines from Landsat 5 TM imagery.

For additional coal resource development (ACRD) mines, the projected future mine footprints were obtained either directly from mining companies or from mine EIS and associated reports.

Table 17 summarises the sources of groundwater mine footprint data and mine flow rates for groundwater modelling. While the footprints have been obtained from a range of sources, flow rates were obtained only from EIS or similar reports. Table 18 summarises data sources for the surface water mine footprints used in the surface water modelling. Details of the source data and methods for extracting data are also provided. Mine extraction periods considered for each open-cut in the surface water modelling are also presented in Table 18. The mining periods were extracted from various mining company documents published at different times and there may be inconsistencies between reports. As noted in companion product 2.3 (conceptual modelling) for the Hunter subregion (Dawes et al., 2018), the dates used to determine whether a mine was baseline or additional coal resource development are not necessarily the same as the dates used for modelling. Differences are likely to be small (not more than a few years), and are unlikely to significantly impact the estimates of year of maximum difference between the modelled CRDP and baseline.

Table 17 Data sources for mine footprints and mine flow rates used in the groundwater modelling for the Hunter subregion

Mine	Mining company or operator	Open-cut or underground	Footprint source	Flow rate and footprint references and datasets
Abel	Donaldson Coal (Yancoal)	UG	EIS	Donaldson Coal Pty Ltd (2011, 2013); NSW Department of Planning and Infrastructure (2013a); RW Corkery and Co Pty Ltd (2012a, 2014a)
Ashton	Yancoal Australia	OC & UG	EIS	Ashton Coal Operations Pty Ltd (2011, 2012, 2014); Aquaterra (2009, 2010); NSW Department of Planning and Infrastructure (2012); Wells Environmental Services (2009a, 2009b)
Austar	Yancoal Australia	UG	EIS	Austar Coal Mine Pty Ltd (2010, 2011, 2012, 2013a, 2013b,2014); Connell Wagner Pty Ltd (2007); Umwelt Australia Pty Ltd (2008a, 2011a, 2011b)
Awaba	Centennial Coal	UG	EIS and DTI	NSW Department of Industry, Resource and Energy Division (Dataset 9); GeoTerra Pty Ltd (2013); NSW Department of Planning and Infrastructure (2011)
Bengalla	Rio Tinto	OC	EIS	Australasian Groundwater and Environmental Consultants Pty Ltd (2013a); Bengalla Mining Company Pty Ltd (2014); Hansen Bailey (2014)
Bloomfield	Bloomfield Collieries	OC	Mining company	Bloomfield Group (Dataset 14); Aquaterra (2008a)
Bulga	Glencore	OC & UG	Mining company	Glencore Xstrata (2015); Mackie Environmental Research (2013a)
Bylong	KEPCO	OC & UG	EIS	Australasian Groundwater and Environmental Consultants Pty Ltd (2013b)
Chain Valley	Lake Coal (LDO Coal)	UG	EIS	AECOM Australia Pty Ltd (2011a); GeoTerra Pty Ltd (2013); LakeCoal Pty Ltd (2014); Lake Coal PTY LTD (Dataset 16); NSW Department of Planning and Infrastructure (2013b)
Cumnock	Glencore	UG	DTI	NSW Department of Industry, Resource and Energy Division (Dataset 9)
Dartbrook	Anglo American	UG	Mining company	Anglo American (Dataset 12); NSW Department of Planning (2002)
Donaldson	Donaldson Coal (Yancoal)	OC	DTI	NSW Department of Industry, Resource and Energy Division (Dataset 9)

Mine	Mining company or operator	Open-cut or underground	Footprint source	Flow rate and footprint references and datasets
Drayton (aka Kayuga Mine)	Anglo American	OC	Mining company	Anglo American (Dataset 12); Australasian Groundwater and Environmental Consultants Pty Ltd (2006a); WRM Water and Environment Pty Ltd (2012)
Drayton South	Anglo American	OC	EIS	Australasian Groundwater and Environmental Consultants Pty Ltd (2012, 2015); Hansen Bailey Pty Ltd (2012, 2015)
Glendell	Glencore	OC	Mining company	CSIRO (Dataset 20)
Hunter Valley Operations	Rio Tinto	OC	EIS	Environmental Resources Management Australia Pty Ltd (2008); Mackie Environmental Research (2003, 2010)
Integra	Vale Australia	OC & UG	EIS	Australasian Groundwater and Environmental Consultants Pty Ltd (2007); Environmental Resources Management Australia Pty Ltd (2009); GeoTerra Pty Ltd (2009a, 2009b); Pegasus Technical (2009a, 2009b); RW Corkery and Co Pty Ltd (2010); SCT Operations Pty Ltd (2009)
Liddell	Glencore	OC	Mining company	Glencore (Dataset 10); Sinclair Knight Merz Pty Ltd (2013)
Mandalong	Centennial Coal	UG	EIS	Ditton Geotechnical Services Pty Ltd (2013); GHD Pty Ltd (2013); GSS Environmental (2013)
Mangoola	Glencore	OC	Mining company	Glencore (Dataset 10); Mackie Environmental Research (2006)
Mannering	Lake Coal (Centennial Coal)	UG	EIS	Centennial Mannering Pty Ltd (2012); EMM Consulting Pty Ltd (2014); GSS Environmental (2012); Hansen Bailey Pty Ltd (2007)
Moolarben	Yancoal Australia	OC & UG	EIS	Aquaterra (2008b); Pegasus Technical (2009c, 2009d); RPS Aquaterra (2011)
Mount Arthur	BHP Billiton	OC & UG	EIS	Australasian Groundwater and Environmental Consultants Pty Ltd (2006b, 2009, 2013c); Mackie Environmental Research (2007); Mine Subsidence Engineering Consultants Pty Ltd (2007); Resource Strategies (2013); Umwelt Australia Pty Ltd (2007, 2008b)
Mount Owen	Glencore	OC	Mining company	Glencore (Dataset 10); Glencore (2014a); Jacobs Group Australia Pty Ltd (2014)

Mine	Mining company or operator	Open-cut or underground	Footprint source	Flow rate and footprint references and datasets
Mount Pleasant	Rio Tinto	OC	EIS	Australasian Groundwater and Environmental Consultants Pty Ltd (2013a); Bengalla Mining Company Pty Ltd (2014); Coal and Allied (1997); Cumberland Ecology (2010); Hansen Bailey Pty Ltd (2014)
Mount Thorley-Warkworth	Coal and Allied (Rio Tinto)	OC	Mining company	Rio Tinto (Dataset 17); Australasian Groundwater and Environmental Consultants Pty Ltd (2010, 2014a, 2014b)
Muswellbrook	Muswellbrook Coal Company (Idemitsu)	OC & UG	Mining company	Idemistu Australia Resources (Dataset 15); Muswellbrook Coal Company Ltd (2007, 2008, 2009, 2010, 2011, 2012 , 2013, 2014)
Myuna	Centennial Coal	UG	EIS	AECOM Australia Pty Ltd (2011b); GHD Pty Ltd (2010a); GeoTerra Pty Ltd (2013)
Newstan	Centennial Coal	UG	EIS and DTI	NSW Department of Industry, Resource and Energy Division (Dataset 9); Centennial Coal Company Ltd (2012); GeoTerra Pty Ltd (2013); GHD Pty Ltd (2010b); GSS Environmental (2011)
Ravensworth Complex	Glencore	OC & UG	Mining company	Glencore (Dataset 10); Australasian Groundwater and Environmental Consultants Pty Ltd (2013d); Mackie Environmental Research (2009, 2012); Xstrata Coal Pty Ltd (2013)
Rix's Creek	Bloomfield Collieries	OC	EIS and mining company	Bloomfield Group (Dataset 14); AECOM Australia Pty Ltd (2015); RPS (2014)
Spur Hill	Malabar Coal	UG	Mining company	Spur Hill Management Pty Ltd (Dataset 18); HydroSimulations (2013a)
Tasman	Donaldson Coal (Yancoal)	UG	EIS	RW Corkery and Co Pty Ltd (2012b, 2013, 2014b); Resource Strategies (n.d.); RPS Aquaterra (2012)
Ulan	Glencore	UG	EIS and mining company	Glencore (Dataset 10); Mackie Environmental Research (2011, 2015); Umwelt Australia Pty Ltd (2009, 2011c)
Wambo	Peabody Energy Australia	OC & UG	Mining company	Wambo Coal Pty Ltd (Dataset 13); HydroSimulations (2014)
Wallarah 2	Wyong Coal	UG	EIS and mining company	Wyong Areas Joint Venture (Dataset 19); Mackie Environmental Research (2013b); NSW Department of Planning and Infrastructure (2014)

Mine	Mining company or operator	Open-cut or underground	Footprint source	Flow rate and footprint references and datasets
West Wallsend	Glencore	UG	Mining company and DTI	Glencore (Dataset 10); NSW Department of Industry, Resource and Energy Division (Dataset 9); Glencore (2014b, 2014c); HydroSimulations (2013a)
Wilpinjong	Peabody Energy Australia	OC	EIS	Australasian Groundwater and Environmental Consultants Pty Ltd (2005); Gilbert and Associates Pty Ltd (2013c); HydroSimulations (2013b)

DTI = NSW Department of Trade and Investment, EIS = environmental impact statement, OC = open-cut, UG = undergroundc

Table 18 Data sources for mine footprints used in the surface water modelling for the Hunter subregion

Mine	Mining company	Mining period[a]	Footprint source	Reference or dataset
Ashton	Yancoal Australia	2003–2035	Landsat 5 TM imagery, EIS and DTI	Aquaterra (2009); RPS Aquaterra and Ashton Coal Operations Pty Ltd (2012); Wells Environmental Services (2009b); Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Austar	Yancoal Australia	2005–2036	EIS and DTI	Austar Coal Mine Pty Ltd (2013a); Umwelt Australia Pty Ltd (2008a); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Bengalla	Rio Tinto	1998–2049	Landsat 5 TM imagery, EIS and DTI	WRM Water and Environment Pty Ltd (2013a); Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Bulga	Glencore	1986–2035	Landsat 5 TM imagery, EIS, DTI and mining company	Hansen Bailey Pty Ltd (2010) Umwelt Australia Pty Ltd (2013); Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9); Glencore (Dataset 10, Dataset 11)
Bylong	KEPCO	2017–2046	EIS	Australasian Groundwater and Environmental Consultants Pty Ltd (2013b); WRM Water and Environment Pty Ltd (2015a)
Dartbrook	Anglo American	1993–2016	EIS and mining company	NSW Department of Planning (2005); Anglo-American (Dataset 12)
Drayton	Anglo American	2007–2027	EIS	Hansen Bailey Pty Ltd (2006)
Drayton South	Anglo American	2016–2036	EIS	WRM Water and Environment Pty Ltd (2015b)
Glendell	Glencore	2007–2033	Google Earth imagery	Bloomfield Group (Dataset 14)
Hunter Valley Operations	Rio Tinto	1968–2040	Landsat 5 TM imagery and DTI	Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Integra	Vale Australia	1991–2045	Landsat 5 TM imagery, EIS and DTI	Australasian Groundwater and Environmental Consultants Pty Ltd (2007); Environmental Resources Management Australia Pty Ltd (2009); SCT Operations Pty Ltd (2009); WRM Water and Environment Pty Ltd (2009); Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Liddell	Glencore	1983–2044	Landsat 5 TM imagery, EIS and DTI	Gilbert and Associates Pty Ltd (2013a); Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Mangoola	Glencore	2008–2036	EIS and DTI	WRM Water and Environment (2013b); NSW Department of Industry, Resource and Energy Division (Dataset 9)

Mine	Mining company	Mining period[a]	Footprint source	Reference or dataset
Moolarben	Yancoal Australia	2009–2055	EIS	Patterson Britton and Partners Ltd (2006); Pegasus Technical (2009d); Worley Parsons Services Pty Ltd (2008)
Mount Arthur	BHP Billiton	2001–2046	Landsat 5 TM imagery and EIS	Gilbert and Associates Pty Ltd (2009); Gilbert and Associates Pty Ltd (2013b); Bioregional Assessment Programme (Dataset 7)
Mount Owen	Glencore	1993–2047	EIS and DTI	Umwelt Australia Pty Ltd (2014); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Mount Pleasant	Rio Tinto	2018–2056	EIS	Coal and Allied (1997)
Mount Thorley-Warkworth	Coal and Allied (Rio Tinto)	1980–2057	Landsat 5 TM imagery and EIS	Mackie Environmental Research (2002); WRM Water and Environment Pty Ltd (2014); Bioregional Assessment Programme (Dataset 7)
Muswellbrook	Muswellbrook Coal Company (Idemitsu)	1983–2032	Landsat 5 TM imagery and DTI	Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Ravensworth Complex	Glencore	1999–2059	EIS and mining company	Umwelt Australia Pty Ltd (2010a, 2010b); Glencore (Dataset 10)
Rix's Creek	Bloomfield Collieries	1989–2058	Landsat 5 TM imagery, EIS and DTI	AECOM Australia Pty Ltd (2015); Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9)
Ulan	Glencore	1980–2041	Landsat 5 TM imagery and EIS	Umwelt Australia Pty Ltd (2009); Bioregional Assessment Programme (Dataset 7)
Wambo	Peabody Energy Australia	1987–2036	Landsat 5 TM imagery, DTI and mining company	Bioregional Assessment Programme (Dataset 7); NSW Department of Industry, Resource and Energy Division (Dataset 9); Wambo Coal Pty Ltd (Dataset 13)
Wallarah 2	Wyong Coal	2018–2056	EIS	WRM Water and Environment Pty Ltd (2013c)
Wilpinjong	Peabody Energy Australia	2005–2102	EIS	Gilbert and Associates (2005, 2013c)

[a] Mining period referred to in the table corresponds to assumed active phase of mine extraction for the open cut mines in the surface water model
DTI = NSW Department of Trade and Investment, EIS = environmental impact statement
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3, Dataset 4)

Environmental impact statements and other mine documents

Environmental impact statements (EIS), Director-General's and Secretary's environmental assessment reports, mining operation plans and water management plans were downloaded from the websites of the NSW Department of Planning and Environment Major Projects Assessments and mining companies.

The groundwater modelling uses the maximum extent of extraction, rather than a time series of extraction area, to define where pumping occurs. Reports were searched for maps or plans of the mine working areas that included spatial coordinates. The maximum mine working areas were digitised from these figures and georeferenced. The footprints have been simplified by reducing the number of vertices to speed up modelling while ensuring that mine footprints are never more than 300 m from known mining boundaries, such as the edge of mining extraction panels. The sources of data for each mine footprint for groundwater modelling are summarised in Table 17.

The depth of each footprint was determined and expressed as elevation in metres above the Australian Height Datum (mAHD). Most of the depths were contained in computer-aided design (CAD) drawings supplied by the mining companies. In some cases, the depths had to be found in the EISs and similar documents. The simplest of these were listed in the text, retrieved from a cross-section or stratigraphic column, or used pit or seam floor contour images. Other mine elevations were calculated by subtracting the depth of geological cover from the topographic elevation obtained from the EIS or Google Earth. For Integra Underground Coal Mine, the elevation of the Hebden seam was determined from seam floor contours. The approximate vertical separation between the Hebden seam, the Barrett seam and the Middle Liddell seam was calculated from the stratigraphic column of the mine (SCT Operations Pty Ltd, 2009, p. 2, Figure 2). From this information, the elevations of the Barrett and Middle Liddell seams were calculated. If none of these methods were possible, the depth of a nearby mine working was used instead. The groundwater footprints were exported in polygon file format (as .ply files) for groundwater modelling.

To obtain mine footprints for surface water modelling, the mining reports were searched for past and future projected mine layouts and surface water contributing areas. Each figure was digitised and georeferenced using one of four methods:

1. The preferred method was to use maps or plans with coordinates already on them.
2. If there were no coordinates, then three point locations were matched with points on Google Earth and the latitude and longitude from Google Earth were used to georeference the image.
3. If there were not three clearly identifiable point locations in the image, then supplementary points were found by matching contour information to the Shuttle Radar Topography Mission Smoothed Digital Elevation Model (SRTM DEM-S) grid (Geoscience Australia, Dataset 5).
4. Other site-specific approaches:
    a. Mangoola Coal Mine did not have adequate georeferencing points in the Year 10 and Final Landform images so these images were georeferenced to the matching project boundary in the other Mangoola Coal Mine images.
    b. The West Wallsend Colliery existing pit top surface facilities image, containing a satellite photo background, was georeferenced using Google Earth. The West Wallsend Colliery pit top facility outline was used to georeference the water management system image as they both contained the same outline.

The runoff contributing areas were calculated as a time series over the life of the mine, where possible. If a contributing area was not provided, the mine layout was used in conjunction with the SRTM DEM-S data to determine the area draining into the mine. Any area upslope of a water storage or dirty water area that was not diverted around the mine was included in the surface water mine footprint area. If these areas could not be determined from published information, only the area of the open-cut pit was used to define the mine footprint. The surface water footprints were exported as shapefiles (.shp) for modelling. Details of the mines and sources from which surface water mine footprints were obtained are summarised in Table 18.

Mining company spatial data

The Hunter Bioregional Assessment team (Assessment team) submitted a request to mining companies in the Hunter subregion for mine footprint data for the life of the mine, including the rehabilitation period. Some mining companies supplied mine footprint polygons under a restricted access licence agreement, which permits use for modelling purposes, but cannot be made publicly available. The mines for which footprints were obtained from mining companies are summarised in Table 17 and Table 18.

These mining companies provided approximately 600 files, mostly in AutoCAD and shapefile formats, but data were also provided as PDFs and PowerPoint documents. In most cases the data were provided in Map Grid of Australia (MGA) coordinates, otherwise these data were converted to MGA coordinates. Although some companies provided year-by-year mine plans from 2012 to mine completion, most data were provided at less frequent intervals, and some companies provided just the final mined area. Most data covered only future plans and did not include plans or discussion of historical operations. For open-cut operations, most data represented the pitshell, while for underground operations, the data represented individual longwall panels or perimeters of proposed mined areas. Some data were three-dimensional, with the elevation or depth of the mining seam or pit floor included. The data were synthesised manually, including combining various individual files where necessary, to produce the polygons (and seam-depth information, if available). During this process, the 500 m resolution of the groundwater model was always taken into account, which allowed a simplified polygonal representation that did not include individual roadways, bords, etc.

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

The Assessment team submitted a request to DTI for mine footprint data for Hunter subregion mines for every fourth year from 2000 to 2015. This interval was adopted as a convenient way of managing the size of the data request and providing a reasonable time step to represent the change in footprint areas over time. The dataset supplied was a complex assortment of files (10,937 files in 615 folders), including a number of format types (e.g. PDFs, shapefiles, e00 files, AutoCAD files) and containing information on different aspects of mine operations. In all, there were 473 e00 files and 1627 shapefiles that were potentially useful. Only a subset of these datasets represented the spatial extent of mine workings that were needed for defining the impacted areas for modelling. Some files for years other than those specifically requested were also included in the dataset supplied. All data were supplied under a restricted access licence agreement, which permits use for modelling purposes in the bioregional assessment, but cannot be made publicly available.

DTI also provided the drafting instructions sent to mines, which specify the formats in which mine footprint data are to be supplied to DTI by the mines. The drafting specifications have changed a few times over this period and adherence to the specifics of the standards has also varied, meaning that there was sufficient variability in file formats and naming conventions to make the extraction of the required data a very manual task of potentially limited value.

Following analyses of the files, a set of rules was developed based on the various file naming conventions to select the data files that were deemed most likely to contain mine working spatial data. A script was written that mined the folders for spatial files based on keywords, including mine name and year, in the file path name. For each of the files identified, an attempt was made to extract any polygon features. There were 45,267 mine footprint polygons extracted for 47 mines from 396 (19%) of the spatial data files. Figure 37 shows the number of polygons extracted for each year from the supplied data. The extracted data were biased towards the years 2008 and 2012, which reflects more consistent adoption by the mining sector of the formats and naming conventions specified in the drafting specifications. Comparatively few polygons were obtained for 2004 and none were obtained for 2000.

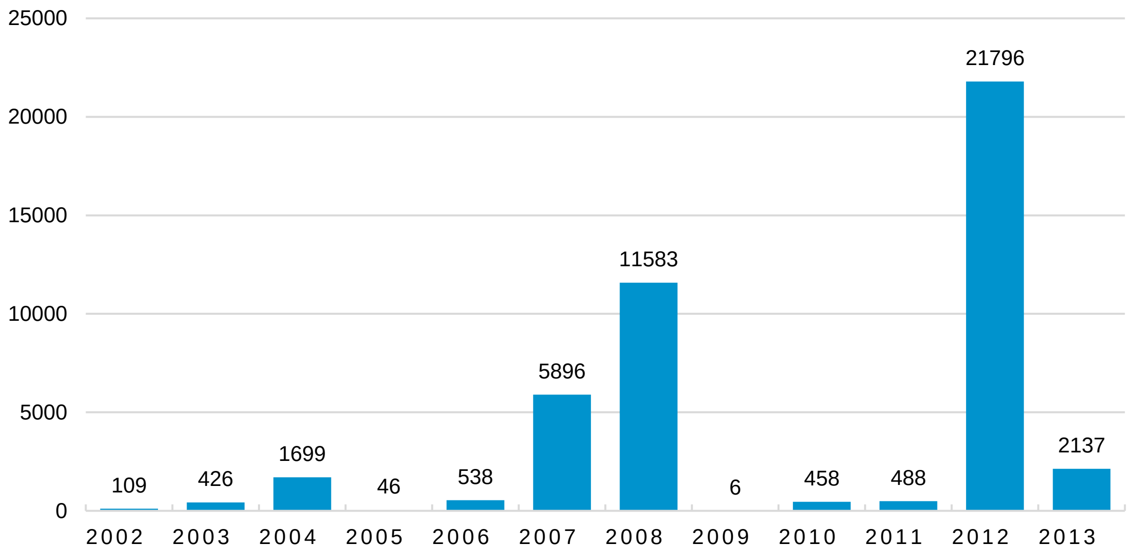


Figure 37 Number of mine footprint polygons obtained from NSW Department of Trade and Investment data by year

Data: NSW Department of Industry, Resource and Energy Division (Dataset 9)

Due to the large number of heterogeneous datasets, summarising the attribute data within these spatial datasets proved difficult. As a result, the attribute information should be viewed as indicative of the attributes in the underlying files.

Based on inspection of the data, the projection for most of the polygons was determined to be EPSG:28356 (MGA zone 56); however, a few of the source datasets were not in this projection and were not incorporated into the derived dataset (Bioregional Assessment Programme, Dataset 7 (restricted access)). DTI footprint areas were used for only some mines (see Table 17 and Table 18).

Landsat imagery open-cut mine footprints (1983 to 2002)

Landsat 5TM images were downloaded from Australian Geoscience Data Cube (AGDC; Geoscience Australia, 2015) between July and August 2015. The AGDC is an integrated gridded data analysis environment established by Geoscience Australia, CSIRO and the NCI, and maintained by Geoscience Australia. It contains the full archive of Australian Landsat 5 TM imagery. Images are provided at a one-by-one degree resolution (nominally 25 m) called a tile.

The historical open-cut mines for the Hunter subregion are covered by three tiles: 149_-033, 150_-033 and 151_-033. All available summer images, including both Landsat 5 TM and Landsat 7 ETM images, for the years 1987, 1992, 1997 and 2002 for these three tiles were downloaded (Geoscience Australia, Dataset 5). In addition, imagery was obtained for a number of open-cut mines that commenced between 2002 and 2008. This period was identified as a potential gap in the footprint data supplied by DTI because the early DTI files varied so much in format and naming conventions that consistent patterns for mining the files prior to 2007 could not be defined. Two open-cut mines had mine footprints digitised from Landsat images in 2004 and 2005.

Images were displayed in ArcMap for quality assessment and the best images were selected for digitising. Identifiable open-cut mine footprints were manually digitised in ArcGIS and saved as Arc shapefiles (Bioregional Assessment Programme, Dataset 7). Publicly available materials were used to help define the mine boundaries where necessary, including reports published by mine operators and Google Map. For example, a figure in an EIS from Rio Tinto (2015), which showed the boundaries between the Bulga, Mount Thorley-Warkworth and Wambo mining leases, was used to identify which open-cut mine in the imagery belonged to its respective mining operation.

The open-cut mine footprint areas obtained from the Landsat 5 TM imagery are summarised in Table 19.

Table 19 Mine footprint areas for open-cut mines in the Hunter subregion between 1987 and 2006

Open-cut mine	Mine footprint area 1987 (km^2)	Mine footprint area 1992 (km^2)	Mine footprint area 1997 (km^2)	Mine footprint area 2002 (km^2)	Mine footprint area 2004 (km^2)	Mine footprint area 2005 (km^2)	Mine footprint area 2006 (km^2)
Ashton	)NA	NA	NA	NA	2.28	NA	NA
Bengalla	NA	NA	NA	2.39	NA	NA	NA
Bloomfield	1.69	3.31	3.52	2.01	NA	NA	1.69
Bulga	4.98	5.72	2.61	13.05	NA	NA	4.98
Donaldson	NA	NA	NA	1.49	NA	NA	NA
Drayton	10.50	11.59	13.71	10.38	NA	NA	10.50
Hunter Valley Operations	41.47	41.83	72.21	66.67	NA	NA	41.47
Integra	NA	5.23	11.96	14.52	NA	NA	NA
Liddell	4.93	3.81	7.11	12.02	NA	NA	4.93
Mount Arthur	NA	NA	NA	5.56	NA	14.42	NA
Mount Thorley (part of Mount Thorley-Warkworth)	11.34	15.09	17.76	17.92	NA	NA	11.34
Muswellbrook	0.74	1.10	1.77	1.71	NA	NA	0.74
Narama (part of Ravensworth Complex)	6.06	9.21	7.69	5.94	NA	NA	6.06
Rix's Creek	NA	3.69	8.75	11.19	NA	NA	NA
Ulan	2.67	5.59	5.92	6.38	NA	NA	2.67
Wambo	2.70	6.99	8.78	6.07	NA	NA	2.70

NA = data not available
Data: Geoscience Australia (Dataset 6), Bioregional Assessment Programme (Dataset 7)

Google Earth imagery

During the data compilation and pre-processing stage for generating the footprint time series, quality assurance checks were performed using Google Earth. During this process, some gaps were identified for the Glendell Coal Mine footprint areas and were resolved by digitising from the Google Earth imagery. These were obtained from images in years 2008, 2009, 2013 and 2015 (Bloomfield Group, Dataset 14).

2.1.6.1.2 Flow rates

The annual groundwater flow rate (also referred to as 'mine water make') is the amount of water that flows into the groundwater footprint area in a year. Mine reports were the source of flow rate information (see Table 17), in which flow rate data were typically published in tables or graphs of groundwater inflow or influx. The latest version of a report was used to accommodate for any overlap in data. When only a maximum flow rate was available, it was assumed that this flow rate would be achieved in the final year of mining, and that the flow rate would increase from zero at the commencement of mining to this maximum in a linear fashion. Where possible, the flow rates were split into individual pits or mine sections to more accurately reflect the distribution of groundwater inflow across the mine site. Any data gaps in groundwater flow rates were estimated by a linear interpolation between available data. Flow rates were assumed to be zero before mining commenced, and return to zero upon mine closure, unless otherwise indicated in the literature. Flow data were not obtained for the baseline Ulan open-cut mine and there were insufficient data to represent the additional coal resource developments of West Muswellbrook open-cut, Wambo underground and Wilpinjong open-cut in the groundwater model (see Section 2.3.4 of companion product 2.3 conceptual modelling for the Hunter subregion (Dawes et al., 2018)).

2.1.6.2 Translating surface water mine footprint areas into time series of hydrological changes

A number of assumptions need to be made in the surface water modelling to represent the hydrological impacts of mining developments on water-dependent assets. These assumptions are consistent with the policy and legislative framework governing the operation of mines (see Section 2.3.4 of Dawes et al. (2018)). This section discusses the approach for defining surface water footprint time series and characterising their hydrological responses pre- and post-development.

Table 20 lists the assumptions made in generating the time series of footprint areas to represent the areas within AWRA-L where hydrological changes must be applied. It also includes the assumptions made for representing hydrological changes due to mines. More detail about the implementation of these assumptions can be found in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

Table 20 Assumptions made in surface water modelling for representing hydrological impacts of mines and generation of time series data

	Characteristic	Assumption for modelling	Basis for assumption
Generating time series	Start date for baseline mines	As specified in development consent that was current at December 2012	Many mines have been operating in the Hunter subregion for decades. Over that time, the mining companies have changed, operations have been consolidated, some operations have ceased and new developments have commenced. The Assessment team does not have the information to model impacts of all historical mines. For modelling, the Assessment team use the timelines of the operation that was current at the date selected for defining baseline and additional coal resource developments.
	Start date for additional coal resource development (ACRD) mines	1. as specified in development consent or 2. as indicated by a mining company report or representative, if different from what was in development consent or 3. if not commenced and uncertain when it will commence, assume 2018.	ACRD activities do not always commence when the proposal indicates. This can be because of delays in the approval process, or following approval delays related to the mines operations. Start dates have been determined from current mine reports or mine company contacts. A start date has been estimated for mines that were proposing to start by a date that has passed without them having done so.
	End date for baseline mines	As specified in development consent (includes a change in end date from an approved modification that does not involve an expansion of mining area). Does not include extensions in time to accommodate expansion of mining areas that commenced after December 2012. These become part of coal resource development pathway (CRDP) as ACRD.	
	End date for ACRD mines	Either: 1. end date in development consent or 2. end date estimated from mine plan life.	

Characteristic	Assumption for modelling	Basis for assumption
Maximum footprint	Assumed to occur at end of mining operations (i.e. rehabilitation is assumed to commence at end of mine life). Except, where data have been obtained that indicates a footprint has contracted and expanded over time (applies to baseline only).	Rehabilitation is typically undertaken progressively, but details of this and also hydrological recovery times are not known. Approach is conservative.
Interpolation between data points	Linear	Use only data available.
Post-mining longwall footprints	Sustained at maximum footprint to 2102	Subsidence is permanent.
Post-mining open-cut footprints	Sustained at maximum footprint for 10 years. Scaled back to final void area (if known) or to 0.16 times the maximum footprint area for a further 10 years	Backfilling of pit is likely to occur more quickly than this; infiltration properties of infilled mine unknown.
Final void areas	1. If there are polygon(s) from environment impact statement (EIS), then use these 2. If final voids not known, then use 0.16 of maximum footprint area	For mines for which data were available, final void area was compared to the maximum footprint area. The median of the ratio of final void area to the maximum footprint area was 16%, with a range of 4% to 32%.
Open-cut mines above longwall panels	Open-cut disturbances over-ride longwall disturbances – longwall footprints must be clipped using open-cut footprint to avoid double accounting. Open-cut hydrological impact (i.e. 100% reduction in runoff) in areas of intersection; longwall hydrological impact in unique areas	Open-cut mining impacts are at the surface and assumed to have direct and complete impact on surface drainage. Where longwall panels go under existing open-cut excavations, they will have no additional impact on drainage at surface.
Longwall mine site facilities over longwall panels	Underground mining site facilities override longwall mine panel hydrological impacts. To avoid double accounting, clip the site facilities area from longwall panel polygon.	As above. Site facilities associated with any mining operation involve disturbances at the surface, which have direct impact on runoff processes.
Longwall panels over longwall panels	Union of the polygons to obtain maximum footprint. Adding polygons will result in double accounting of hydrological impacts.	Extractions from deeper seams are assumed to not increase the impact at the surface caused by the first level of excavation.

	Characteristic	Assumption for modelling	Basis for assumption
Surface water hydrological impact	Longwall mine	Some minor subsidence ensues resulting in a long-term (permanent) 5% reduction in surface water runoff from the affected area.	Subsidence is not modelled, but is inevitable where longwall mining occurs. Impacts on surface runoff can vary from very little to more than 50% interception, although the latter is unlikely. A 5% reduction in runoff is assumed as mines are required to minimise this impact and make good on streamflow reductions. The Assessment team does not have any basis for varying this by mine location, longwall panel depth or other factors.
	Bord-and-pillar mines	Zero impact on surface runoff.	There is negligible subsidence because bord-and-pillar mining method generally involves minimal collapsing of the mine access shaft once extraction is completed.
	Longwall mine site facilities	100% reduction in surface runoff (from affected areas) for duration of mining and subsequent 10 years, then linearly reduced to zero over the next ten years.	• Mines comply with NSW Water Act 1912, NSW Mining Act 1992, NSW Protection of the Environment Operations Act 1997 and NSW Water Management Act 2000. • Runoff generated from disturbed areas is retained on-site. Site drainage is designed to ensure that dirty water is not discharged to river network. • Assume that site facilities are not abandoned immediately when mining ceases, allowing for rehabilitation of site. Rehabilitation is assumed to return disturbed areas to pre-disturbance conditions over 10 years, following completion of rehabilitation. Anecdotal evidence from environmental officers at Glencore suggested 5-10 years for return to undisturbed conditions.
	Open-cut mine, site facilities, runoff contributing areas to water management storages	100% reduction in runoff from affected areas for duration of mining; sustained for 10 years following cessation of mining; reduced over a further 10 years to 0.16 of maximum footprint area (see final voids).	• Mines comply with NSW’s Water Act 1912, NSW’s Mining Act 1992, NSW’s Protection of the Environment Operations Act 1997 and NSW’s Water Management Act 2000. • Runoff generated from disturbed areas and intercepted catchments is retained on site. Site water management is designed to ensure that dirty water is not discharged to river network. • Assume 10 years to complete rehabilitation and abandon site following cessation of mining. Rehabilitation is assumed to return disturbed areas to pre-disturbance conditions over 10 years, following completion of rehabilitation.

ACRD = additional coal resource development, CRDP = coal resource development pathway

2.1.6.2.1 Calculating final void areas for surface water modelling

The final void in an open-cut mining operation refers to the pit or pits that are left following the completion of landscape rehabilitation. For some open-cut mines, final void areas were specified in environmental management plans and these have been used directly in defining the final area of disturbance in the footprint time series. For open-cut mines, where the final void area was not provided, it has been assumed that (i) there is a final void and (ii) a reasonable estimate can be made based on final void area to maximum footprint area from other mines where data are available. The ratio of final void area to maximum footprint area for each of the mines for which these data were available was quantified (Table 21). The median proportion was estimated to be 16% of the maximum footprint area (mean 20%), with a range of 4% to 52%. The median value was adopted for calculating the final void area (A_{final_void}) from maximum footprint area ($A_{max\_footprint}$) at other open-cut mine sites as follows:

$$A_{final\_void} = 0.16 * A_{max\_footprint} \quad (3)$$

Table 21 Open-cut mines used to define the ratio of final void area to maximum footprint area

Mine	Maximum area (km^2)	Final void area (km^2)	Ratio of final void area to max area (%)
Ashton	5.07	0.34	6.7%
Bulga	44.24	7.09	16%
Drayton	7.69	2.42	31.5%
Drayton South	17.01	2.62	15.4%
Liddell	10.67	2.88	27.0%
Mangoola	19.93	0.86	4.3%
Mount Pleasant	32.58	4.15	12.7%
Mount Thorley	27.33	14.13	51.7%
Ravensworth	26.85	1.34	5.0%
Wilpinjong	12.76	3.63	28.5%
Median	**18.47**	**2.75**	**15.7%**

Refer to Table 18 for references and datasets for each mine
Data: Bioregional Assessment Programme (Dataset 4, Dataset 21)

2.1.6.3 *Summary of baseline and coal resource development pathway model data for surface water and groundwater modelling*

Table 22 summarises the areas of changed surface water hydrology for three key points in the footprint time series for each open-cut mine: end of 2012 prior to commencement of any additional coal resource development mines in the CRDP; the maximum disturbed area represented in the model; and the final disturbed area following full rehabilitation. Open-cut mines and site facilities (whether they be for open-cut or underground operations) are included in the areas given, as they have the same hydrological effect in the surface water model. The table also includes the maximum disturbed area at the surface for underground mines (final column). Maximum extent, maximum seam depth and maximum flow rate for each mine working represented in the Hunter subregion groundwater model are summarised in Table 23. The data in Table 22 and Table 23 were extracted from the various sources identified in Table 17 and Table 18.

Table 22 Key characteristics of data used to represent mine impacts in the surface water model for the Hunter subregion

Mine or mine complex	Open-cut or underground	In baseline?	In CRDP?	2012 area disturbed by open-cut pits, site facilities (km^2)	Maximum area disturbed by open-cut pits, site facilities (km^2)	Final area disturbed by open-cut pits, site facilities (km^2)	Maximum area disturbed above longwall panels (km^2)	Name of post-2012 mine expansion project
Ashton	OC	Y	Y	2.38	2.38	0.38	na	na
	OC	N	Y	2.38	5.07	0.72	na	South East Open-Cut mine
	UG	Y	Y	0	0	0	5..12	na
Austar	UG	Y	Y	1.25	1.25	0	1674	na
Bengalla	OC	Y	Y	4.66	4.24	0.68	na	na
	OC	N	Y	4.66	15.86	1.83	na	Expansion
Bulga	OC	Y	Y	11.97	19.62	3.14	na	na
	OC	N	Y	11.97	44.24	7.09	na	Bulga Coal Optimisation Project
	UG	Y	Y	0	0	0	20.15	na
Bylong	OC	N	Y	0	8.49	1.37	na	Bylong Coal Project (new mine)
	UG	N	Y	0	0	0	18.05	Bylong Coal Project (new mine)
Dartbrook	UG	Y	Y	0.74	0.74	0	5.07	na
Drayton	OC	Y	Y	7.69	6.55	2.42	na	na
Drayton South	OC	N	Y	0	17.01	2.62	na	Drayton South Coal Project
Glendell	OC	Y	Y	4.38	5.12	0.49	na	na
Hunter Valley Operations	OC	Y	Y	37.83	37.83	6.05	na	na
Integra	OC	Y	Y	20.6	21.8	3.49	na	na
	UG	Y	Y	0.08	0.08	0	13.31	na

Mine or mine complex	Open-cut or underground	In baseline?	In CRDP?	2012 area disturbed by open-cut pits, site facilities (km^2)	Maximum area disturbed by open-cut pits, site facilities (km^2)	Final area disturbed by open-cut pits, site facilities (km^2)	Maximum area disturbed above longwall panels (km^2)	Name of post-2012 mine expansion project
Liddell	OC	Y	Y	7.61	10.49	1.68	na	na
	OC	N	Y	7.61	12.46	1.99	na	Expansion
Mangoola	OC	Y	Y	3.72	19.93	0.86	na	na
Moolarben	OC	Y	Y	5.17	15.88	2.54	na	na
	OC	N	Y	5.17	23.75	4.58	na	Stage 1
	UG	Y	Y	0	0	0	10.41	na
	UG	N	Y	0	0	0	17.91	Stage 2
Mount Arthur	OC	Y	Y	39.67	59.27	9.48	na	na
	OC	N	Y	39.67	60.72	9.71	na	Expansion of South Pit into Bayswater No.3 mining lease
	UG	N	Y	0	0	0	19.09	na
Mount Owen	OC	Y	Y	5.74	17.38	2.78	na	na
	OC	N	Y	5.74	23.05	3.69	na	Mount Owen Continued Operations Project
Mount Pleasant	OC	N	Y	0	32.58	4.15	na	na
Mount Thorley–Warkworth	OC	Y	Y	27.33	27.33	14.13	na	na
	OC	N	Y	27.33	43.31	14.13	na	Expansion
Muswellbrook	OC	Y	Y	3.46	3.46	0.55	na	na
Ravensworth	OC	Y	Y	10.99	26.85	1.34	na	na
	UG	Y	Y	0	0	0	14.62	na
Rix's Creek	OC	Y	Y	4.58	8.75	1.4	na	na

Mine or mine complex	Open-cut or underground	In baseline?	In CRDP?	2012 area disturbed by open-cut pits, site facilities (km^2)	Maximum area disturbed by open-cut pits, site facilities (km^2)	Final area disturbed by open-cut pits, site facilities (km^2)	Maximum area disturbed above longwall panels (km^2)	Name of post-2012 mine expansion project
Ulan	OC	Y	Y	11.57	16.25	2.6	na	na
	UG	Y	Y	0	0	0	33.74	na
	UG	N	Y	0	0	0	45.61	Expansion
Wallarah 2	UG	N	Y	0	0.4	0	37.52	na
Wambo	OC	Y	Y	9.27	20.38	3.26	na	na
Wilpinjong	OC	Y	Y	8.38	12.76	3.63	na	na

baseline = baseline coal resource development, OC = open-cut, UG = underground, na = not applicable
Mines in the coal resource development pathway (CRDP) include mines in the baseline and additional coal resource developments. Data from various sources (see Table 18)
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3, Dataset 4, Dataset 21)

Table 23 Key characteristics of data used to represent mine impacts in the groundwater model for the Hunter subregion

Mine	Open-cut or underground	In baseline?	In CRDP?	Maximum footprint area (km^2)	Minimum seam depth (mAHD)	Maximum flow rate (ML/y)	Period of pumping	Name of post-2012 mine expansion project
Abel	UG	Y	Y	23.82	–220	2300	2009–2027	na
Ashton	OC	Y	Y	1.5	10	47	2004–2013	na
	OC	N	Y	3.82	–50	51	2004–2013, 2017–2026	South East Open-Cut mine
	UG	Y	Y	5.12	–265	584	2004–2026	na
Austar	UG	Y	Y	16.74	–390	505	2009–2014	na
	UG	N	Y	16.74	–390	770	2009–2044	Modification to Stage 3 area
Bengalla	OC	Y	Y	7.17	0	475	1998–2023	na
	OC	N	Y	11.99	0	475	1998–2035	Expansion
Bloomfield	OC	Y	Y	6.31	–55	750	2006–2018	na
Bulga	OC	Y	Y	5.96	–46	73	1990–2031	na
	OC	N	Y	6.72	–237.6	73	1990–2031	Bulga Coal Optimisation Project
	UG	Y	Y	27.17	–202	950	2008–2041	na
Bylong	OC	N	Y	4.08	270	548	2016–2024	Bylong Coal Project (new mine)
	UG	N	Y	18.33	180	183	2023–2044	Bylong Coal Project (new mine)
Chain Valley	UG	Y	Y	8.55	–200	2800	2005–2015	na
	UG	N	Y	8.55	–200	3900	2005–2028	Chain Valley Modification 1
Cumnock	UG	Y	Y	8.54	–60	400	1951–2011	na
Dartbrook	UG	Y	Y	5.07	–60	274	1997–2005	na
Donaldson	OC	Y	Y	2.45	–55	250	2001–2013	na
Drayton	OC	Y	Y	3.66	128	983	2010–2021	na

Mine	Open-cut or underground	In baseline?	In CRDP?	Maximum footprint area (km²)	Minimum seam depth (mAHD)	Maximum flow rate (ML/y)	Period of pumping	Name of post-2012 mine expansion project
Drayton South	OC	N	Y	8.86	90	175	2015–2031	Drayton South Coal Project
Glendell	OC	Y	Y	2.01	–14	438	2007–2024	na
Howick West (part of Hunter Valley Operations)	OC	Y	Y	30.15	–25	225	1979–2027	na
Hunter Valley Operations	OC	Y	Y	29.31	–125	5831	2002–2035	na
Integra	OC	Y	Y	4.96	–125	117	1997–2019	na
	UG	Y	Y	14.02	–400	478	1999–2041	na
Liddell	OC	Y	Y	2.71	–17.5	3468	2009–2023	na
	OC	N	Y	3.37	–17.5	3468	2009–2023	Expansion
Mandalong	UG	Y	Y	15.06	–280	885	2004–2016	na
	UG	N	Y	44.01	–280	2154	2004–2052	Mandolong Southern Expansion Project
Mangoola	OC	Y	Y	8.94	124	660	2006–2029	na
Mannering	UG	Y	Y	16.35	–200	624	2001–2019	na
Moolarben	OC	Y	Y	10.63	380	160	2011–2016, 2030–2036	na
	OC	N	Y	23.94	380	664	2011–2036	Stage 1
	UG	Y	Y	17.19	260	1797	2011–2042	na
	UG	N	Y	27.89	260	1797	2011–2042	Stage 2

Mine	Open-cut or underground	In baseline?	In CRDP?	Maximum footprint area (km^2)	Minimum seam depth (mAHD)	Maximum flow rate (ML/y)	Period of pumping	Name of post-2012 mine expansion project
Mount Arthur	OC	Y	Y	42.57	100	952	2008–2029	Expansion of South Pit into Bayswater No.3 mining lease
	UG	N	Y	30.62	−60	2101	2007–2030	na
Mount Owen	OC	Y	Y	4.13	−70	915	2007–2022	na
	OC	N	Y	5.92	−70	915	2007–2031	Mount Owen Continued Operations Project
Mount Pleasant	OC	N	Y	19.99	0	694	2016–2038	na
Mount Thorley–Warkworth	OC	Y	Y	15.58	−50	949	1980–2020	na
	OC	N	Y	15.58	−50	949	1980–2036	Expansion
Muswellbrook	UG	Y	Y	2.58	−80	1372	2006–2015	na
	OC	Y	Y	2.96	149	115	2009–2014	na
Myuna	UG	Y	Y	62.61	−140	10360	1980–2032	na
Newstan	UG	Y	Y	35.35	−65	2051	1999–2015	na
Ravensworth	OC	Y	Y	8.76	−124	546	2006–2041	na
	UG	Y	Y	18.41	−180	497[a]	2005–2036	na
Rix's Creek	OC	Y	Y	5.12	−5	299	2013–2038	na
Tasman	UG	Y	Y	14.61	−50	70	2007–2014	na
Ulan	UG	Y	Y	47.3	287.6	5950	1985–2031	na
	UG	N	Y	78.88	287.6	9335	1985–2031	Ulan West (expansion)
Wallarah 2	UG	N	Y	37.52	−412	876	2018–2058	na

Mine	Open-cut or underground	In baseline?	In CRDP?	Maximum footprint area (km^2)	Minimum seam depth (mAHD)	Maximum flow rate (ML/y)	Period of pumping	Name of post-2012 mine expansion project
Wambo	OC	Y	Y	21.01	–100	365	1968–2029	na
	UG	Y	Y	10.49	–48	1350	2007–2019	na
West Wallsend	UG	Y	Y	26.22	–127.3	1213	2008–2028	na
Wilpinjong	OC	Y	Y	19.15	345	1950	2005–2026	na

[a]reported maximum is 558 ML/y, but lower value was used in modelling due to mine being put in care and maintenance
baseline = baseline coal resource development, ACRD= additional coal resource development, OC = open-cut, UG = underground, na = not applicable
Mines in the coal resource development pathway (CRDP) include the mines in the baseline and additional coal resource developments. Data from various sources (see Table 17)
Data: Bioregional Assessment Programme (Dataset 22, Dataset 23, Dataset 24, Dataset 25)

Figure 38 and Figure 39 illustrate spatial distribution of the maximum footprint areas under baseline (Figure 38) and additional coal resource development (Figure 39) for surface water and groundwater models in the Hunter subregion. As discussed in Section 2.3.4 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018), not all mines are incorporated in both the surface water and groundwater models for both baseline and CRDP model runs. There were mines where flow rate data were not available and other mines where the surface water models were not able to represent the key processes influencing local hydrology (e.g. tidal dynamics and urban runoff), which precluded them from being modelled.

Figure 40 shows the footprint time series for baseline and CRDP for the period from 1983 to 2102. These time series were derived for each mine from available data (points) using the assumptions summarised in Table 20. The time series baseline and CRDP data are used in surface water modelling to estimate impacts of the additional coal resource development mines on hydrological response variables. The hydrological impacts are reported in companion product 2.6.1 for the Hunter subregion (Zhang et al., 2018).

Figure 41 shows the flow rate time series for baseline and CRDP mine areas for the period from 1968 to 2058. Deriving the time series from available data (points) for each mine is based on the assumptions described in companion product 2.6.2 for the Hunter subregion (Herron et al., 2018). Some plots present a flow rate time series for multiple mines (e.g. Bloomfield plot includes Donaldson; Newstan and Awaba) or by complex (e.g. Mt Owen Complex includes Glendell, Mount Owen and Ravensworth East open-cuts). When time series for individual workings are combined into a single time series, the maximum flow rate is not necessarily equal to the sum of the individual maxima (Table 23), which may occur in different years. The time series baseline and CRDP data are used in groundwater modelling to estimate the effects of the additional coal resource developments on hydrological response variables and are reported in Herron et al. (2018). There can be differences in the start and end dates used in the surface water and groundwater models, which reflect lack of certainty about when additional coal resource development mines will commence, assumptions about when groundwater pumping commenced and ceased and assumptions about how long impacts of mining are sustained after mining ceases (see Table 20).

Figure 38 Maximum footprint areas for baseline mines used in surface water and groundwater models

Baseline coal resource development (baseline) is defined as a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012. This figure is not representative of all mines in the baseline. Maximum footprint areas for mines in the baseline depict only those mines with sufficient data and information to be qualitatively assessed through surface water and groundwater modelling.

Data: Bioregional Assessment Programme (Dataset 21, Dataset 22, Dataset 23, Dataset 24, Dataset 25)

Figure 39 Maximum mine footprint areas for the additional coal resource developments (ACRD) used in surface water and groundwater models

ACRD is defined as all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012. CRDP is defined as a future that includes all coal mines and coal seam gas (CSG) fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.
This figure is not representative of all ACRD mines in the CRDP. Maximum footprint areas for ACRD depict only those ACRDs with sufficient data and information to be qualitatively assessed through surface water and groundwater modelling.
Data: Bioregional Assessment Programme (Dataset 21, Dataset 22, Dataset 23, Dataset 24, Dataset 25)

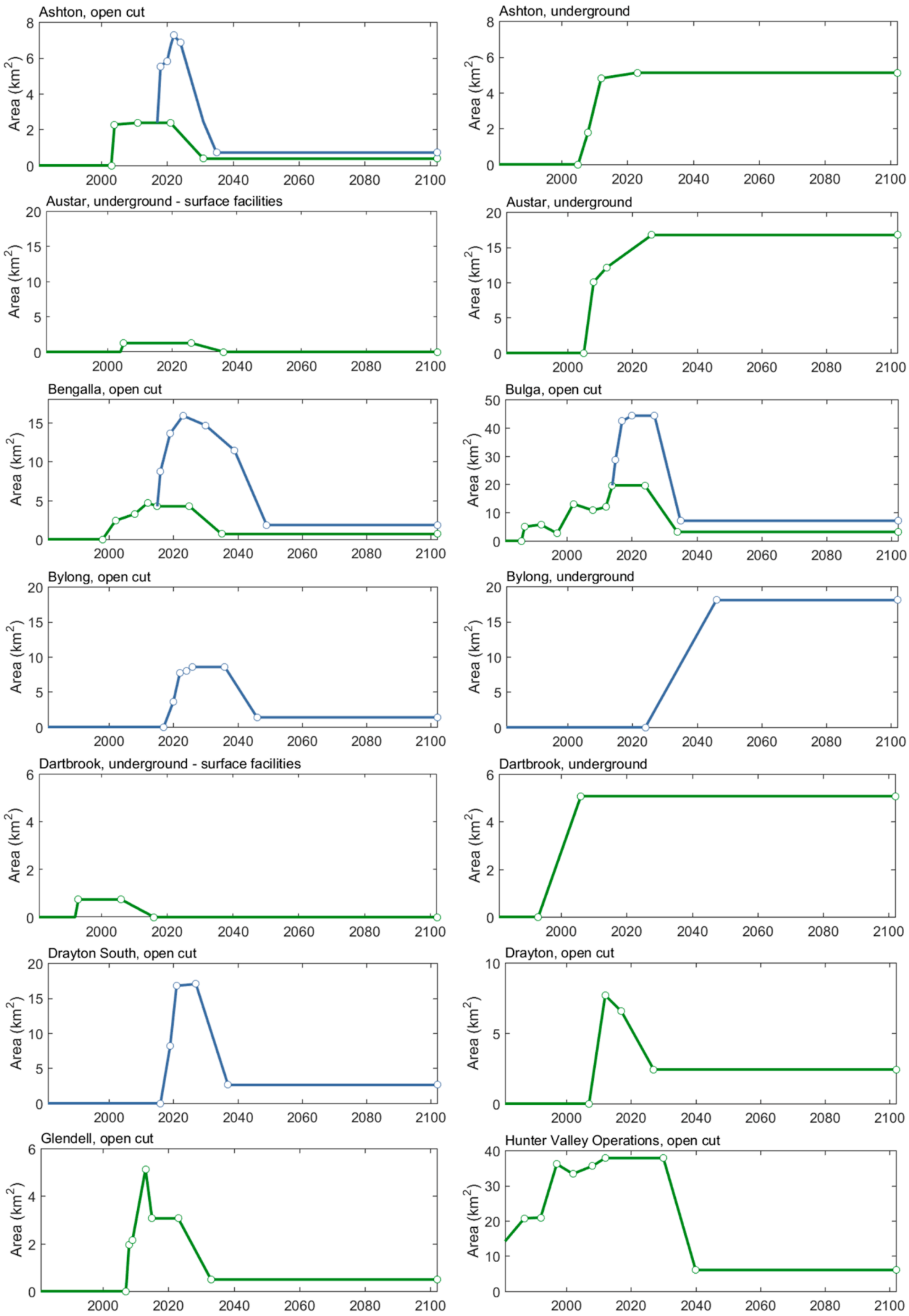


Figure 40 continued on following page

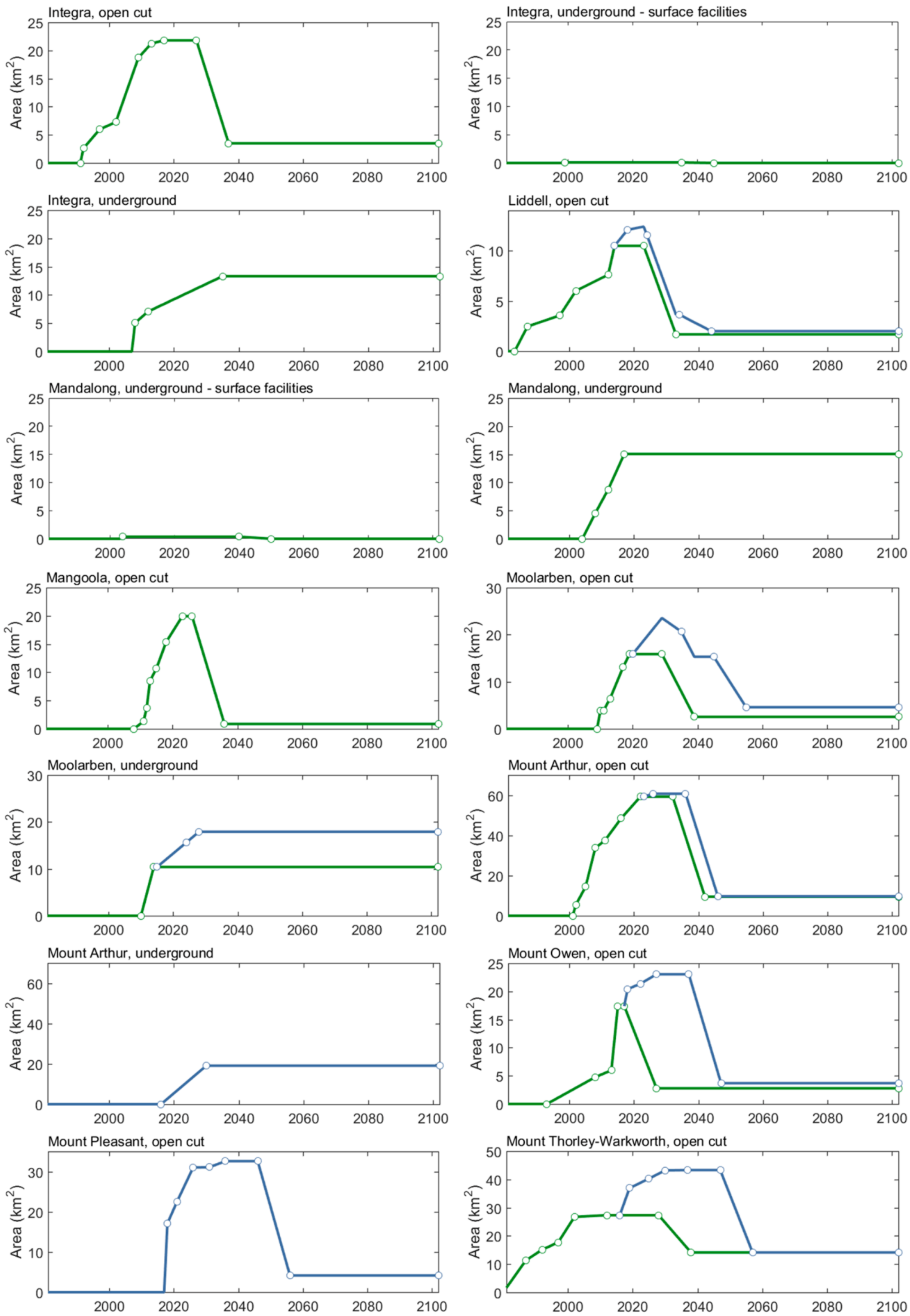


Figure 40 continued on following page

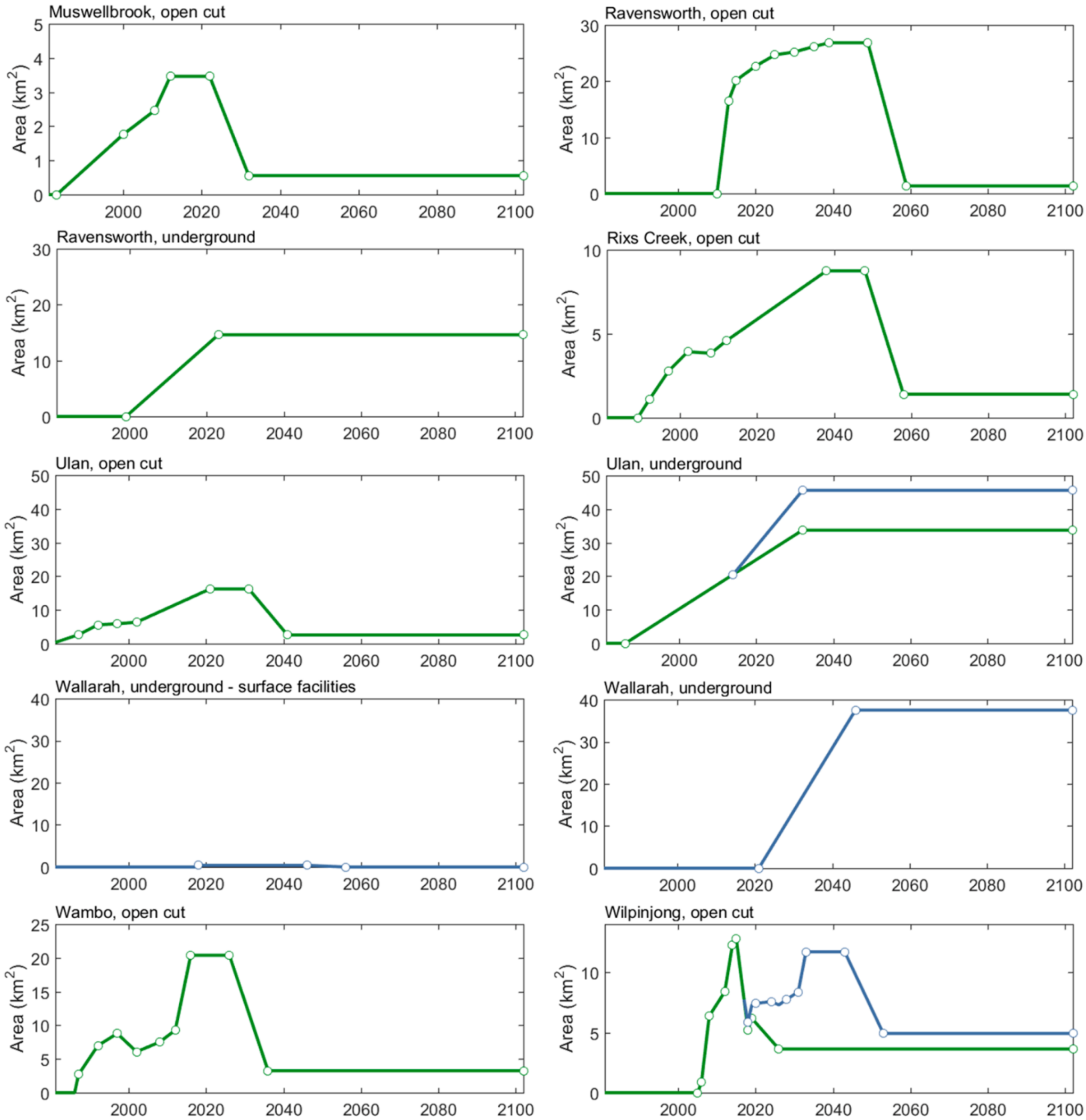


Figure 40 Time series graphs of open-cut and underground mine footprint areas for surface water modelling

Green = baseline, blue = CRDP mines; lines are interpolations between data points, represented by open circles

Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3, Dataset 4, Dataset 21)

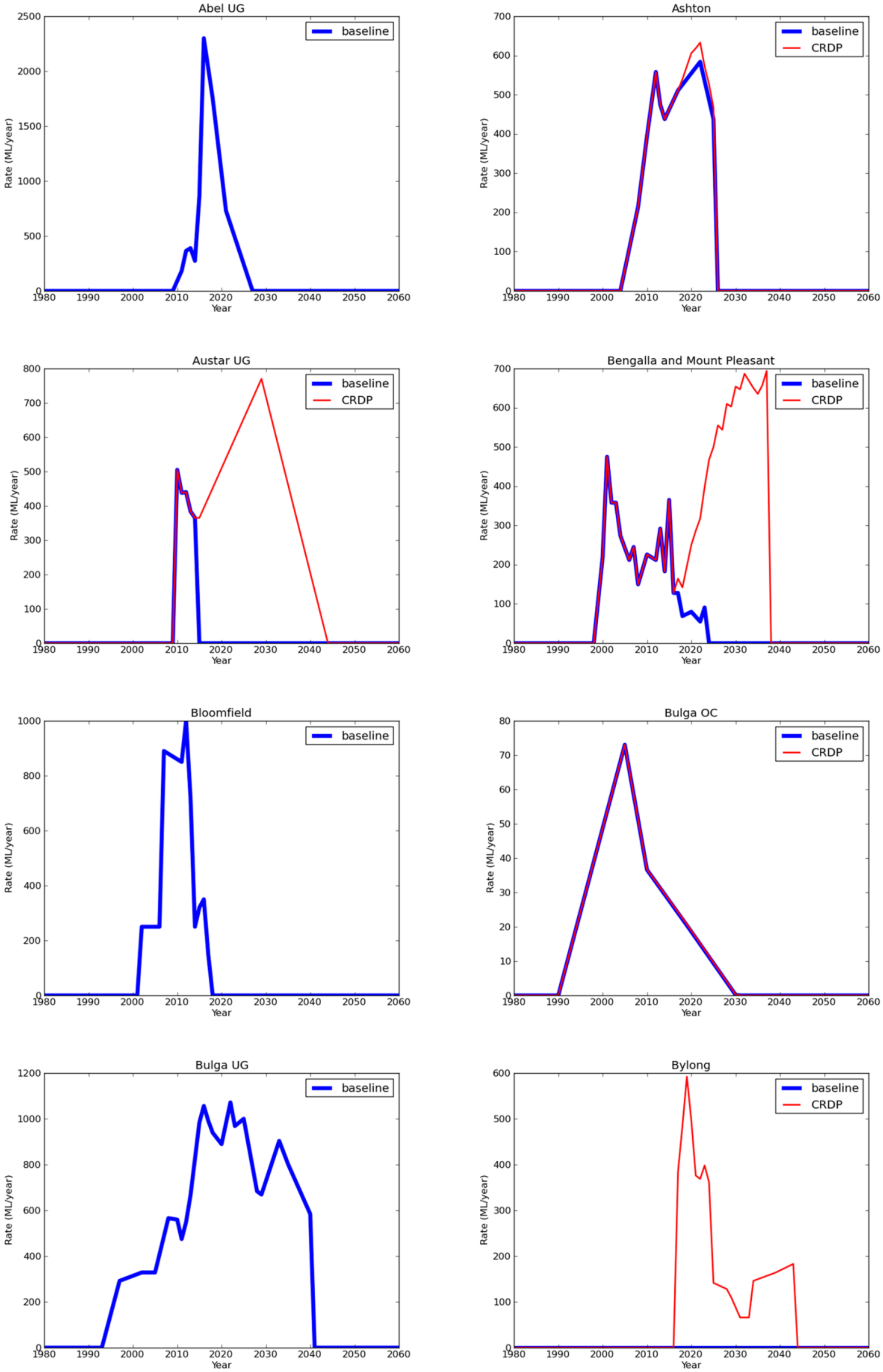


Figure 41 continued on following page

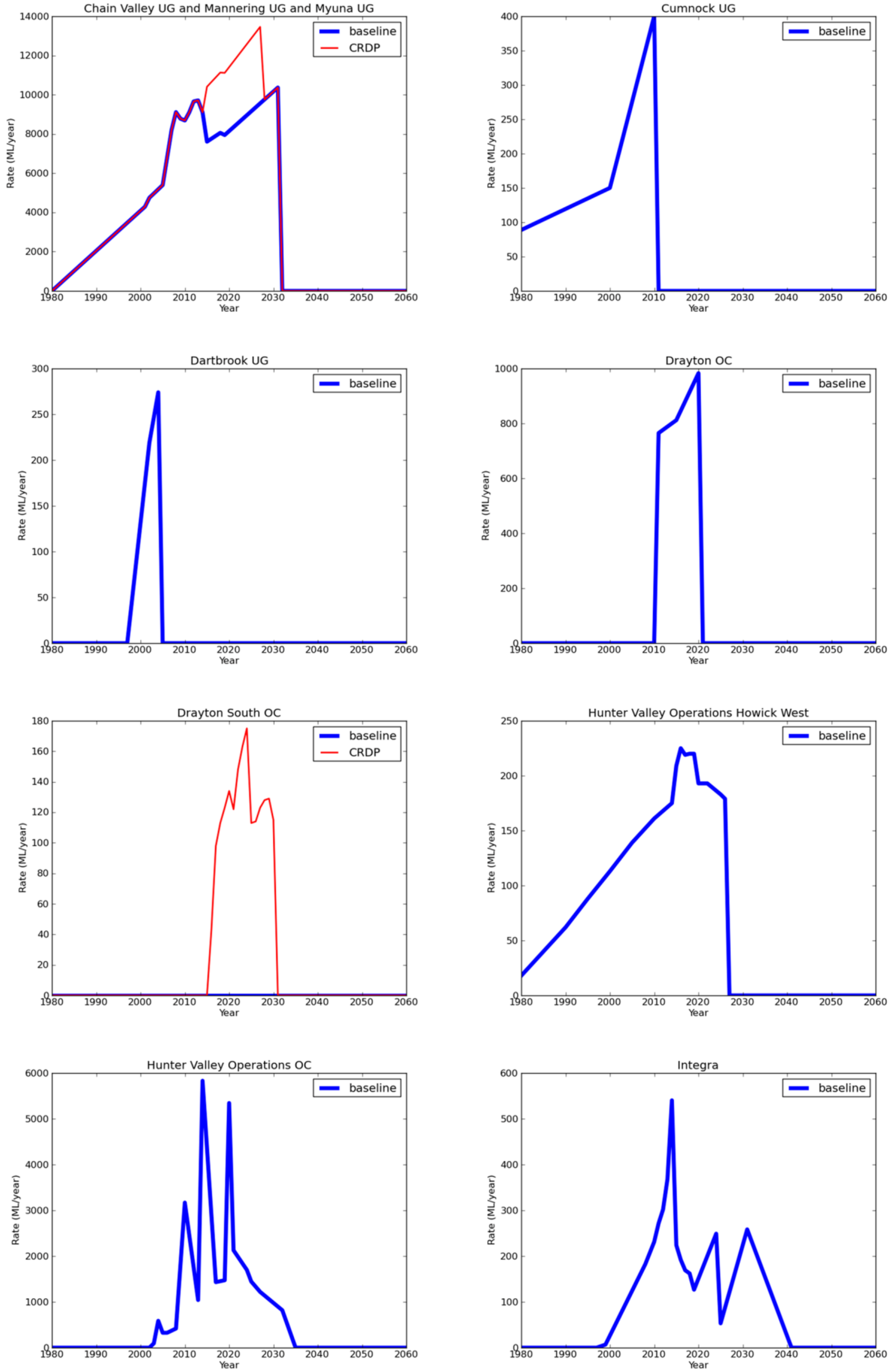


Figure 41 continued on following page

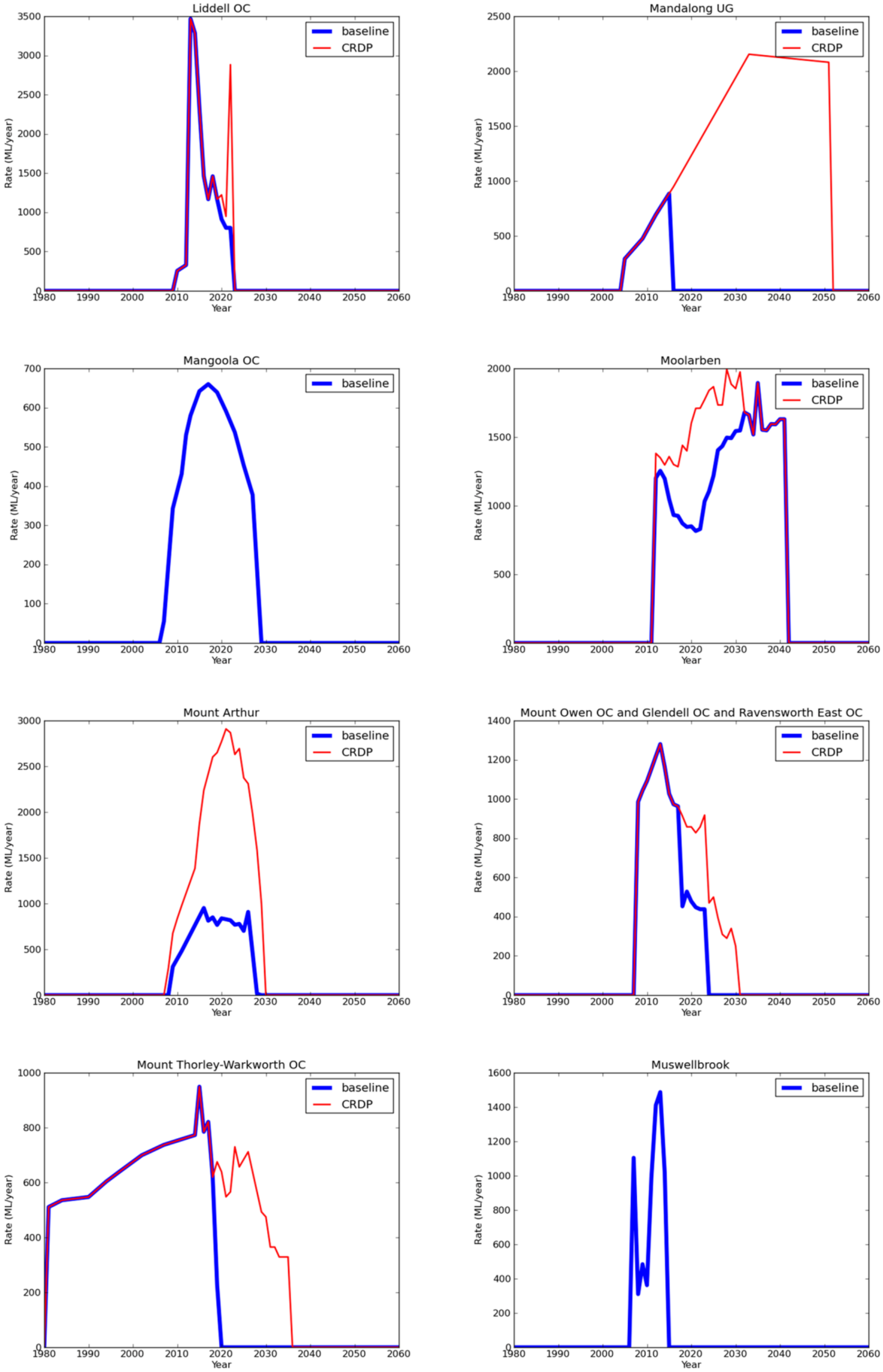


Figure 41 continued on following page

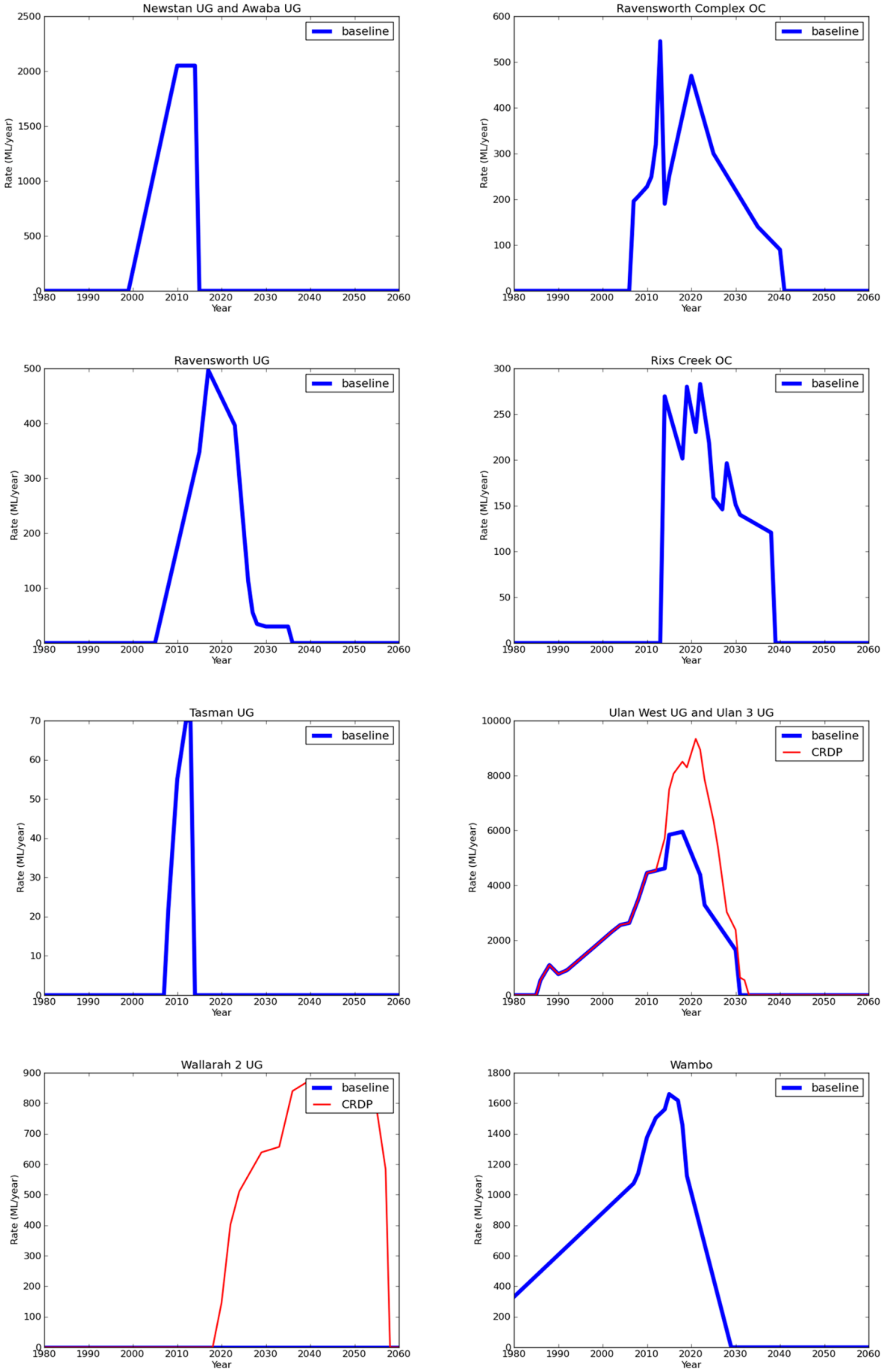


Figure 41 continued on following page

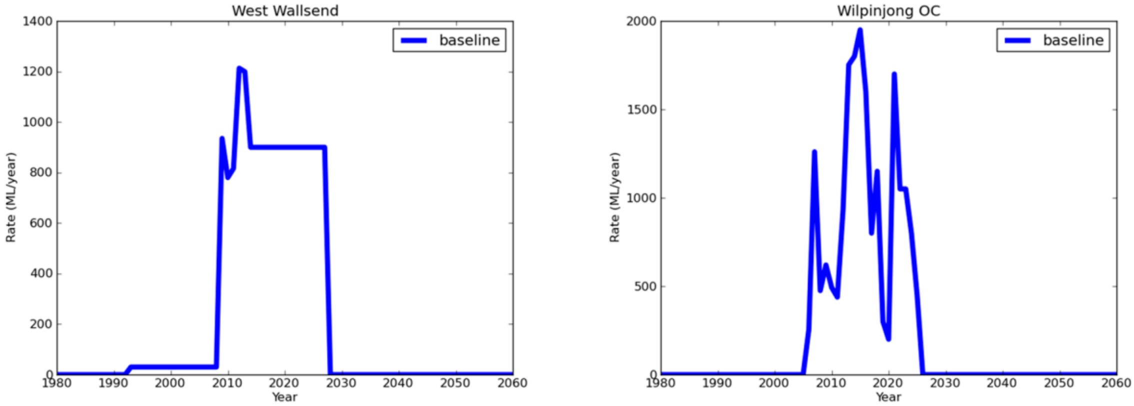


Figure 41 Time series graphs of open-cut and underground mine flow rates used in groundwater modelling

Mount Arthur UG was approved in 2008 and expected to start in 2009, which would have made it a baseline development. As mining did not commence prior to December 2012, it was classified as an ACRD. However, it was incorrectly modelled as starting in 2008. Where time series is composite of a number of mine workings, the maximum flow rate on the graph is not necessarily equal to the sum of the maxima of the individual workings given in Table 23 due to the maxima occurring in different years.
Data: Bioregional Assessment Programme (Dataset 22; Dataset 23; Dataset 24; Dataset 25)

2.1.6.4 Gaps

The Hunter subregion has a long history of mining. There are 42 baseline mines and 22 additional coal resource developments that have been represented in the numerical modelling. To quantify the effects that these developments have on regional-scale hydrology requires a significant investment of time, in terms of obtaining the relevant digital data from the mines and state agencies that produce or hold these data, sifting through the large number of environmental assessment documents produced by mining companies to extract relevant bits of information to inform the modelling, digitising maps and remotely sensed imagery to obtain footprint areas, undertaking analyses to determine patterns of change and rules for representing hydrological changes in the models and so on. Excluding those coal resource developments identified in companion product 2.3 (conceptual modelling) for the Hunter subregion (Dawes et al., 2018) as having insufficient data available to model, data have been obtained to represent the hydrological effect of every modelled mine. Thus gaps in the context of the mine water management data used in the numerical modelling relate to opportunities to improve the input datasets and better represent processes in the model beyond what was possible with the time and resources that were available. The following are where uncertainties could be reduced through acquiring more data and/or making better use of the available data:

- Mine footprint data – a range of sources of data and methods for defining areas where hydrology is affected by mining were relied upon, resulting in a dataset with considerable uncertainty in extent of areas affected hydrologically by mining over time. There is potential to improve footprint time series data through closer collaboration with mining companies and state agencies that have mining data to access more data, to better understand the available data (e.g. what it represents, purpose, provenance), to undertake quality assurance (e.g. method of mapping, scale of mapping) and to collate data from different sources into a combined dataset based on the foregoing.

- Final voids – use actual data from all sites with open-cut operations to define the final voids, rather than estimating from mines with data.
- Analysis of modelled flow rates (undertaken to determine water licence entitlement volumes) and actual flow rates data to determine extraction rates relative to licensed volume and drivers of use rates (e.g. climate).

Companion product 2.6.1 (surface water numerical modelling; Zhang et al. (2018)) and companion product 2.6.2 (groundwater numerical modelling; Herron et al. (2018)) for the Hunter subregion provide more details of the sources of uncertainty in representing the hydrological effects of coal resource development and implications for modelling results.

References

AECOM Australia Pty Ltd (2011a) Main Water Balance – Chain Valley Colliery continuation of mining. In: AECOM Australia Pty Ltd (2011) Environmental Assessment – Chain Valley Colliery domains 1 and 2 continuation project. LakeCoal Pty Ltd, Australia. Viewed 14 July 2014, https://majorprojects.affinitylive.com/public/67dd409499bdaf95431a191f5659ef13/Environmental%20Assessment_For%20Exhibition%2015July2011_%20Appendix%20F.pdf.

AECOM Australia Pty Ltd (2011b) Myuna Colliery extension of mining environmental assessment. Centennial Myuna Pty Ltd, Australia. Viewed 23 July 2014, http://data.centennialcoal.com.au/domino/centennialcoal/cc205.nsf/0/BD0FF0D8B99E797ECA257CA70013C3D4/$file/Myuna_EA_Volume_1.pdf.

AECOM Australia Pty Ltd (2015) Environmental Impact Statement Rix's Creek Mine – continuation of mining project. Bloomfield Collieries Pty Ltd, Australia. Viewed 02 November 2015, https://majorprojects.affinitylive.com/public/eef8fb95aacd5aa75c72f5ae1b3d50c8/01.%20Rix's%20Creek%20EIS_Main%20Report_Part%20A.pdf.

Aquaterra (2008a) Bloomfield Colliery completion of mining and rehabilitation – groundwater impact assessment. In: Business Environment (2008) Part 3A Environmental Assessment Project Application 07_0087. Bloomfield Collieries Pty Ltd, Australia. Viewed 13 July 2014, https://majorprojects.affinitylive.com/public/50eb3ae9bdbae0c400c84b1ff98de926/Appendix%20I1.pdf.

Aquaterra (2008b) Moolarben Stage 2 groundwater assessment. In: Wells Environmental Services and Coffey Natural Systems (2009) Moolarben Coal Project Stage 2 environmental assessment. Moolarben Coal Mines Pty Ltd, Australia. Viewed 21 July 2014, http://www.moolarbencoal.com.au/__documents/major-project-approvals/environmental-assessment-report/environmental-assessment-part-2/appendix/vol3_appendix-05---groundwater-assessment.pdf

Aquaterra (2009) Ashton South East Open Cut Project: hydrogeological impact assessment. In: Wells Environmental Services (2009) South East Open Cut Project and modification to the existing ACP consent environmental assessment report. Ashton Coal Operations Pty Ltd, Australia. Viewed 09 July 2014. http://www.ashtoncoal.com.au/Resources/Reports--Publications/Environmental-Assessments/South-East-Open-Cut-EA/VOL3_Appendix_05_Groundwater_Assessment.pdf.

Aquaterra (2010) Ashton Coal Mine 2009-2010 AEMR groundwater management report. In: Ashton Coal Operations Pty Ltd (2010) Annual Environmental Management Report 2009/2010. Ashton Coal Operations Pty Ltd, Australia. Viewed 12 August 2015, http://www.ashtoncoal.com.au/Resources/Reports--Publications/Annual-Environmental-Management-Reports/AEMR-2009-2010/Appendix_2_Aquaterra_003b_S56C_Final_signed.pdf.

Ashton Coal Operations Pty Ltd (2011) Annual environmental management report 2010/2011. Ashton Coal Operations Pty Ltd, Australia. Viewed 12 August 2015, http://www.ashtoncoal.com.au/Resources/Reports--Publications/Annual-Environmental-Management-Reports/AEMR-2010---2011/AEMR-2010-2011-Final-Full-Report.pdf.

Ashton Coal Operations Pty Ltd (2012) Annual environmental management report 2011/2012. Ashton Coal Operations Pty Ltd, Australia. Viewed 02 August 2013, http://www.ashtoncoal.com.au/Resources/Reports--Publications/Annual-Environmental-Management-Reports/AEMR-2012/AEMR-2011-12-Final-pdf.pdf.

Ashton Coal Operations Pty Ltd (2014) Ashton Coal Project annual environmental management report 2013. Ashton Coal Operations Pty Ltd, Australia. Viewed 09 July 2014, http://www.ashtoncoal.com.au/Resources/Reports--Publications/Annual-Environmental-Management-Reports/AEMR-2013/140323-AEMR-Compressed.pdf

Austar Coal Mine Pty Ltd (2010) Austar annual environmental management report July 2009 – June 2010. Austar Coal Mine Pty Ltd, Australia. Viewed 28 April 2015. http://www.austarcoalmine.com.au/Portals/3/pdfs/environment/AEMR_2009-2010/Austar_AEMR_2009-2010_MainText.pdf.

Austar Coal Mine Pty Ltd (2011) Austar annual environmental management report July 2010 – June 2011. Austar Coal Mine Pty Ltd, Australia. Viewed 28 April 2015. http://www.austarcoalmine.com.au/Portals/3/pdfs/environment/AEMR_2010-2011/Austar_AEMR_2010-2011_MainTextOnly.pdf.

Austar Coal Mine Pty Ltd (2012) Austar annual Environmental Management Report July 2011 – June 2012. Austar Coal Mine Pty Ltd, Australia. Viewed 28 April 2015. http://www.austarcoalmine.com.au/Portals/3/pdfs/environment/AEMR_2011-2012/Austar_AEMR_2011-2012_MainText.pdf.

Austar Coal Mine Pty Ltd (2013a) Austar annual environmental management report July 2012 – June 2013. Austar Coal Mine Pty Ltd, Australia. Viewed 10 July 2014. http://www.austarcoalmine.com.au/Portals/3/pdfs/environment/AEMR_2012-2013/Austar_AEMR_2012-2013_Final_Plans.pdf.

Austar Coal Mine Pty Ltd (2013b) Austar annual environmental management report July 2012 – June 2013 Plans. Austar Coal Mine Pty Ltd, Australia. Viewed 10 July 2014. http://www.austarcoalmine.com.au/Portals/3/pdfs/environment/AEMR_2012-2013/Austar_AEMR_2012-2013_Final_Plans.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2005) Wilpinjong Coal Project groundwater impact assessment. In: Resource Strategies Pty Ltd (2005) Wilpinjong Coal Project Environmental Impact Statement. Wilpinjong Coal Pty Ltd, Australia. Viewed 30 July 2014, https://majorprojects.affinitylive.com/public/e881fe0de90002f800209f3907d68070/Appendix%20B.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2006a) Drayton Mine Extension groundwater impact assessment. In: Hansen Bailey Pty Ltd (2006) Drayton Mine Extension environmental assessment. Anglo Coal Pty Ltd, Australia. Viewed 16 July 2014, https://majorprojects.affinitylive.com/public/ddb51456cb44fedb50b9de2e77963590/Drayton%20Extension%20EA%20-%20Appendix%20G%20-%20Groundwater%20Impact%20Asses.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2006b) Groundwater impact assessment – Mt Arthur Coal South Pit Extension Project. In: Umwelt Australia Pty Ltd (2007) Environmental Assessment – proposed South Pit Extension Project. Mt Arthur Coal, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/e93c0ef8fec22e5d52be20872c011844/Environmental%20Assessment%20-%20Appendix_8.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2007) Glennies Creek Open Cut Coal Mine groundwater assessment. Integra Coal Operations Pty Ltd, Australia. Viewed 17 July 2014, https://majorprojects.affinitylive.com/public/95fcb9daa7c571db0f7bc8362b40664b/36.%20Specialist%20Report%20Part%208_Groundwater.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2009) Mt Arthur Coal Consolidation Project groundwater impact assessment. In: Hansen Bailey (2009) Mt Arthur Consolidation Project environmental assessment. Hunter Valley Energy Coal Pty Ltd, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/f196ce49c659ca1b8cc6a44f574fdca8/Appendix%20N%20-%20Groundwater%20Impact%20Assessment.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2010) Warkworth Mine Extension groundwater impact assessment. In: EMM Consulting Pty Ltd (2010) Proposed Warkworth Extension Environmental Assessment. Warkworth Mining Ltd, Australia.

Australasian Groundwater and Environmental Consultants Pty Ltd (2012) Drayton South Coal Project groundwater impact assessment. In: Hansen Bailey Pty Ltd (2012) Drayton South Coal Project Environmental Assessment. Anglo American Metallurgical Coal Pty Ltd, Australia. Viewed 16 July 2014, https://majorprojects.affinitylive.com/public/db910da08494f5ea321972c4796bd6b1/54.%20Drayton%20South%20-%20EA%20Appendix%20N%20-%20Ground%20Water%20Impact%20Assessment.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2013a) Continuation of Bengalla Mine groundwater impact assessment. In: Hansen Bailey Pty Ltd (2013) Continuation of Bengalla Mine Environmental Impact Statement. Bengalla Mining Company Pty Ltd, Australia. Viewed 13 July 2014, https://majorprojects.affinitylive.com/public/3d43968a8b1f343136700553308 90b92/12.%20Bengalla%20Continuation%20Project%20-%20EIS%20-%20Appendix%20K%20-%20Groundwater.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2013b) Bylong Coal Project gateway groundwater study. In: Hansen Bailey Pty Ltd (2014) Bylong Coal Project Gateway Certificate Application. KEPCO Bylong Australia Pty Ltd, Australia. Viewed 30 July 2014, https://majorprojects.affinitylive.com/public/2a250871394bd4a75fb2c3cdc7d81494/Appendix%20E%20Groundwater%20Impact%20Assessment%20Part%201.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2013c) Mt Arthur Coal Open Cut modification groundwater impact assessment. In: Resource Strategies Pty Ltd (2013) Mt Arthur Coal Open Cut Modification – environmental assessment. BHP Billiton, Australia. Viewed 06 June 2013, https://majorprojects.affinitylive.com/public/245a7605de39c581680e259d8e707818/05.%20Mt%20Arthur%20Coal%20Open%20Cut%20-%20Mod%201%20-%20EA%20-%20Appendix%20B%20-%20Groundwater%20Impact%20Assessment.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2013d) Narama West Modification groundwater impact assessment. In: Hansen Bailey (2013) Narama West modification environmental assessment. Xstrata Coal Pty Ltd, Australia. Viewed 28 July 2014, https://majorprojects.affinitylive.com/public/1233557dcf7b5d1b6a35b1927e14e1d9/11.%20Ravensworth%20Operations%20Project%20%20Mod%201%20EA%20-%20Appendices%20A%20-%20D.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2014a) Mount Thorley operations 2014 groundwater assessment. In: EMM Consulting Pty Ltd (2014) Mount Thorley Operations 2014 Environmental Impact Statement. Mt Thorley Operations Pty Ltd, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/b71d63e8a389ed1e767c8508dc070e0b/17.%20Mt%20Thorley%20Continuation%20Project%20EIS%20-%20Appendix%20I%20Groundwater.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2014b) Warkworth Continuation 2014 groundwater assessment. In: EMM Consulting Pty Ltd (2014) Warkworth Continuation 2014 Environmental Impact Statement. Warkworth Mining Ltd, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/58ec858f4e1ee0d44ad2dfbee414f60f/20.%20Warkworth%20Continuation%20Project%20EIS%20-%20Appendix%20K%20Groundwater.pdf.

Australasian Groundwater and Environmental Consultants Pty Ltd (2015) Drayton South Coal Project EIS – groundwater impact assessment. In: Hansen Bailey Pty Ltd (2015) Drayton South Coal Project Environmental Impact Assessment. Anglo American Metallurgical Coal Pty Ltd, Australia. Viewed 15 May 2015, https://majorprojects.affinitylive.com/public/3dfcb8accd7fc1a98909303f94a0c04b/26.%20Drayton%20South%20Coal%20Project%20-%20EIS%20Appendix%20R%20-%20Groundwater%20Impact%20Assessment%20-%20Part%201%20of%204.pdf.

Bengalla Mining Company Pty Ltd (2014) Annual environmental management report (annual review) January – December 2013. Bengalla Mining Company Pty Ltd, Australia. Viewed 13 July 2014, http://www.bengalla.com.au/wp-content/uploads/2016/01/BMC%20Annual%20Review%202013.pdf.

Centennial Coal Company Ltd (2012) Northern Coal Services Coal Logistics Project briefing paper. Centennial Coal Company Ltd, Australia.

Centennial Mannering Pty Ltd (2012) Mannering Colliery water management plan. Centennial Mannering Pty Ltd, Australia. Viewed 21 July 2014, http://manneringmine.com.au/wp-content/uploads/2012/04/Mannering-Water-Management-Plan.pdf.

Coal and Allied (1997) Mount Pleasant Mine Environmental Impact Statement. Coal and Allied, Australia. Viewed 22 July 2014, http://www.riotinto.com/documents/_Energy/1997_MTP_EIS_Figures.pdf.

Connell Wagner Pty Ltd (2007) Future mine development groundwater impact assessment Austar Coal Mine. In: Umwelt Australia Pty Ltd (2008) Austar Coal Mine Project – stage 3 environmental assessment. Austar Coal Mine Pty Ltd, Australia. Viewed 10 July 2014, https://majorprojects.affinitylive.com/public/d97cde70cfaae500320be6bbe3218103/Appendix%2014.pdf.

Cumberland Ecology (2010) Mount Pleasant Project modification ecological assessment. In: EMM Consultants Pty Ltd (2010) Mount Pleasant Project modification environmental assessment. Coal and Allied Operations Pty Ltd, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/081c84b24142f43c64b517f3db95581c/Environmental%20Assessment%20-%20Volume%202.pdf.

Dawes WR, Herron NF, Macfarlane C, Rachakonda PK, Henderson BL, Ford JH, Wilkes PG, Marvanek SP, Ramage A (2018) Conceptual modelling for the Hunter subregion. Product 2.3 for the Hunter 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/HUN/2.3.

Ditton Geotechnical Services Pty Ltd (2013) Subsidence predictions and general impact assessment for the Mandalong South Extension Project. In: GSS Environmental (2013) Mandalong Southern Extension Project Environmental Impact Statement. Centennial Mandalong Pty Ltd, Australia. Viewed 19 July 2014, https://majorprojects.affinitylive.com/public/ffc4d2c1269901efb2469b37df1a4065/51.%20Mandalong%20Southern%20Extension%20_%20EIS%20_%20Appendix%20M%20_%20Subsidence%20Assessment_%20Figures%201-10.pdf.

Donaldson Coal Pty Ltd (2011) March 2011 modification (Upcast ventilation shaft) environmental assessment. Donaldson Coal Pty Ltd, Australia. Viewed 14 July 2013, https://majorprojects.affinitylive.com/public/94e2a1f0be671dd9f338b1c13b5fbbe8/Abel%20-%20Environmental%20Assessment.pdf.

Donaldson Coal Pty Ltd (2013) Abel Mine subsidence management plan end of year report 2012. Donaldson Coal Pty Ltd, Australia. Viewed 26 August 2013, http://www.doncoal.com.au/documents/community_environment/abel/subsidence_reports/Abel_SMP_End_of_Year_Report_2012.pdf.

EMM Consulting Pty Ltd (2014) Mannering Colliery – modification 2 environmental assessment. LakeCoal Pty Ltd, Australia. Viewed 23 September 2014, https://majorprojects.affinitylive.com/public/4714413fa6e34947fd9eff7a49d6ebb8/Mannering%20Colliery%20Mod%202_Environmental%20Assessment.pdf.

Environmental Resources Management Australia Pty Ltd (2008) Hunter Valley Operations South Coal Project environmental assessment report. Coal and Allied Operations Pty Ltd, Australia. Viewed 16 July 2014, https://majorprojects.affinitylive.com/public/85b250917eae1059930ed29e4a1715f4/Environmental%20Assessment.pdf.

Environmental Resources Management Australia Pty Ltd (2009) Proposed Integra Underground Coal Project environmental assessment. Integra Coal Operations Pty Ltd, Australia. Viewed 17 July 2014, http://c.cld.pw/127/cms/files/IntegraUndergroundEA-Volume1(1).pdf.

Geoscience Australia (2015) Australian Geoscience Data Cube. Viewed 04 December 2015, http://www.datacube.org.au/.

GeoTerra Pty Ltd (2009a) Integra Open Cut Project and Open Cut extension Groundwater assessment. In: URS Australia (2009) Environmental assessment – Integra Open Cut Project. Integra Coal Operations Pty Ltd, Australia. Viewed 14 July 2014, http://www.bloomcoll.com.au/Portals/5/Files/RixsCreekNorth/INTEGRA%20COMPLEX/Integra%20Open%20Cut%20Project%20EA%202009/Volume%202/AppendixCGroundwater.pdf.

GeoTerra Pty Ltd (2009b) Underground project area groundwater assessment, Integra Underground NSW. In: Integra Coal Operations Pty Ltd (2009) Proposed Integra Underground Coal Project environmental assessment. Integra Coal Operations Pty Ltd, Australia. Viewed 17 July 2014, http://c.cld.pw/127/cms/files/integraeaannexg(1).pdf.

GeoTerra Pty Ltd (2013) Mining Extension 1 Groundwater Assessment. In: EMM Consulting Pty Ltd (2013) Chain Valley Colliery Mining Extension 1 Project Environmental Impact Assessment. LakeCoal Pty Ltd, Australia. Viewed 14 July 2014, https://majorprojects.affinitylive.com/public/301b449d975d17e6f14df99f291d4823/2.%20Chain%20Valley%20Colliery%20Mining%20Extension%201%20Project%20-%20EIS%20-%20Appendices%20D%20to%20G%20-%20Groundwater%20Impact%20Assessment,%20Surface%20Water%20Impact%20Assessment,%20Noise%20Impact%20Assessment%20and%20Air%20Quality%20and%20Greenhouse%20Gas%20Impact%20Assessment.pdf.

GHD Pty Ltd (2010a) Myuna Colliery water management assessment. In: AECOM Australia Pty Ltd (2011a) Myuna Colliery extension of mining environmental assessment. Centennial Myuna Pty Ltd, Australia. Viewed 23 July 2014, https://majorprojects.affinitylive.com/public/fb0ec80491fa7dacf7e99bcaaf6d9ab9/EA%20Volume%202_%20Appendix%20G.pdf.

GHD Pty Ltd (2010b) Newstan S75W modification groundwater impact assessment. In: GSS Environmental (2011) Newstan Colliery Main West Mining Project, Section 75W modification environmental assessment. Centennial Coal Company Ltd, Australia. Viewed 13 July 2014, https://majorprojects.affinitylive.com/public/4cd3c9f60c6d85f9b94f783690d95eb1/Main%20West%20Mining%20Project_Appendix%206_Groundwater%20Impact%20Assessment.pdf.

GHD Pty Ltd (2013) Mandalong Southern Extension Project groundwater impact assessment. In: GSS Environmental (2013) Mandalong Southern Extension Project Environmental Impact Statement. Centennial Mandalong Pty Ltd, Australia. Viewed 19 July 2014, https://majorprojects.affinitylive.com/public/fed9ca81637797bdb6474953874076fb/43.%20Mandalong%20Southern%20Extension%20_%20EIS%20_%20Appendix%20H%20_%20Groundwater%20Impact%20Assessment_%20Part%201%20main%20text.pdf.

Gilbert and Associates (2005) Wilpinjong Coal Project surface water assessment. In: Resource Strategies Pty Ltd (2005) Wilpinjong Coal Project Environmental Impact Assessment. Wilpinjong Coal Pty Ltd, Australia. Viewed 30 July 2014, https://majorprojects.affinitylive.com/public/313747bc02f1e3e8b4ffc90b5a413967/Appendix%20A.pdf.

Gilbert and Associates Pty Ltd (2009) Mt Arthur Coal Consolidation Project surface water assessment. In: Hansen Bailey (2009) Mt Arthur Consolidation Project environmental assessment. Hunter Valley Energy Coal Pty Ltd, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/75d7843736334fb1953b947dba47c74c/Appendix%20M%20-%20Surface%20Water%20Impact%20Assessment.pdf.

Gilbert and Associates Pty Ltd (2013a) Liddell Coal Mine modification 5 surface water assessment. In: SLR Consulting (2013) Proposed modification to DA 305-11-01 environmental assessment. Liddell Coal Operations, Australia. Viewed 19 July 2014, https://majorprojects.affinitylive.com/public/bc44c3b98e402eddd7bf9932e07f3184/Liddell%20Coal%20Mine%20Mod%205%20EA%20-%20Appendix%20K.pdf.

Gilbert and Associates Pty Ltd (2013b) Mt Arthur Coal open cut modification surface water assessment. In: Resource Strategies Pty Ltd (2013) Mt Arthur Coal open cut modification – environmental assessment. BHP Billiton, Australia. Viewed 06 June 2013, https://majorprojects.affinitylive.com/public/c1cad5c77feec12975bd91acb91f01a9/06.%20Mt%20Arthur%20Coal%20Open%20Cut%20-%20Mod%201%20-%20EA%20-%20Appendix%20C%20-%20Surface%20Water%20Assessment.pdf.

Gilbert and Associates Pty Ltd (2013c) Wilpinjong Coal Mine modification surface water assessment. In: Resource Strategies Pty Ltd (2013) Environmental assessment. Wilpinjong Coal Pty Ltd, Australia. Viewed 30 July 2014, https://majorprojects.affinitylive.com/public/42d22c0da84411c1bb157de3bc85b61e/08.%20Wilpingjong%20Coal%20Mine%20Mod%205%20EA%20-%20Appendix%20D%20-%20Surface%20Water%20Assessment.pdf.

Glencore (2014a) Mt Owen Complex groundwater monitoring program. Glencore, Australia. Viewed 02 February 2015, http://www.mtowencomplex.com.au/EN/EnvironmentalManagement/Plans%20and%20Programs/MOC%20Groundwater%20Monitoring%20Program%20August%202014%20with%20Approval%20Ltr.pdf.

Glencore (2014b) West Wallsend Colliery annual review 2013. Glencore, Australia. Viewed 29 July 2014, http://www.westwallsendmine.com.au/EN/Publications/AMER/WWC%202013%20Annual%20Review.pdf.

Glencore (2014c) West Wallsend Colliery surface water management plan. Glencore, Australia.

GSS Environmental (2011) Newstan Colliery Main West Mining Project Section 75W modification environmental assessment. Centennial Coal Company Ltd, Australia. Viewed 13 July 2014, https://majorprojects.affinitylive.com/public/7584657a737a70dca1655e7e6363dd39/Main%20West%20Mining%20Project_Environmental%20Assessment_Main%20Text_Part%201.pdf.

GSS Environmental (2012) Mannering Colliery – extension of Mine Project, Section 75W modification to Project Approval 06_0311. Centennial Mannering Pty Ltd, Australia. Viewed 21 July 2014, https://majorprojects.affinitylive.com/public/1d6c820daeeb78076811cdba9834a9d9/%20Manning%20Underground%20Coal%20Project%20%20MOD%201%20-%20EA_Final%20Vol-1%20.pdf.

GSS Environmental (2013) Mandalong Southern Extension Project Environmental Impact Statement. Centennial Mandalong Pty Ltd, Australia. Viewed 19 July 2014, https://majorprojects.affinitylive.com/public/dbffc4df1cecdee499610de29968f768/04.%20Mandalong%20Southern%20Extension%20_%20EIS%20_%20Section%204%20_%20The%20Project.pdf.

Hansen Bailey Pty Ltd (2006) Drayton Mine extension environmental assessment. Anglo Coal Pty Ltd, Australia. Viewed 16 July 2014, https://majorprojects.affinitylive.com/public/472a349dc5fe2584d0800263a9dce04d/Drayton%20Extension%20EA%20-%20Appendix%20I%20-%20Surface%20Water%20Impact%20Ass.pdf.

Hansen Bailey Pty Ltd (2007) Mannering Colliery continuation of mining environmental assessment. Centennial Coal Company Ltd, Australia. Viewed 21 July 2014, http://manneringmine.com.au/wp-content/uploads/2012/02/Mannering-Colliery-EA-March-2007.pdf.

Hansen Bailey Pty Ltd (2010) Bulga Coal Complex, modification to development consent (DA 41-03-99) environmental assessment. Bulga Coal Management Pty Ltd, Australia. Viewed 14 July 2014, https://majorprojects.affinitylive.com/public/7877902cab2e418b1269870bbb5c505a/Environmental%20Assessment.pdf.

Hansen Bailey Pty Ltd (2012) Drayton South Coal Project environmental assessment. Anglo American Metalluirgical Coal Pty Ltd, Australia. Viewed 16 July 2014, https://majorprojects.affinitylive.com/public/67303a74077d2d49f3bef2e45d6197a1/40.%20Drayton%20South%20-%20EA%20Main%20Report.pdf.

Hansen Bailey Pty Ltd (2014) Bengalla Mine development consent modification environmental assessment. Bengalla Mining Company Pty Ltd, Australia. Viewed 13 July 2014, https://majorprojects.affinitylive.com/public/bd57b165cf178cd53a4a99674ff30595/Bengalla%20Coal%20Mine%20-%20Mod%205%20EA.pdf.

Hansen Bailey Pty Ltd (2015) Drayton South Coal Project environmental impact assessment. Anglo American Metallurgical Coal Pty Ltd, Australia. Viewed 15 May 2015, https://majorprojects.affinitylive.com/public/ccde96716b77f3b187d413b619a48fb9/02.%20Drayton%20South%20Coal%20Project%20-%20EIS%20Main%20Report.pdf.

Herron NF, Peeters L, Crosbie R, Marvanek SP, Pagendam D, Ramage A, Rachakonda PK and Wilkins A (2018) Groundwater numerical modelling for the Hunter subregion. Product 2.6.2 for the Hunter 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/HUN/2.6.2.

HydroSimulations (2013a) Spur Hill Underground Coking Coal Project gateway application preliminary groundwater assessment. Spur Hill Management Pty Ltd, Australia. Viewed 30 July 2014, https://majorprojects.affinitylive.com/public/931cc92f489d8b317f01c261cf0903af/Appendix%20C_%20Preliminary%20Groundwater%20Assessment%20Part%20B.pdf.

HydroSimulations (2013b) Wilpinjong Coal Mine modification groundwater assessment. In: Resource Strategies Pty Ltd (2013) Environmental Assessment. Wilpinjong Coal Pty Ltd, Australia. Viewed 30 July 2014, https://majorprojects.affinitylive.com/public/6eaf5251427c54d30474e286a7bee9aa/07.%20Wilpingjong%20Coal%20Mine%20Mod%205%20EA%20-%20Appendix%20C%20-%20Groundwater%20Assessment.pdf.

HydroSimulations (2014) North Wambo Underground Mine longwall 10A modification groundwater assessment. In: Resource Strategies Pty Ltd (2014) North Wambo Underground Mine Longwall 10A Modification Environmental Assessment. Wambo Coal Pty Ltd, Australia. Viewed 03 October 2014, https://majorprojects.affinitylive.com/public/dd37cf489a7f2cbd6c10ac0196c69d65/05.%20Wambo%20Mine%20-%20Mod%2014%20-%20EA%20Appendix%20B%20-%20Groundwater%20Assessment.pdf.

Jacobs Group Australia Pty Ltd (2014) Groundwater impact assessment. In: Umwelt Australia Pty Ltd (2014) Mount Owen Continued Operations Project Environmental Impact Statement. Glencore, Australia. Viewed 20 January 2015, https://majorprojects.affinitylive.com/public/ccc1d746b60afb9cfb4f9c19df4a9365/11.%20MOCO%20Project%20-%20EIS%20-%20Appendix%2010%20-%20Groundwater%20Impact%20Assessment.pdf.

LakeCoal Pty Ltd (2014) Chain Valley Colliery annual review 2013. LakeCoal Pty Ltd, Australia. Viewed 14 July 2014, http://www.chainvalleymine.com.au/wp-content/uploads/2012/04/RPT-D-18710-Annual-Review-2013-V2.pdf.

Mackie Environmental Research (2002) Extension of Warkworth Coal Mine assessment of environmental impacts, surface and groundwater management studies. Warkworth Mining Ltd, Australia. 22 July 2014, http://www.riotinto.com/documents/_Energy/Volume%202%20Reduced_Part2.pdf.

Mackie Environmental Research (2003) Hunter Valley Operations West Pit Extension and minor modifications surface and groundwater management studies. In: Environmental Resources Management Australia Pty Ltd (2003) Hunter Valley Operations West Pit Extension and Minor Modifications Environmental Impact Statement. Coal and Allied Operations Pty Ltd, Australia.

Mackie Environmental Research (2006) Anvil Hill Project: groundwater management studies. In: Umwelt Australia Pty Ltd (2006) Anvil Hill Project Environmental Assessment. Centennial Hunter Pty Ltd, Australia. Viewed 21 July 2014, https://majorprojects.affinitylive.com/public/15987e1d6effbca80892d85cb7626029/Environmental%20Assessment-Appendix08-Groundwater.pdf.

Mackie Environmental Research (2007) Mt Arthur Underground Project environmental assessment groundwater management studies. In: Umwelt Australia Pty Ltd (2008a) Environmental Assessment – Proposed Mt Arthur Underground Project. Mt Arthur Coal, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/9ad1dee23acc3ae056741dbf6ad64918/EA%20-%20Appendix%2010.pdf.

Mackie Environmental Research (2009) Groundwater management studies – Ravensworth Operations Project. In: Umwelt Australia (2010) Ravensworth Operations Project Environmental Assessment. Ravensworth Operations Pty Ltd, Australia. Viewed 28 July 2014, http://www.ravensworthoperations.com.au/EN/Publications/EAs/Appendix_9_Groundwater_Part-A_MainText.pdf.

Mackie Environmental Research (2010) Carrington West Wing modification groundwater assessment. In: EMM Consultants Pty Ltd (2010) Carrington West Wing Environmental Assessment. Coal and Allied Operations Pty Ltd, Australia. Viewed 16 July 2014, https://majorprojects.affinitylive.com/public/bb5a8779cce7451c49d761140dd148a8/Environmental%20Assessment%20-%20Volume%202.pdf.

Mackie Environmental Research (2011) Ulan Coal Mines Ltd – continued operations, North 1 modifications – groundwater assessment. In: Umwelt Australia Pty Ltd (2011a) Environmental Assessment, Modification of Ulan Coal – Continued Operations, North 1 Underground Mining Area, Minor Modifications to Ulan No. 3 and Ulan West Mine Plans and Proposed Concrete Batching Plant. Ulan Coal Mines Ltd, Australia. Viewed 28 January 2015, http://ulancoal.com.au/EN/OperatingApprovals/Documents/Appendix%203_Pt4.pdf.

Mackie Environmental Research (2012) Ravensworth Underground Mine assessment of groundwater impacts associated with modifications to mining in the Liddell Seam. In: GSS Environmental (2012) Ravensworth Underground Mine Liddell Seam Project Environmental Assessment. Resource Pacific Pty Ltd, Australia. Viewed 23 July 2014, https://majorprojects.affinitylive.com/public/0af26ab31468881603c69c173753746b/13.%20RUM_Mod%209_EA%20Appendix%20L%20-%20Groundwater%20Assessment.pdf.

Mackie Environmental Research (2013a) Assessment of groundwater related impact arising from the proposed Bulga Optimisation Project. In: Umwelt Australia Pty Ltd (2013) Bulga Optimisation Project Environment Assessment. Bulga Coal Management Pty Ltd, Australia. Viewed 14 July 2014, https://majorprojects.affinitylive.com/public/6e2fb2159f4932120372285de06881a7/12.%20Bulga%20Optimisation%20Project%20-%20EIS%20Appendix_11%20Groundwater%20Impact%20Assessment.pdf.

Mackie Environmental Research (2013b) Wallarah 2 Coal Project groundwater impact assessment. In: Hansen Bailey (2013) Wallarah 2 Coal Project Environmental Impact Statement. Wyong Areas Coal Joint Venture, Australia. Viewed 12 August 2014, https://majorprojects.affinitylive.com/public/4af1d9804380abfb6c9412514c24030f/10.%20Wallarah%202%20Coal%20Project%20EIS%20-%20Appendix%20I%20-%20Groundwater%20Impact%20Assessment.pdf.

Mackie Environmental Research (2015) Assessment of groundwater related impact arising from modifications to the Ulan West Mine Plan. In: Umwelt Australia Pty Ltd (2015) Ulan West Modification Environmental Assessment. Ulan Coal Mines Ltd, Australia. Viewed 20 March 2015, https://majorprojects.affinitylive.com/public/d7f1de331598005a6896a36a051d22e2/Appendix%203_%20Groundwater.pdf.

Mine Subsidence Engineering Consultants Pty Ltd (2007) Subsidence assessment. In: Umwelt Australia Pty Ltd (2008a) Environmental assessment – proposed Mt Arthur Underground Project. Mt Arthur Coal, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/a63dfd8b2d1f01098187983ea9e995d4/EA%20-%20Appendix%205.pdf.

Muswellbrook Coal Company Ltd (2007) Annual environmental management report (AEMR) 1 July 2006 to 30 June 2007. Muswellbrook Coal Company Ltd, Australia. Viewed 24 April 2015, https://idemitsu.com.au/uploads/files/Mccenviro/Env_Reports/MCC_OC_Extension_2006_2007_AEMR.pdf.

Muswellbrook Coal Company Ltd (2008) Annual environmental management report (AEMR) 1 July 2007 to 30 June 2008. Muswellbrook Coal Company Ltd, Australia. Viewed 24 April 2015, https://idemitsu.com.au/uploads/files/Mccenviro/Env_Reports/MCC_OC_Extension_2007_2008_AEMR.pdf.

Muswellbrook Coal Company Ltd (2009) Annual environmental management report (AEMR) 1 July 2008 to 30 June 2009. Muswellbrook Coal Company Ltd, Australia. Viewed 24 April 2015, https://idemitsu.com.au/uploads/files/Mccenviro/Env_Reports/MCC_OC_Extension_2008_2009_AEMR.pdf.

Muswellbrook Coal Company Ltd (2010) Annual environmental management report (AEMR) 1 July 2009 to 30 June 2010. Muswellbrook Coal Company Ltd, Australia. Viewed 23 July 2014, https://idemitsu.com.au/uploads/files/Mccenviro/Env_Reports/MCC_OC_Extension_2009_2010_AEMR.pdf.

Muswellbrook Coal Company Ltd (2011) Annual environmental management report 1 July 2010 to 30 June 2011. Muswellbrook Coal Company Ltd, Australia. Viewed 24 April 2015, https://idemitsu.com.au/uploads/files/Mccenviro/Env_Reports/MCC_OC_Extension_2010_2011_AEMR.pdf.

Muswellbrook Coal Company Ltd (2012) Annual environmental management report 1 July 2011 to 30 June 2012. Muswellbrook Coal Company Ltd, Australia. Viewed 23 July 2014, https://idemitsu.com.au/uploads/files/MCC_OC_Extension_2011_2012_AEMR.pdf.

Muswellbrook Coal Company Ltd (2013) 2012 – 2013 annual environmental management report. Muswellbrook Coal Company Ltd, Australia. Viewed 23 July 2014, https://idemitsu.com.au/uploads/files/Mccenviro/Env_Reports/2012_13_AEMR_FINAL.pdf.

Muswellbrook Coal Company Ltd (2014) 2013 – 2014 annual environmental management report. Muswellbrook Coal Company Ltd, Australia. Viewed 24 April 2015, https://idemitsu.com.au/uploads/files/Mccenviro/Env_Reports/2013_14_AEMR_FINAL.pdf.

NSW Department of Planning (2002) Dartbrook Underground Coal Mine – proposed modification to development consent – planning report on the assessment of a modification application lodged pursuant to Section 96(2) of the Environmental Planning and Assessment Act 1979. NSW Department of Planning, Australia. Viewed 31 July 2014, https://majorprojects.affinitylive.com/public/6b70322b5337e48c48a2cca259cf6264/pr_dartbrook.pdf.

NSW Department of Planning (2005) Assessment report, proposed modification to the Dartbrook Coal Mine development consent. NSW Department of Planning, Australia. Viewed 31 July 2014, https://majorprojects.affinitylive.com/public/cb34023592b1dc76b41ae221188bcb17/mod129-8-2005_ass_rep.pdf.

NSW Department of Planning and Infrastructure (2011) Major project assessment Awaba Colliery Mining Project Director-General's Environmental Assessment Report. NSW Department of Planning and Infrastructure, Australia. Viewed 21 August 2014, https://majorprojects.affinitylive.com/public/9b5d741d78f7336cea085194587a5107/Director-General's%20Assessment%20Report.pdf.

NSW Department of Planning and Infrastructure (2012) Ashton South East Open Cut Project – conditions of approval. NSW Department of Planning and Infrastructure, Australia.

NSW Department of Planning and Infrastructure (2013a) Abel Coal Project longwall mining modification (05_0136 MOD 3) environmental assessment report. NSW Department of Planning and Infrastructure, Australia. Viewed 14 July 2014, https://majorprojects.affinitylive.com/public/9c28b7e48cb6a3e4d8da7bf71ef2de26/Abel%20Coal%20Project%20MOD%203_%20Environmental%20Assessment%20Report.pdf.

NSW Department of Planning and Infrastructure (2013b) Major Project Assessment Chain Valley Extension Project (SSD 5465) environmental assessment report. NSW Department of Planning and Infrastructure, Australia. Viewed 14 July 2014, https://majorprojects.affinitylive.com/public/2bf8c63e051930c064c4cd3f9306034d/Chain%20Valley%20Extension%20Project%20-%20Director-General's%20Report.pdf.

NSW Department of Planning and Infrastructure (2014) Preliminary assessment: Wallarah 2 Coal Project (SSD-4974). NSW Department of Planning and Infrastructure, Australia. Viewed 12 August 2014, https://majorprojects.affinitylive.com/public/bf9566e255af9fca7542353eaf893476/1.%20Wallarah%202%20Coal%20Project%20Assessment%20Report.pdf

Patterson Britton and Partners Ltd (2006) Moolarben Coal Project surface water management strategy. In: Wells Environmental Services (2006) Moolarben Coal Project environmental assessment report. Moolarben Coal Mines Pty Ltd, Australia. Viewed 22 October 2015, https://majorprojects.affinitylive.com/public/a0c8c02150f18f2c6a95762d00452018/APPENDIX%2006%20SURFACE%20WATER%20ASSESSMENT.pdf.

Pegasus Technical (2009a) Plan 5 – conceptual staged mining layout and rehabilitation as at 2010. In: RW Corkery and Co Pty Ltd (2009) Mining Operations Plan for the Integra North Open Cut Coal Mine. Viewed 28 May 2015, http://digsopen.minerals.nsw.gov.au/?rin=R00036926.

Pegasus Technical (2009b) Plan 7 – vertical sections. In: RW Corkery and Co Pty Ltd (2009) Mining operations plan for the Integra North Open Cut Coal Mine. Viewed 28 May 2015, http://digsopen.minerals.nsw.gov.au/?rin=R00036926.

Pegasus Technical (2009c) Moolarben Coal Project Plan 16 – environmental monitoring and weather station locations. In: Wells Environmental Services and Coffey Natural Systems (2009) Moolarben Coal Project Stage 2 Environmental Assessment Report. Moolarben Coal Mines Pty Ltd, Australia. Viewed 21 July 2014, http://www.moolarbencoal.com.au/__documents/major-project-approvals/environmental-assessment-report/environmental-assessment-part-2/volume-2/plan-16.pdf.

Pegasus Technical (2009d) Moolarben Coal Project Plan 30 – hydrogeological units piezometers. In: Wells Environmental Services and Coffey Natural Systems (2009) Moolarben Coal Project Stage 2 environmental assessment report. Moolarben Coal Mines Pty Ltd, Australia. Viewed 21 July 2014, http://www.moolarbencoal.com.au/__documents/major-project-approvals/environmental-assessment-report/environmental-assessment-part-2/volume-2/plan-30.pdf.

RW Corkery and Co Pty Ltd (2010) Mining operations plan amendment 1 for the Integra North Open Cut Coal Mine. Integra Coal Operations Pty Ltd, Australia. Viewed 17 July 2014, http://www.vale.com/australia/EN/aboutvale/regulatory-reports/integra-open-cut-regulatory-information/Mining%20Operations%20Plan/Integra%20Open%20Cut%20-%20Mining%20Operations%20Plan%20Amendment%201%20Part%201.pdf.

RW Corkery and Co Pty Ltd (2012a) Annual Environmental Management Report for the Abel Underground Coal Mine 1 June 2011 to 31 May 2012. Donaldson Coal Pty Ltd, Australia. Viewed 26 August 2013, http://www.doncoal.com.au/documents/community_environment/abel/AEMR/2012/73707_AEMR.pdf.

RW Corkery and Co Pty Ltd (2012b) Annual Environmental Management Report for the Tasman Underground Coal Mine 1 June 2011 to 31 May 2012. Newcastle Coal Company Pty Ltd, Australia. Viewed 26 August 2013, http://www.doncoal.com.au/documents/community_environment/tasman/AEMR/2012/67709_AEMR.pdf.

RW Corkery and Co Pty Ltd (2013) Annual Environmental Management Report for the Tasman Underground Coal Mine 1 June 2012 to 31 May 2013. Newcastle Coal Company Pty Ltd, Australia. Viewed 26 August 2013, http://www.doncoal.com.au/documents/community_environment/tasman/AEMR/2013/67710_AEMR_2013.pdf.

RW Corkery and Co Pty Ltd (2014a) Annual environmental management report for the Abel Underground Coal Mine 1 June 2013 to 31 May 2014. Donaldson Coal Pty Ltd, Australia. Viewed 08 May 2015, http://www.doncoal.com.au/documents/community_environment/abel/AEMR/2014/73709%20AEMR%202014.pdf.

RW Corkery and Co Pty Ltd (2014b) Annual environmental management report for the Tasman Underground Coal Mine 1 June 2013 to 31 May 2014. Newcastle Coal Company Pty Ltd, Australia. Viewed 26 August 2013, http://www.doncoal.com.au/documents/community_environment/tasman/AEMR/2014/67712%20AEMR%202014.pdf.

Resource Strategies Pty Ltd (2013) Mt Arthur Coal Open Cut modification – environmental assessment. BHP Billiton, Australia. Viewed 6 June 2013, https://majorprojects.affinitylive.com/public/5de5c8c0c5eafa5fcb561491eee07cab/03.%20Mt%20Arthur%20Coal%20Open%20Cut%20-%20Mod%201%20-%20EA%20Section%201%20Introduction.pdf.

Resource Strategies Pty Ltd (n.d.) Tasman Extension Project Environmental Impact Statement. Donaldson Coal Pty Ltd, Australia. Viewed 26 August 2013, https://majorprojects.affinitylive.com/public/c3316bc23b0e6cfa13057cda51c299e3/13.%20Tasman%20Extension%20Project%20EIS%20Main%20Report%20Section%202.pdf.

Rio Tinto (2015) Hunter Valley Operations Water Management Plan. Rio Tinto Coal Australia, Sydney. Viewed 01 December 2015, http://www.riotinto.com/documents/20150717_HVO_water_management_plan_Approved_Final.pdf.

RPS (2014) Rix's Creek Continuation of Mining Project groundwater impact assessment. In: AECOM Australia Pty Ltd (2015) Environmental Impact Statement Rix's Creek Mine – Continuation of Mining Project. Bloomfield Collieries Pty Ltd, Australia. Viewed 02 November 2015, https://majorprojects.affinitylive.com/public/85ebc71ed92636fe519100449f569ec1/50.%20Rix's%20Creek%20EIS_App%20S_%20Groundwater%20Impact%20Assessment_Pt%202.pdf.

RPS Aquaterra (2011) Moolarben Coal Complex Stage 2 preferred project report groundwater impact assessment. In: Hansen Bailey Pty Ltd (2011) Moolarben Coal Project Stage 2 Preferred Project Report. Moolarben Coal Mines Pty Ltd, Australia. Viewed 21 July 2014, http://www.moolarbencoal.com.au/__documents/major-project-approvals/stage-2-ppr/appendix_e_groundwater_impact_assessment_part_a.pdf.

RPS Aquaterra (2012) Tasman Extension Project groundwater assessment. In: Resource strategies Pty Ltd (n.d.) Tasman Extension Project Environmental Impact Statement. Donaldson Coal Pty Ltd, Australia. Viewed 26 August 2013, https://majorprojects.affinitylive.com/public/5f1dfe0b3795eb1eee91f93337224081/25.%20Tasman%20Extension%20Project%20EIS%20Appendix%20B.pdf.

RPS Aquaterra, and Ashton Coal Operations Pty Ltd (2012) Water management plan. Ashton Coal Operations Pty Ltd, Australia. Viewed 09 July 2014, http://www.ashtoncoal.com.au/Reports--Publications/Environmental/Environmental-Management-Plans/Site-Water-Management-Plan.aspx.

Sinclair Knight Merz Pty Ltd (2013) Groundwater impact assessment. In: SLR Consulting (2013) Proposed modification to DA 305-11-01 environmental assessment. Liddell Coal Operations, Australia. Viewed 19 July 2014, https://majorprojects.affinitylive.com/public/ecc0cd1d653688201255d2c8af95859a/Liddell%20Coal%20Mine%20Mod%205%20EA%20-%20Appendix%20G.pdf.

SCT Operations Pty Ltd (2009) Subsidence assessment for longwall mining in the Hebden and Barratt seams. In: Integra Coal Operations Pty Ltd (2009) Proposed Integra Underground Coal Project environmental assessment. Integra Coal Operations Pty Ltd, Australia. Viewed 17 July 2014, http://c.cld.pw/127/cms/files/integraeaannexe(1).pdf.

Umwelt Australia Pty Ltd (2007) Mt Arthur Coal Underground Project surface water assessment. In: Umwelt Australia Pty Ltd (2008a) Environmental assessment – proposed Mt Arthur Underground Project. Mt Arthur Coal, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/4364e6de4600d4df1eebc25061943e1d/EA%20-%20Appendix%209.pdf.

Umwelt Australia Pty Ltd (2008a) Austar Coal Mine Project – Stage 3 environmental assessment. Austar Coal Mine Pty Ltd, Australia. Viewed 10 July 2014, https://majorprojects.affinitylive.com/public/03e75aabe7dc5a11e1da475e7be60bda/Austar%20Stage%203%20Environmental%20Assessment.pdf.

Umwelt Australia Pty Ltd (2008b) Environmental Assessment – Proposed Mt Arthur Underground Project. Mt Arthur Coal, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/36c53adc231d3ce55c80a922d5dea20e/EA%20-%20Main%20Text.pdf.

Umwelt Australia Pty Ltd (2009) Ulan Coal - continued operations environmental assessment. Ulan Coal Mines Ltd, Australia. Viewed 06 June 2013, http://www.ulancoal.com.au/EN/OperatingApprovals/Volume%20Two/Appendix7_B_Sec3-8_AppendixA.pdf.

Umwelt Australia Pty Ltd (2010a) Ravensworth Operations Project surface water assessment. In: Umwelt Australia (2010) Ravensworth Operations Project environmental assessment. Ravensworth Operations Pty Ltd, Australia. Viewed 28 July 2014, http://www.ravensworthoperations.com.au/EN/Publications/EAs/Appendix_8_Water_Part-A_Main-Text.pdf.

Umwelt Australia Pty Ltd (2010b) Ravensworth Operations Project surface water assessment. In: Umwelt Australia (2010) Ravensworth Operations Project environmental assessment. Ravensworth Operations Pty Ltd, Australia. Viewed 28 July 2014, http://www.ravensworthoperations.com.au/EN/Publications/EAs/Appendix_8_Water_Part-B_Main-Text.pdf.

Umwelt Australia Pty Ltd (2011a) Austar Coal Mine Project – Stage 3 Modification Environmental Assessment. Austar Coal Mine Pty Ltd, Australia. Viewed 10 July 2014, https://majorprojects.affinitylive.com/public/3dbf3fb5742b79119deabb89de02d249/Main%20Text%20Part%201.pdf.

Umwelt Australia Pty Ltd (2011b) Austar Coal Mine Project – Stage 3 Modification Environmental Assessment. Austar Coal Mine Pty Ltd, Australia. Viewed 10 July 2014, https://majorprojects.affinitylive.com/public/47b42c7ed0e059d68cc345ca7f797925/Main%20Text%20Part%202.pdf.

Umwelt Australia Pty Ltd (2011c) Environmental assessment, modification of Ulan Coal – continued operations, North 1 Underground Mining Area, minor modifications to Ulan No. 3 and Ulan West Mine plans and proposed concrete batching plant. Ulan Coal Mines Ltd, Australia. Viewed 28 July 2014, http://ulancoal.com.au/EN/OperatingApprovals/Documents/Main%20Text%20Pt1.pdf.

Umwelt Australia Pty Ltd (2013) Bulga Optimisation Project Environmental Impact Statement. Bulga Coal Management Pty Ltd, Australia. Viewed 14 July 2014, https://majorprojects.affinitylive.com/public/6631d78360e93a502f8ea6cdd109758d/01.Bulga%20Optimisation%20Project%20-%20Environmental%20Impact%20Statement.pdf.

Umwelt Australia Pty Ltd (2014) Mount Owen Continued Operations Project Environmental Impact Statement. Glencore, Australia. Viewed 20 January 2015, https://majorprojects.affinitylive.com/public/95f961e969f065ed01fd83f153f55272/10.%20MOCO%20Project%20-%20EIS%20-%20Appendix%209%20-%20Surface%20Water%20Assessment.pdf.

Wells Environmental Services (2009a) South East Open Cut Preliminary Environmental Assessment. Ashton Coal Operations Pty Ltd, Australia. Viewed 21 August 2014, http://www.ashtoncoal.com.au/Resources/Reports--Publications/Environmental-Assessments/South-East-Open-Cut-EA/South_East_Open_Cut_Preliminary_Environmental_Assessment_(PEA).pdf.

Wells Environmental Services (2009b) South East Open Cut Project and modification to the existing ACP consent environmental assessment report. Ashton Coal Operations Pty Ltd, Australia. Viewed 09 July 2014, http://www.ashtoncoal.com.au/Resources/Reports--Publications/Environmental-Assessments/South-East-Open-Cut-EA/VOL2_A3_PLANS_PART_C.pdf.

Worley Parsons Services Pty Ltd (2008) Moolarben Coal Project EA2 surface water management strategy. In: Wells Environmental Services and Coffey Natural Systems (2009) Moolarben Coal Project Stage 2 environmental assessment. Moolarben Coal Mines Pty Ltd, Australia. Viewed 21 July 2014, http://www.moolarbencoal.com.au/__documents/major-project-approvals/environmental-assessment-report/environmental-assessment-part-2/appendix/vol4_appendix-6a-surface-water-assessment.pdf.

WRM Water and Environment Pty Ltd (2009) Surface water assessment for Integra Open Cut Project environmental assessment. In: URS Australia environmental assessment – Integra Open Cut Project. Integra Coal Operations Pty Ltd, Australia. Viewed 14 July 2014, http://www.bloomcoll.com.au/Portals/5/Files/RixsCreekNorth/INTEGRA%20COMPLEX/Integra%20Open%20Cut%20Project%20EA%202009/Volume%202/AppendixDSurfaceWater.pdf.

WRM Water and Environment Pty Ltd (2012) Surface Water Impact Assessment for the Drayton South Coal Project. In: Hansen Bailey Pty Ltd (2012) Drayton South Coal Project Environmental Assessment. Anglo American Metalluirgical Coal Pty Ltd, Australia. Viewed 16 July 2014, https://majorprojects.affinitylive.com/public/72982696fba5e4d7b347208fe4cc0d17/53.%20Drayton%20South%20-%20EA%20Appendix%20M%20-%20Surface%20Water%20Impact%20Assessment.pdf.

WRM Water and Environment Pty Ltd (2013a) Bengalla continuation of mining project – surface water impact assessment. In: Hansen Bailey Continuation of Bengalla Mine Environmental Impact Statement. Bengalla Mining Company Pty Ltd, Australia. Viewed 13 July 2014, https://majorprojects.affinitylive.com/public/947321f47737f5522ed9325aeb5a2465/11.%20Bengalla%20Continuation%20Project%20-%20EIS%20-%20Appendix%20J%20-%20Surface%20Water.pdf.

WRM Water and Environment Pty Ltd (2013b) Mangoola Coal modification to project approval surface water assessment. In: EMM Consulting Pty Ltd (2013) Mangoola Coal modification 6 environmental assessment. Xstrata Mangoola Pty Ltd, Australia. Viewed 6 June 2013, https://majorprojects.affinitylive.com/public/31ef2db69db72ee9e1856fbab25aea27/22.%20Mangoola%20Mine_%20Mod%206_%20Vol%203_%20Appendix%20H_%20Surface%20water%20assessment.pdf.

WRM Water and Environment Pty Ltd (2013c) Wallarah 2 Coal Project surface water impact assessment. In: Hansen Bailey Wallarah 2 Coal Project Environmental Impact Statement. Wyong Areas Coal Joint Venture, Australia. Viewed 12 August 2014, https://majorprojects.affinitylive.com/public/4b1755678e4f0e62e47175207ea9f598/11.%20Wallarah%202%20Coal%20Project%20EIS%20-%20Appendix%20J%20-%20Surface%20Water%20Impact%20Assessment.pdf.

WRM Water and Environment Pty Ltd (2014) Mount Thorley operations 2014 and Warkworth continuation 2014 – surface water assessment. In: EMM Consulting Pty Ltd Mount Thorley operations 2014 Environmental Impact Statement. Mt Thorley Operations Pty Ltd, Australia. Viewed 22 July 2014, https://majorprojects.affinitylive.com/public/0fb62b282f6a5a26585a9075269b9c51/18.%20Mt%20Thorley%20Continuation%20Project%20EIS%20-%20Appendix%20J%20Surface%20Water.pdf.

WRM Water and Environment Pty Ltd (2015a) Surface water impact assessment. In: Hansen Bailey Pty Ltd Bylong Coal Project Environmental Impact Statement. KEPCO Bylong Australia Pty Ltd, Australia. Viewed 25 September 2015, https://majorprojects.affinitylive.com/public/039074dbff023c7fd5b5f828c18e331d/21.%20Bylong%20Coal%20Project%20EIS%20-%20Appendix%20L%20Surface%20Water%20Part%201.pdf.

WRM Water and Environment Pty Ltd (2015b) Surface water impact assessment Drayton South Coal Project. In: Hansen Bailey Pty Ltd Drayton South Coal Project Environmental Impact Statement. Anglo American Coal Pty Ltd, Australia. Viewed 15 May 2015, https://majorprojects.affinitylive.com/public/116e90b5f9a7156bfafdf206369a977b/25.%20Drayton%20South%20Coal%20Project%20-%20EIS%20Appendix%20Q%20-%20Surface%20Water%20Impact%20Assessment.pdf.

Xstrata Coal Pty Ltd (2013) Ravensworth Mine Complex Water Management Plan. Xstrata Coal Pty Ltd, Australia.

Zhang YQ, Peña-Arancibia JL, Viney NR, Peeters LJM, Herron NF, Yang A, Wang W, Marvanek SP, Ramage A (2018) Surface water numerical modelling for the Hunter subregion. Product 2.6.1 for the Hunter 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/HUN/2.6.1.

Datasets

Dataset 1 Bioregional Assessment Programme (2016) HUN Mine footprints for timeseries. Bioregional Assessment Source Dataset. Viewed 02 August 2016, https://data.bioregionalassessments.gov.au/dataset/1e18f597-c8dd-4dae-b460-de9f5ebb1c6a.

Dataset 2 Bioregional Assessment Programme (2016) HUN Mine timeseries tables v01. Bioregional Assessment Source Dataset. Viewed 02 August 2016, https://data.bioregionalassessments.gov.au/dataset/cc1f9124-89f7-4b8e-accc-86d778b6c9c4.

Dataset 3 Bioregional Assessment Programme (2016) HUN Mine Footprints Timeseries Graph v01. Bioregional Assessment Source Dataset. Viewed 02 August 2016, https://data.bioregionalassessments.gov.au/dataset/11493517-df5f-49ed-84dc-23afdbe00c5e.

Dataset 4 Bioregional Assessment Programme (2016) HUN SW footprint shapefiles v01. Bioregional Assessment Source Dataset. Viewed 02 August 2016, https://data.bioregionalassessments.gov.au/dataset/2a9520c8-1569-4e0e-8bd8-26e2c7b9e9e0.

Dataset 5 Geoscience Australia (2011) Geoscience Australia, 1 second SRTM Digital Elevation Model (DEM). Bioregional Assessment Source Dataset. Viewed 31 March 2016, http://data.bioregionalassessments.gov.au/dataset/9a9284b6-eb45-4a13-97d0-91bf25f1187b.

Dataset 6 Geoscience Australia (2015) HUN Historical Landsat Images Mine Foot Prints v01. Bioregional Assessment Source Dataset. Viewed 04 December 2015, http://data.bioregionalassessments.gov.au/dataset/28de7771-28f5-4d24-943f-0addea07c8c4.

Dataset 7 Bioregional Assessment Programme (2015) HUN Historical Landsat 5 Derived Mine Foot Prints v01. Bioregional Assessment Derived Dataset. Viewed 04 December 2015, http://data.bioregionalassessments.gov.au/dataset/e852e582-d0e7-4543-ac70-feba694597c0.

Dataset 8 NSW Department of Primary Industries, NSW Office of Water (2015) Groundwater Entitlement Hunter NSW Office of Water 20150324. Bioregional Assessment Source Dataset. Viewed 18 March 2016, http://data.bioregionalassessments.gov.au/dataset/19697f0a-4513-42a4-a7ce-4e00f48a715a.

Dataset 9 NSW Department of Industry, Resource and Energy Division (2015) Historical Mining Footprints DTIRIS HUN 20150707. Bioregional Assessment Source Dataset. Viewed 08 April 2016, http://data.bioregionalassessments.gov.au/dataset/7b91b53c-2f09-4cd7-a38b-746446c06a72.

Dataset 10 Glencore (2014) Mining Footprints Glencore 20141107. Bioregional Assessment Source Dataset. Viewed 08 April 2016, http://data.bioregionalassessments.gov.au/dataset/cd1a6a82-1bfd-4cae-bdca-40ba77166407.

Dataset 11 Glencore Xstrata (2015) Mining Footprints Glencore Xstrata Bulga Pilot 20150203. Bioregional Assessment Source Dataset. Viewed 08 April 2016, http://data.bioregionalassessments.gov.au/dataset/e1e997b4-4f49-40c5-b930-26b87683f71f.

Dataset 12 Anglo American (2014) Mining Footprints Anglo American 20141126. Bioregional Assessment Source Dataset. Viewed 08 April 2016, http://data.bioregionalassessments.gov.au/dataset/47bb7f49-2c65-49ce-883d-14296920e1a2.

Dataset 13 Wambo Coal Pty Ltd (2015) Mining Footprints Peabody Wambo 20150224. Bioregional Assessment Source Dataset. Viewed 08 April 2016, http://data.bioregionalassessments.gov.au/dataset/3aee4c12-9cc3-4078-95db-d6f8bcc58815.

Dataset 14 Bloomfield Group (2014) Mining Footprints Bloomfield 20141219. Bioregional Assessment Source Dataset. Viewed 27 April 2016, http://data.bioregionalassessments.gov.au/dataset/d5acf11a-36a7-4432-a5c0-37ab0903e5ce.

Dataset 15 Idemitsu Australia Resources (2014) Mining Footprints Idemitsu Australia Resources 20141125. Bioregional Assessment Source Dataset. Viewed 27 April 2016, http://data.bioregionalassessments.gov.au/dataset/660a94c5-42e0-40a4-9dc4-e0fac35a740e.

Dataset 16 Lake Coal PTY LTD (2014) Mining Footprints Lake Coal Pty Ltd 20141020. Bioregional Assessment Source Dataset. Viewed 27 April 2016, http://data.bioregionalassessments.gov.au/dataset/a0e89257-cefb-4cf8-a523-e6ae3345cd1c.

Dataset 17 Rio Tinto (2014) Mining Footprints RioTinto MTW 20141229. Bioregional Assessment Programme Source Dataset. Viewed 27 April 2016, http://data.bioregionalassessments.gov.au/dataset/875eb52d-d988-4d68-9df6-da04786190b6.

Dataset 18 Spur Hill Management Pty Ltd (2015) Mining Footprints Spur Hill Management 20150218. Bioregional Assessment Source Dataset. Viewed 27 April 2016, http://data.bioregionalassessments.gov.au/dataset/7abc534f-d942-46fd-a966-ebd24318f265.

Dataset 19 Wyong Areas Coal Joint Venture (2015) Mining Footprints Wyong Areas Coal Joint Venture 20150312. Bioregional Assessment Source Dataset. Viewed 27 April 2016, http://data.bioregionalassessments.gov.au/dataset/61a87e97-7879-4faa-9ba4-723648da2dc3.

Dataset 20 CSIRO (2016) HUN SW footprint shapefiles v01. Bioregional Assessment Source Dataset. Viewed 18 August 2016, http://data.bioregionalassessments.gov.au/dataset/2a9520c8-1569-4e0e-8bd8-26e2c7b9e9e0.

Dataset 21 Bioregional Assessment Programme (2016) HUN SW modelling total mine footprint v01. Bioregional Assessment Derived Dataset. Viewed 18 August 2016, https://data.bioregionalassessments.gov.au/dataset/b78597ba-4781-4b95-80c3-d6c11cb2e595.

Dataset 22 CSIRO (2016) HUN_Groundwater footprint polygons v01. Bioregional Assessment Source Dataset. Viewed 18 August 2016, https://data.bioregionalassessments.gov.au/dataset/c7672a9d-422e-425e-82ef-11afc5fb7ba6.

Dataset 23 CSIRO (2016) HUN_Groundwater footprint kmz files v01. Bioregional Assessment Derived Dataset. Viewed 18 August 2016, https://data.bioregionalassessments.gov.au/dataset/a16c503d-4ec7-4319-b8e1-c8e8a629d71a.

Dataset 24 Bioregional Assessment Programme (2016) HUN GW modelling total mine footprint v01. Bioregional Assessment Derived Dataset. Viewed 18 August 2016, https://data.bioregionalassessments.gov.au/dataset/b35e1ff3-7c99-4542-8e24-4840ee29325a.

Dataset 25 Bioregional Assessment Programme (2016) HUN Mine footprints for GW modelling v01. Bioregional Assessment Derived Dataset. Viewed 18 August 2016, https://data.bioregionalassessments.gov.au/dataset/93f99710-e84a-41c0-9c4f-4da9712c3263.

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.

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

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

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

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

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

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

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

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

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

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

component: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a coal seam gas (CSG) operation or coal mine. For example, components during the development life-cycle stage of a coal mine include developing the mine infrastructure, the open pit, surface facilities and underground facilities. Components are grouped into life-cycle stages.

conceptual model: abstraction or simplification of reality

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

consequence: synonym of impact

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

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

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

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

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

diversion: see extraction

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

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

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels formation: rock layers that have common physical characteristics (lithology) deposited during a specific period of geological time

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-dependent ecosystem: ecosystems that rely on groundwater - typically the natural discharge of groundwater - for their existence and health

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

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

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

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

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

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

inflow: surface water runoff and deep drainage to groundwater (groundwater recharge) and transfers into the water system (both surface water and groundwater) for a defined area landscape class: for bioregional assessment (BA) purposes, an ecosystem with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. Note that there is expected to be less heterogeneity in the response within a landscape class than between landscape classes. They are present on the landscape across the entire BA subregion or bioregion and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of ecosystem assets.

material: pertinent or relevant

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

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

porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass

receptor: a point in the landscape where water-related impacts on assets are assessed

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

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)

stratigraphy: stratified (layered) rocks

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

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

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs 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 make: the groundwater extracted for dewatering mines

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

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

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

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

2.2 Statistical analysis and interpolation

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

www.bioregionalassessments.gov.au

Australian Government

Department of the Environment and Energy

Bureau of Meteorology

Geoscience Australia

CSIRO