Australian Government

BIOREGIONAL ASSESSMENTS

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

Context statement for the Sydney Basin bioregion

Product 1.1 from the Sydney Basin Bioregional Assessment

2018

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

The Bioregional Assessment Programme

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

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

Department of the Environment and Energy

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

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Authorship is listed in relative order of contribution.

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Cover photograph

Surface infrastructure of the Clarence underground coal mine located approximately 15 km east of Lithgow, adjacent to the Greater Blue Mountains World Heritage Area, showing vegetation recovering from bushfire in October 2013. The hillslope drains into the hillslope drains into the Wollangambe River

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Australian Government
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Geoscience Australia

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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 Panton, Paul Sheahan, Kellie Stuart, Carl Sudholz CSIRO: Peter Fitch, Ashley Sommer Geoscience Australia: Neal Evans
Communications	Bureau of Meteorology: Karen de Plater CSIRO: Helen Beringen, Chris Gerbing Department of the Environment and Energy: Amanda Forman, John Higgins, Lea Locke, Milica Milanja Geoscience Australia: Michelle McGranahan
Coordination	Bureau of Meteorology: Julie Burke, Eliane Prideaux, Sarah van Rooyen CSIRO: Ruth Palmer Department of the Environment and Energy: Anisa Coric, James Hill, Bronwyn McMaster, 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
Geology	CSIRO: Deepak Adhikary, Emanuelle Frery, Mike Gresham, Jane Hodgkinson, Zhejun Pan, Matthias Raiber, Regina Sander, Paul Wilkes Geoscience Australia: Steven Lewis (Discipline Leader)

Role or team	Contributor(s)
Geographic information systems	CSIRO: Jody Bruce, Debbie Crawford, Daniel Gonzales, 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, 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: Belinda Allison (Team Leader) CSIRO: Qifeng Bai, Simon Cox, Phil Davies, Mick Hartcher, 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, Clare Brandon, Heinz Buettikofer, Sonja Chandler, Simon Gallant, Karin Hosking, Allison Johnston, Maryanne McKay, Linda Merrin, Joely Taylor, 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, Adrian Ickowicz, Warren Jin, Yang Liu, 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

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This technical product was reviewed by several groups:

- Discipline Leaders: Anthony O'Grady (ecology), Tim Ransley (hydrogeology)
- Senior Science Leaders: David Post (Projects Director), Steven Lewis (Science Director, Geoscience Australia), Maryam Ahmad (Deputy 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.

Introduction

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

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

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

The Bioregional Assessment Programme

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

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

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

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

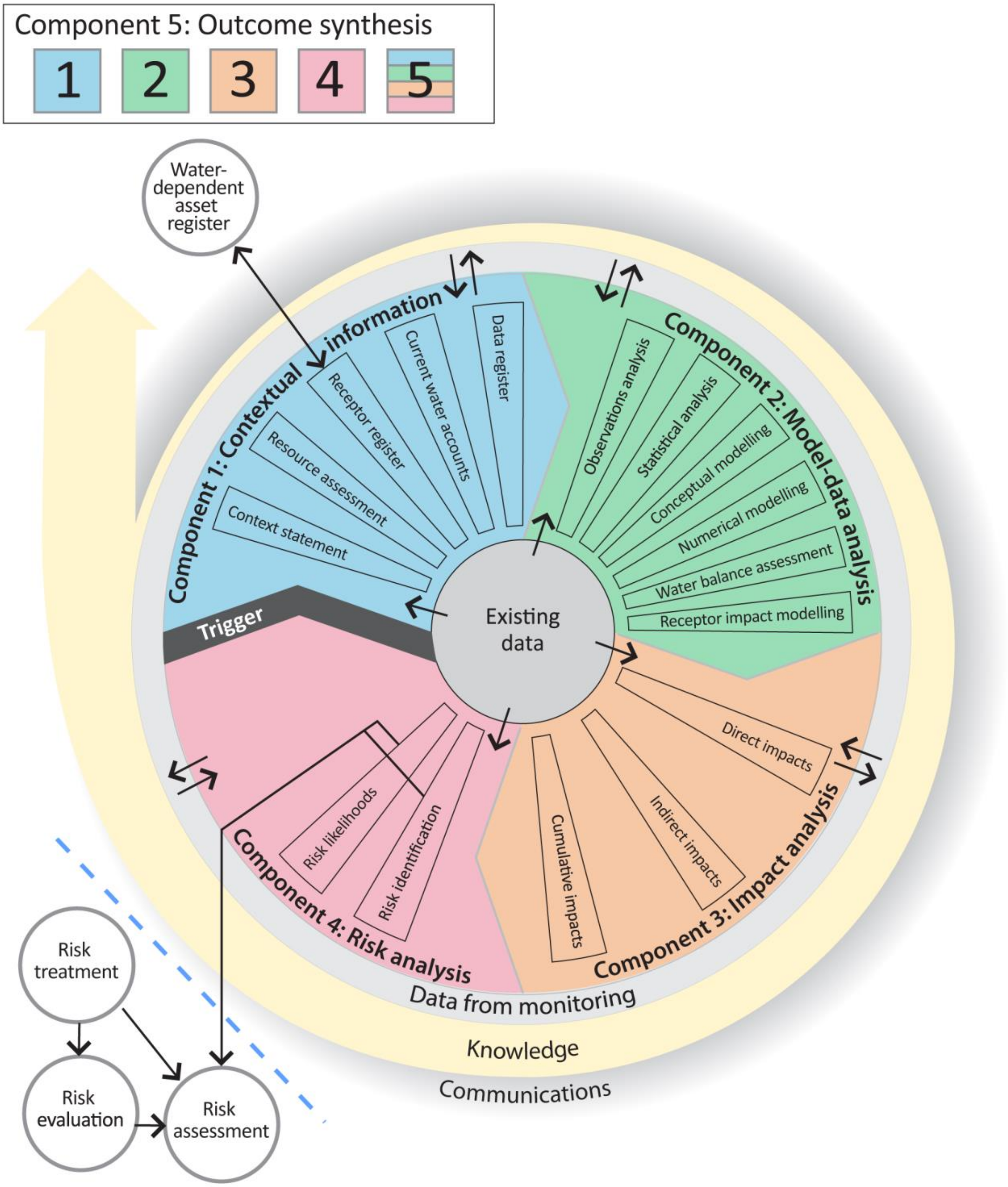

Figure 1 Schematic diagram of the bioregional assessment methodology

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

Methodologies

The overall scientific and intellectual basis of the BAs is provided in the BA methodology (Barrett et al., 2013). Additional guidance is required, however, about how to apply the BA methodology to a range of subregions and bioregions. To this end, the teams undertaking the BAs have developed and documented detailed scientific submethodologies (Table 1) to, in the first instance, support the consistency of their work across the BAs and, secondly, to open the approach to scrutiny, criticism and improvement through review and publication. In some instances, methodologies applied in a particular BA may differ from what is documented in the submethodologies – in this case an explanation will be supplied in the technical products of that BA. Ultimately the Programme anticipates publishing a consolidated 'operational BA methodology' with fully worked examples based on the experience and lessons learned through applying the methods to 13 bioregions and subregions.

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

Table 1 Methodologies

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

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

Technical products

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

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

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

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

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

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

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

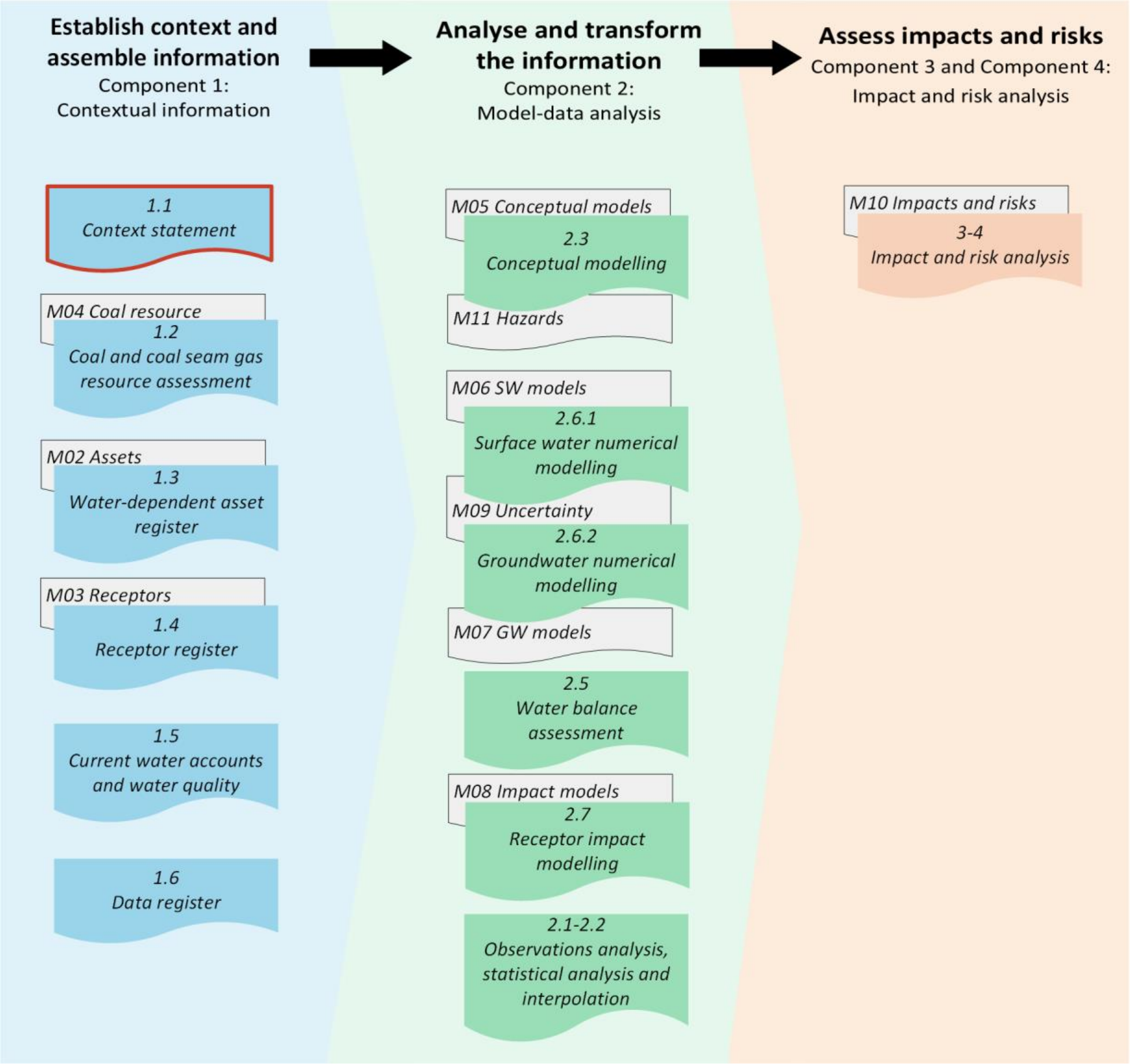

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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

Table 2 Technical products delivered for the Sydney Basin bioregion

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

Component	Product code	Title	Section in the BA methodology[b]	Type[a]
Component 1: Contextual information for the Sydney Basin bioregion	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	HTML-only
	1.6	Data register	2.5.1.6	Register
Component 2: Model-data analysis for the Sydney Basin bioregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2	Not produced
	2.3	Conceptual modelling	2.5.2.3, 4.3	Not produced
	2.5	Water balance assessment	2.5.2.4	Not produced
	2.6.1	Surface water numerical modelling	4.4	Not produced
	2.6.2	Groundwater numerical modelling	4.4	Not produced
	2.7	Receptor impact modelling	2.5.2.6, 4.5	Not produced
Component 3 and Component 4: Impact and risk analysis for the Sydney Basin bioregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	Not produced
Component 5: Outcome synthesis for the Sydney Basin bioregion	5	Outcome synthesis	2.5.5	Not produced

[a] The types of products are as follows:

- 'PDF' indicates a PDF document that is developed by the 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.
- 'HTML-only' indicates content that is only delivered as webpages (with no accompanying PDF document). This content is developed by the Sydney Basin Bioregional Assessment using the structure, standards and format specified by the Programme.
- 'Not produced' indicates that the product was not developed. A webpage explains why and points to relevant submethodologies (Table 1).

[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.

- The context statement is a collation of existing information and thus in some cases figures are reproduced from other sources. These figures were not redrawn for consistency (with respect to format as well as content), and the resolution and quality reflects that found in the source.
- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence. The copyright owners of the following figures, however, did not grant permission to do so: Figure 27. It should be assumed that third parties are not entitled to use this material without permission from the copyright owner.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151° East for the 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 4 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 4 March 2018, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

1.1 Context statement for the Sydney Basin bioregion

The context statement brings together what was known about the geography, ecology, hydrology, geology and hydrogeology of the Sydney Basin bioregion as of February 2017. It provides baseline information that is relevant to understanding the regional context of water resources and water-dependent assets, which might be impacted by coal and coal seam gas development.

The context statement includes materially relevant characteristics of the Sydney Basin bioregion that are needed to adequately interpret output from ecological, surface water and groundwater datasets and models, and from this develop improved knowledge of whole-of-system functioning. However, numerical modelling and impact analysis will not be undertaken for the Sydney Basin bioregion.

No new analysis or modelling is presented in the context statement; rather it draws on existing information as of February 2017. Thus, some figures are reproduced from other sources and the format of these external figures is not consistent with those produced in the bioregional assessment. Likewise, results from different sources may use different methods or inconsistent units.

1.1.1 Bioregion

The Sydney Basin bioregion spans an area of 24,625 km^2 immediately to the north, west and south of Sydney (Figure 3). It is bounded in the north by the Hunter subregion of the Northern Sydney Basin bioregion and extends to just south of Durras on the south coast of NSW. Its westward boundary is defined by the geological Sydney Basin. The bioregion includes the mining areas around Lithgow and Wollongong.

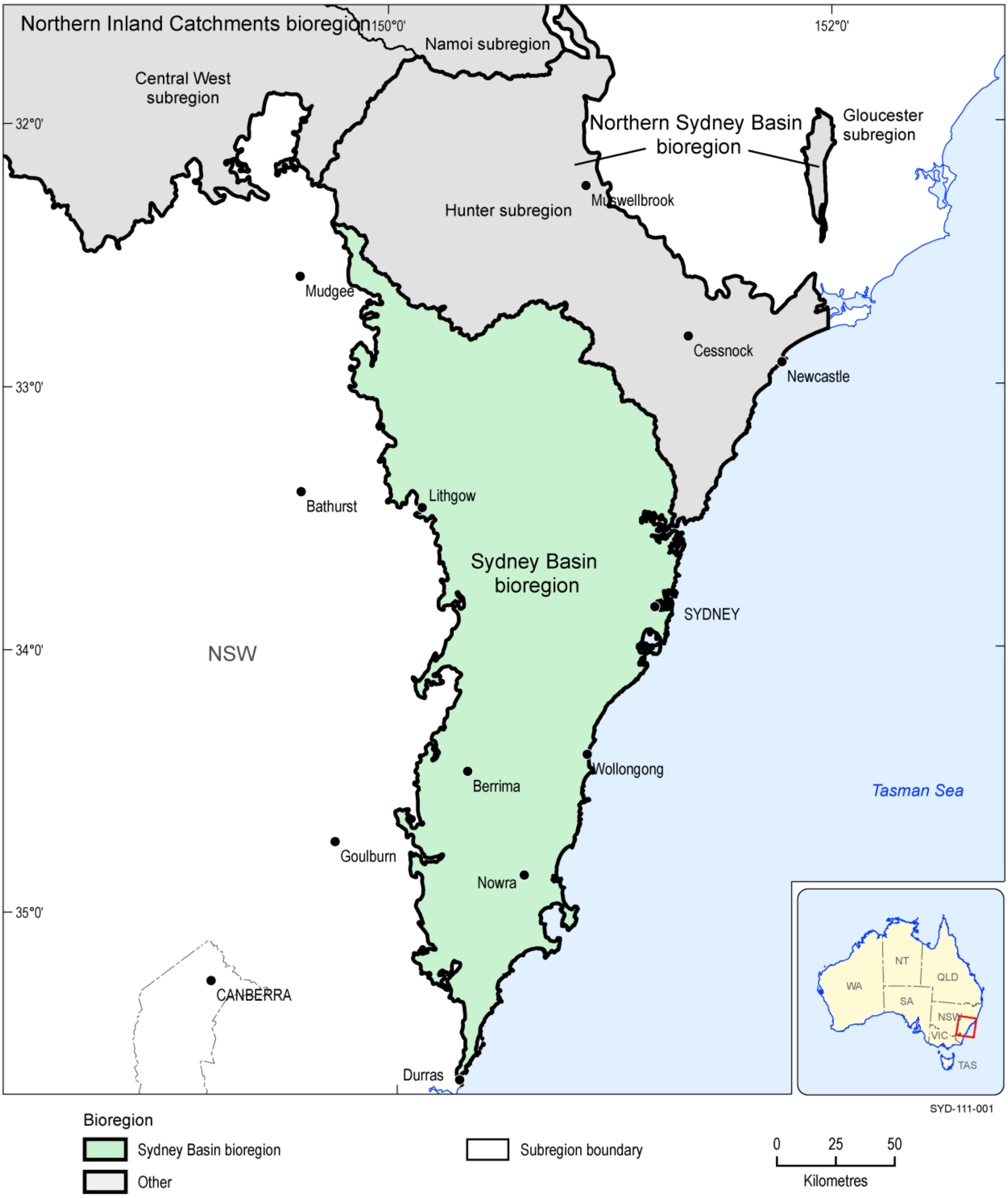

Figure 3 Sydney Basin bioregion

The Northern Sydney Basin bioregion and parts of the Northern Inland Catchments bioregion are also shown.
Data: Bioregional Assessment Programme (Dataset 1)

The Sydney Basin bioregion is defined from three data sources, being: (i) the geological Sydney Basin (Tadros, 1995; Geoscience Australia, Dataset 2), (ii) the Hawkesbury-Nepean and Central West surface water catchments (Geoscience Australia, Dataset 3) and (iii) the Australian coastline derived from the 1:250,000 topographic dataset (Geoscience Australia, Dataset 3). These are shown in Figure 4.

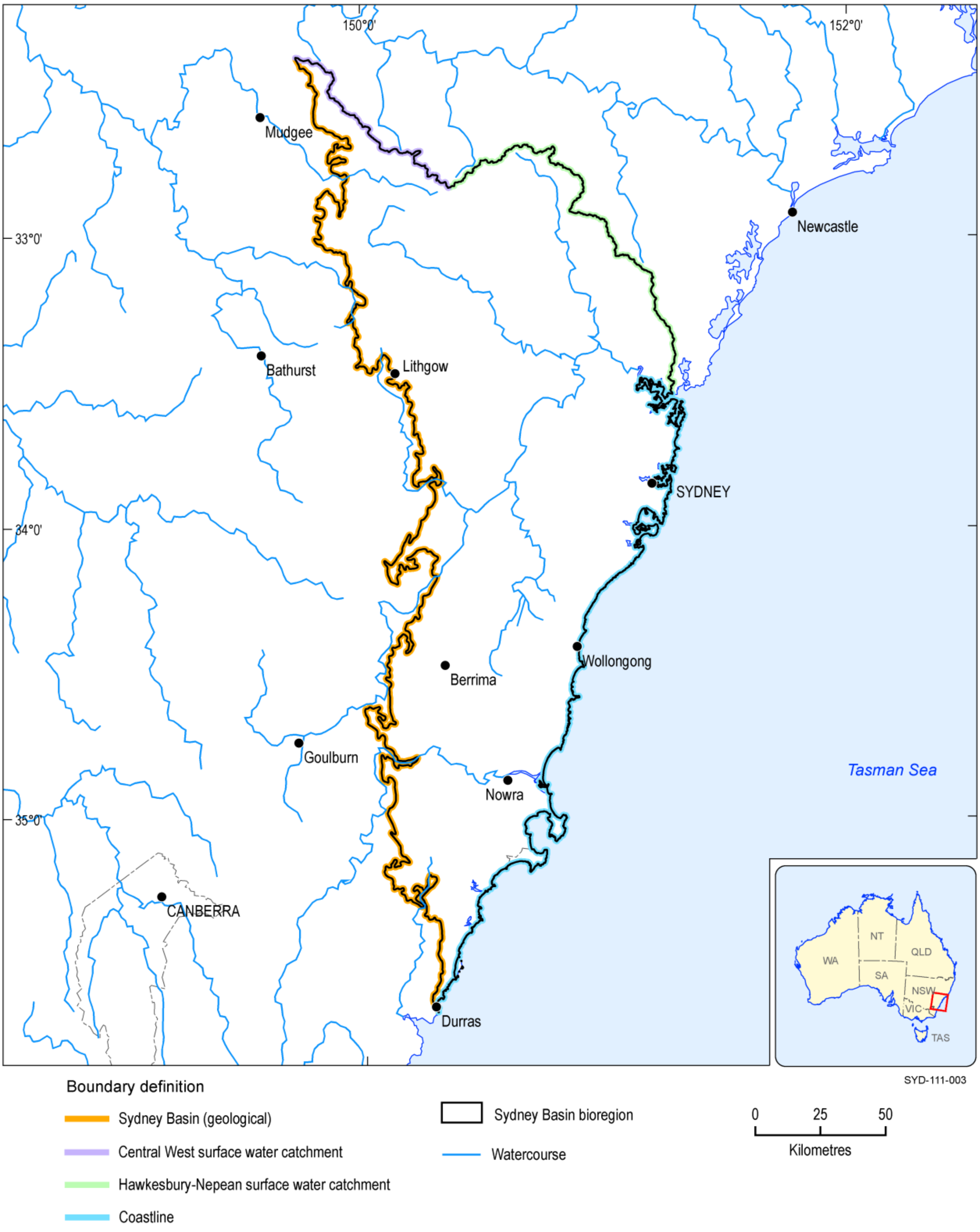

Figure 4 Boundary definitions of the Sydney Basin bioregion

Data: Geoscience Australia (Dataset 2, Dataset 3)

The surface water catchment boundary between the Hawkesbury-Nepean River system and the Hunter-Central Rivers systems conforms to the boundary between the former Hawkesbury-Nepean Catchment Management Authority (CMA) and the Hunter-Central Rivers CMA (DIPNR, 2003). It was this CMA boundary that was the basis for defining the Sydney Basin bioregion and Hunter subregion in 2012. On 1 January 2014, all CMAs in NSW transitioned into local land services (LLS) regions (NSW Government, 2014). Part of the Central-Coast portion of the Hunter subregion became part of what is now the Greater Sydney LLS region and part of the Hawkesbury-Nepean CMA area became part of the Hunter LLS (Figure 5).

1.1.1.1 Definitions used

Various regionalisations are referred to in this context statement, including (i) local land services (LLS) regions (NSW Government, 2014), (ii) Interim Biogeographic Regionalisation for Australia (IBRA) bioregions and subregions (SEWPaC, 2012) and (iii) NSW local government areas (LGAs) (Australian Bureau of Statistics, 2011). Their relationships with the Sydney Basin bioregion are summarised below.

The Sydney Basin bioregion contains parts of four LLS regions (Table 3 and Figure 5). LLSs provide agricultural, biosecurity, natural resources management and emergency management services to regional NSW. About 43% and 30% of the Sydney Basin bioregion lie within the Greater Sydney and South East LLS regions, respectively. Smaller proportions of the bioregion lie within the Hunter and Central Tablelands LLS regions in the north and north-west (Table 3 and Figure 5).

Table 3 Local land services regions contained in the Sydney Basin bioregion

LLS[a] name	Area (km^2)	Area in Sydney Basin bioregion (km^2)	Percentage of LLS[a] in Sydney Basin bioregion (%)	Percentage of Sydney Basin bioregion (%)
Greater Sydney	12,498	10,617	85%	43.2%
South East	55,627	7,383	13.3%	30.1%
Central Tablelands	31,347	4,715	15%	19.2%
Hunter	33,006	1,843	5.6%	7.5%

These data are listed in descending order based on their area in the Sydney Basin bioregion.
[a] Local land services region
Data: Local Land Services, Trade and Investment NSW (Dataset 4)

The Sydney Basin bioregion aligns closely with the Sydney Basin IBRA bioregion (SEWPaC, 2012), but also includes parts of the NSW South Western Slopes and South Eastern Highlands IBRA bioregions. The IBRA bioregions are large, geographically distinct areas of land with common characteristics, such as climate, geology, landforms and ecosystems. The IBRA bioregions are further refined into subregions which are more localised and geomorphologically uniform. The (BA-defined) Sydney Basin bioregion contains all or parts of 18 IBRA subregions (Figure 6 and Table 4), although four of these along the western edge of the Sydney Basin bioregion intersect only slightly (i.e. <2%) and are likely an artefact of the mapping. In Table 4, they are identified and commented on in caption note (b). Nine IBRA subregions are almost wholly contained (i.e. >95%) within the Sydney Basin bioregion. The most significant in terms of areal extent are the Wollemi, Yengo, Cumberland and Burragorang IBRA subregions which cover just over 58% of the Sydney

Basin bioregion. The names and spatial extents for the IBRA subregions contained within the Sydney Basin bioregion are provided in Table 4. Key characteristics of the main IBRA subregions contained in the Sydney Basin bioregion can be found in the geography (Section 1.1.2) and ecology (Section 1.1.7) sections of this context statement.

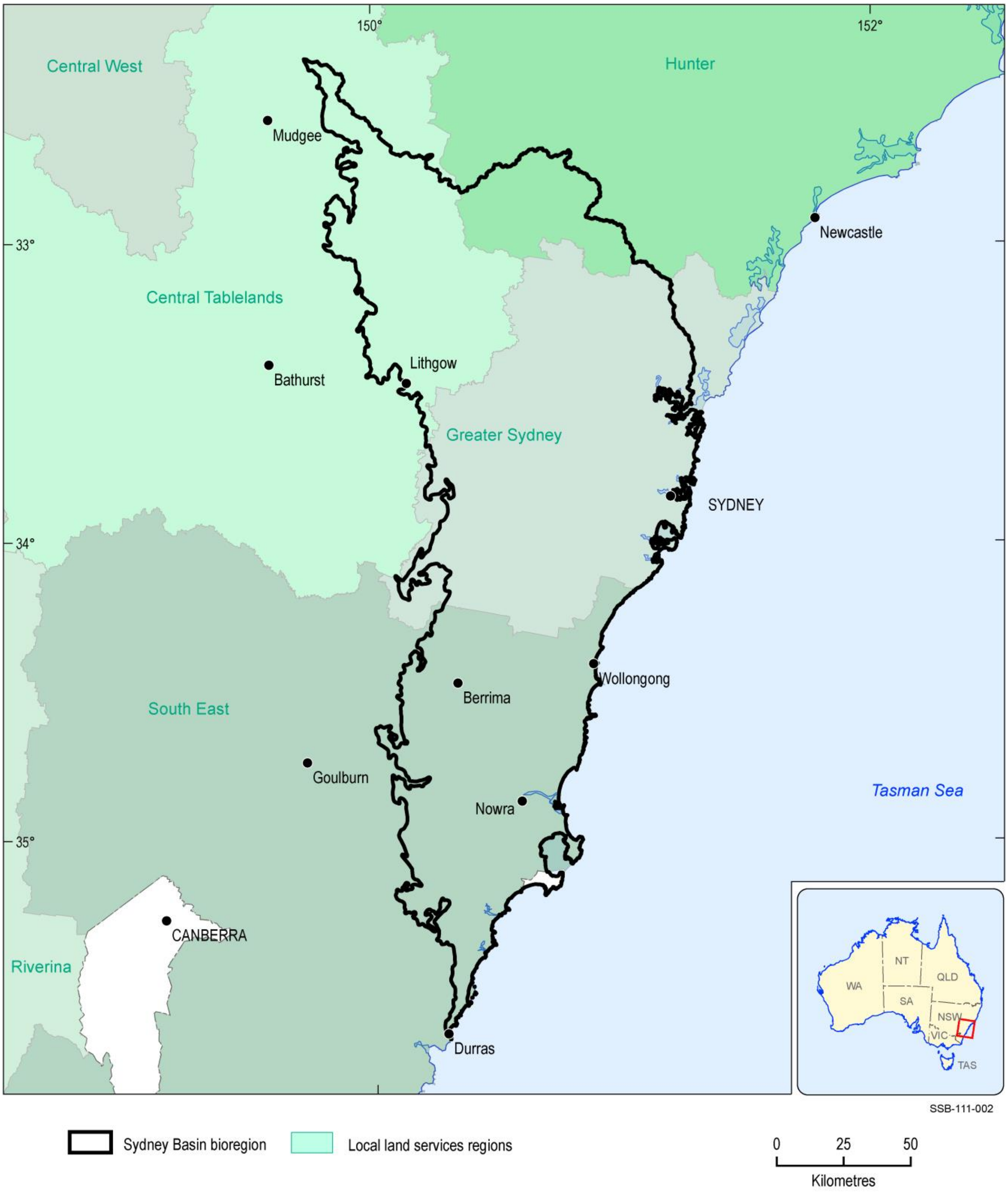

Figure 5 Local land services regions relative to the Sydney Basin bioregion

Data: Local Land Services, Trade and Investment NSW (Dataset 4)

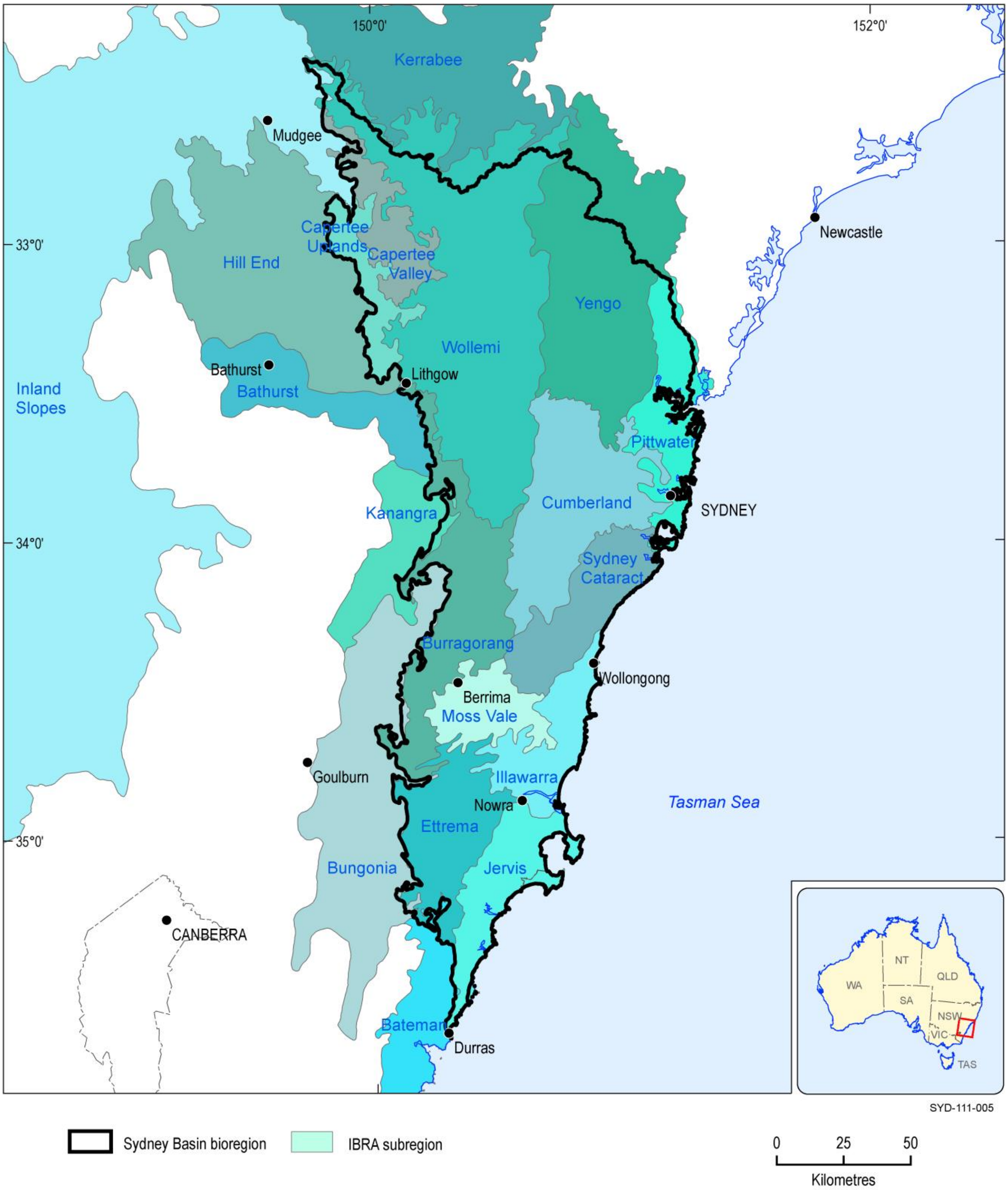

Figure 6 Interim Biogeographic Regionalisation for Australia (IBRA) subregions relative to the Sydney Basin bioregion

Data: Department of Sustainability, Environment, Water, Population and Communities (Dataset 5)

Table 4 Interim Biogeographic Regionalisation for Australia (IBRA) subregions contained within the Sydney Basin bioregion

IBRA[a] name	IBRA[a] subregion code	Area (km^2)	Area in Sydney Basin bioregion (km^2)	Percentage of IBRA[a] subregion in Sydney Basin bioregion (%)	Percentage of Sydney Basin bioregion (%)
Wollemi	SYB04	6,876	5885	85.6%	23.9%
Yengo	SYB05	4,613	3229	70.0%	13.1%
Cumberland	SYB08	2,757	2757	100.0%	11.2%
Burragorang	SYB09	2,576	2519	97.8%	10.2%
Ettrema	SYB13	1,791	1773	99.0%	7.2%
Cataract	SYB10	1,538	1538	100.0%	6.2%
Jervis	SYB14	1,360	1344	98.9%	5.5%
Pittwater	SYB07	1,484	1332	89.8%	5.4%
Illawarra	SYB12	1,228	1227	100.0%	5.0%
Capertee Valley	NSS03	1,015	975	96.0%	4.0%
Moss Vale	SYB11	969	969	100.0%	3.9%
Capertee Uplands	SEH17	805	767	95.3%	3.1%
Bungonia	SEH07	4,312	131	3.0%	0.5%
Kanangra	SEH08	1,313	86	6.5%	0.3%
Inland Slopes[b]	NSS01	40,741	40	0.1%	0.2%
Bateman[b]	SEC03	1,740	31	1.8%	0.1%
Hill End[b]	SEH13	5,044	17	0.3%	0.1%
Bathurst[b]	SEH11	1,615	6	0.3%	0.0%

These data are listed in descending order based on their area in the Sydney Basin bioregion.
[a] Interim Biogeographic Regionalisation for Australia subregion
[b] inclusion of this IBRA subregion could be an artefact of mapped boundaries.
Data: Department of Sustainability, Environment, Water, Population and Communities (Dataset 5)

As at May 2015, the Sydney Basin bioregion contained all or parts of 54 NSW LGAs (Australian Bureau of Statistics, 2011) (Figure 7 and Table 5). The high number of LGAs reflects the high population density within the Sydney metropolitan area, which has 33 LGAs (listed in Figure 7). The largest LGAs (>1000 km^2) are the non-Sydney metropolitan areas of Shoalhaven, Lithgow, Hawkesbury, Wingecarribee, Wollondilly, Singleton, Mid-Western Region and Blue Mountains. Sydney metropolitan LGAs vary in size from around 6 km^2 (Hunters Hill LGA) to 460 km^2 (Hornsby LGA).

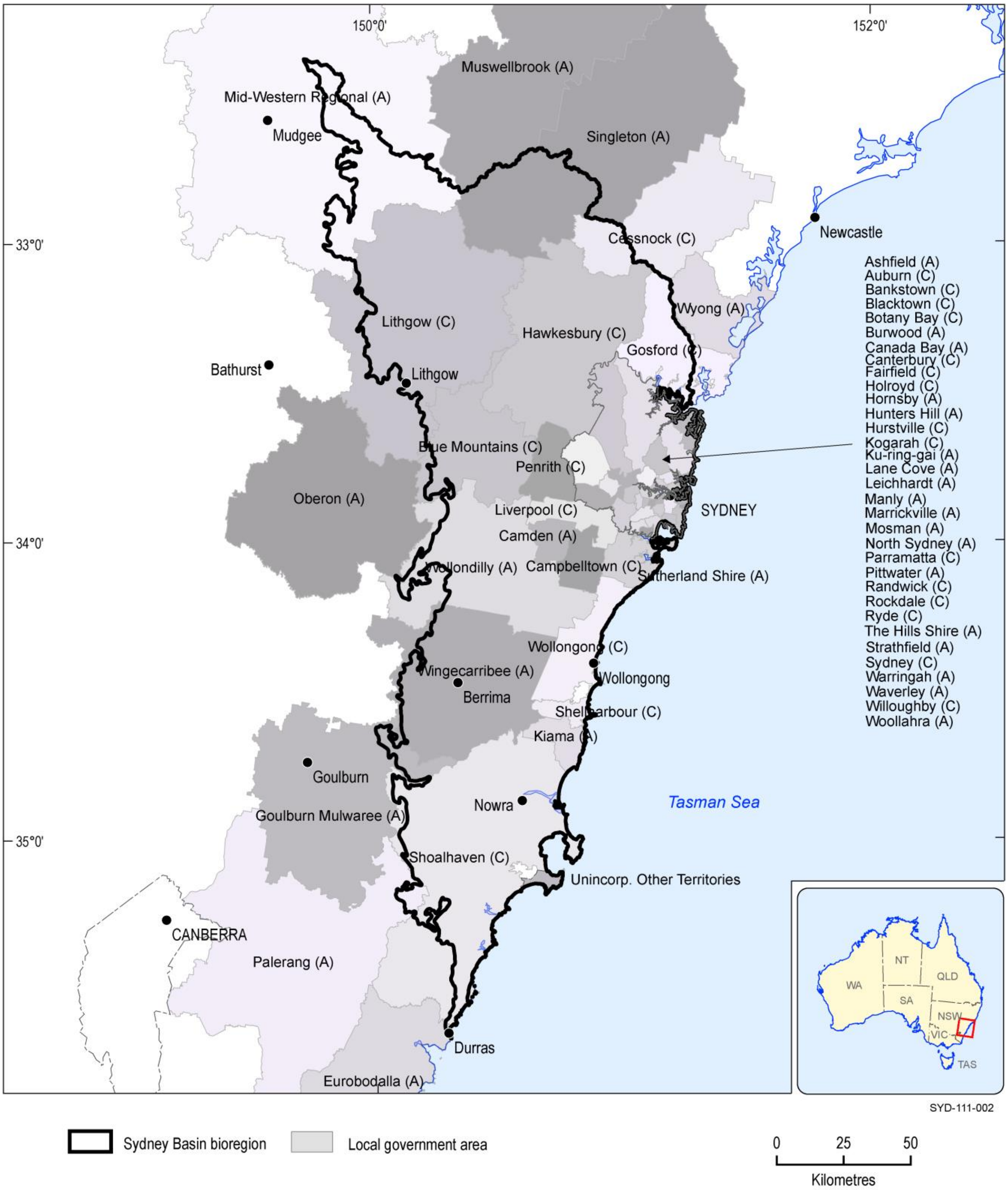

Figure 7 Local government areas relative to the Sydney Basin bioregion

Data: Australian Bureau of Statistics (Dataset 6)

Table 5 Local government areas (LGAs) contained within the Sydney Basin bioregion

LGA name[a]	Area (km^2)	Area in Sydney Basin bioregion (km^2)	Percentage of LGA in Sydney Basin bioregion (%)	Percentage of Sydney Basin bioregion (%)
Shoalhaven (C)	4530	3547	78.3%	14.5%
Lithgow (C)	4512	3332	73.9%	13.6%
Hawkesbury (C)	2775	2774	100.0%	11.3%
Wingecarribee (A)	2688	2383	88.6%	9.7%
Greater Sydney LGAs[b]	2135	2126	99.6%	8.7%
Wollondilly (A)	2556	2046	80.0%	8.4%
Singleton (A)	4893	1462	29.9%	6.0%
Mid-Western Regional (A)	8753	1381	15.8%	5.6%
Blue Mountains (C)	1431	1328	92.8%	5.4%
Gosford (C)	940	698	74.3%	2.9%
Wollongong (C)	684	682	99.8%	2.8%
Penrith (C)	405	405	100.0%	1.7%
Cessnock (C)	1965	380	19.3%	1.6%
Sutherland Shire (A)	334	333	99.7%	1.4%
Campbelltown (C)	312	312	100.0%	1.3%
Liverpool (C)	305	305	100.0%	1.2%
Kiama (A)	258	257	99.7%	1.1%
Goulburn Mulwaree (A)	3220	203	6.3%	0.8%
Camden (A)	201	201	100.0%	0.8%
Shellharbour (C)	147	147	99.4%	0.6%
Palerang (A)	5147	84	1.6%	0.3%
Unincorp. Other Territories	218	66	30.3%	0.3%

These data are listed in descending order based on their area in the Sydney Basin bioregion.

[a] LGA names are as they appear in the database – (A) = area (i.e. shire) council; (C) = city council

[b] includes LGAs of: Ashfield, Auburn, Bankstown, Blacktown, Botany Bay, Burwood, Canada Bay, Canterbury, Fairfield, Holroyd, Hornsby, Hunters Hill, Hurstville, Kogarah, Ku-ring-gai, Lane Cove, Leichhardt, Manly, Marrickville, Mosman, North Sydney, Parramatta, Pittwater, Randwick, Rockdale, Ryde, The Hills Shire, Strathfield, Sydney, Warringah, Waverley, Willoughby, Woollahra

Data: Australian Bureau of Statistics (Dataset 6)

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Dataset 6 Australian Bureau of Statistics (2011) Local Government Areas of Australia. Bioregional Assessment Source Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/1d139f3a-fc76-4717-863c-3689413ee9c0.

1.1.2 Geography

Summary

The Sydney Basin bioregion covers an area of about 24,625 km^2. It extends along the eastern Australian seaboard from the Hawkesbury River estuary in the north to just south of Durras on the southern NSW coast. Its western boundary is defined by the geological Sydney Basin and its eastern boundary by the Australian coastline. Elevation in the subregion ranges from sea level to 1260 mAHD (metres above Australian Height Datum). Much of the bioregion is characterised by relatively rugged terrain associated with the heavily dissected rock outcrops of the Hawkesbury Sandstone. Inland from Sydney and Nowra and south of Wollongong, the terrain is flatter, reflecting the development of coastal plains from the interactions of rivers with the sea.

The bioregion is characterised by a large area of urban land (14% of the bioregion) and very extensive areas of land used for nature conservation (41%) and other minimal uses (almost 16%). It is one of the most species-diverse of the IBRA regions in Australia and home to a large number of national parks, including the Blue Mountains, Wollemi, Kuring-gai Chase and Royal national parks around Sydney and the linked Morton and Budawang national parks to the south of the bioregion.

Two major river basins drain the bioregion: the Hawkesbury-Nepean river basin, which covers 65% of the bioregion and the Shoalhaven river basin (12% of bioregion) in the south. Other river basins include the eastward-draining streams of the Sydney Coast-Georges River, Wollongong Coast and parts of Clyde River-Jervis Bay basins, and a small part of the west-draining Macquarie-Bogan river basin.

The population of the Sydney Basin bioregion is around five million, concentrated mainly within the area occupied by the Greater Sydney region, with smaller concentrations in Wollongong, Nowra and Southern Highlands towns. Most of the water for these cities and towns is supplied from an integrated water supply network, comprising 21 major storages within the Hawkesbury-Nepean and Shoalhaven river basins, with pipelines to move water between different catchments. This water supply system is managed by WaterNSW. Groundwater use is relatively small component of total use within the bioregion.

The Sydney Basin bioregion has a temperate climate. Mean monthly temperatures for winter are below 10 °C and for summer around 20 °C, but parts of the region are characterised by hot summers, particularly along the coast and at lower elevations. The long-term (1900 to 2012) mean precipitation is 951 mm/year, but there is considerable inter-annual variability. The bioregion does not have a dry season, but the temporal pattern indicates summer dominant rainfall with December to March averaging 90 to 120 mm/month, while July to October averages about 60 mm/month.

1.1.2.1 *Physical geography*

The Sydney Basin bioregion extends along the eastern Australian seaboard from the Hawkesbury River estuary in the north to just south of Durras on the southern NSW coast. Its western boundary is defined by the geological Sydney Basin and its eastern boundary by the Australian coastline (Figure 8). Most of the western boundary is east of the Great Divide with the headwaters of the Wollondilly and Shoalhaven rivers lying to the west of the bioregion. In the north-west, the bioregion crosses the Great Dividing Range into the westerly draining Macquarie river basin. The bioregion contains the major cities of Sydney and Wollongong, as well as some smaller urban centres including Lithgow in the west, Nowra in the south and a number of towns in the Southern Highlands. Just over 40% of the bioregion is used for conservation, including the Blue Mountains National Park, Wollemi National Park and Morton National Park.

The Sydney Basin bioregion is defined by geology in the west, the Hunter Range topographic divide in the north and the coastline in the east. Land surface elevations range from sea level to 1260 mAHD (metres Australian Height Datum) at Mount Coricudgy in the north (Figure 8). Much of the bioregion is characterised by relatively rugged terrain associated with the heavily dissected rock outcrops of the Hawkesbury Sandstone. Inland from Sydney and Nowra and south of Wollongong, the terrain is flatter, reflecting the development of coastal plains from the interactions of rivers with the sea. The tableland areas around Berrima in the Southern Highlands and west of Mount Coricudgy also have flatter relief. Figure 9 shows some very marked breaks of slope where the rugged Hawkesbury Sandstone country meets the coastal plains, with dramatic cliffs, giving way to short, steep colluvial slopes and then flat alluvial environments.

Two major river basins drain the bioregion (Figure 10). They are the Hawkesbury-Nepean river basin, which covers 16,049 km^2 or 65% of the bioregion and the Shoalhaven river basin (2905 km^2; 12% of bioregion) in the south. The remaining area includes three small coastal river basins (4805 km^2) – Sydney Coast-Georges River; Wollongong Coast and part of Clyde River-Jervis Bay – and a small part of the Macquarie-Bogan river basin (1530 km^2), which lies to the west of the Sydney Basin bioregion. Major tributaries within the Hawkesbury-Nepean river basin include the Macdonald, Colo and Wollondilly rivers. Much of the river basin upstream of Lake Burragorang, the water supply reservoir created by Warragamba Dam, lies outside the bioregion. Similarly, the headwaters of the Shoalhaven River are outside the bioregion. The Cudgegong River, which flows westward into the Macquarie River, rises in the Sydney Basin bioregion. Section 1.1.5 provides more detail about the surface water hydrology of the bioregion.

The coast is characterised by drowned river valleys and coastal lake systems. Around Sydney, these include Broken Bay, Port Jackson, Botany Bay and Port Hacking; moving southward, they include Lake Illawarra, Sussex Inlet, Lake Conjola and Burrill Lake – all are important water bodies for recreation and habitat (Figure 10).

Figure 8 Surface elevation of the Sydney Basin bioregion

Data: Bioregional Assessment Programme (Dataset 1, Dataset 2); Geoscience Australia (Dataset 3)

Figure 9 Land surface slopes of the Sydney Basin bioregion

Data: CSIRO (Dataset 4)

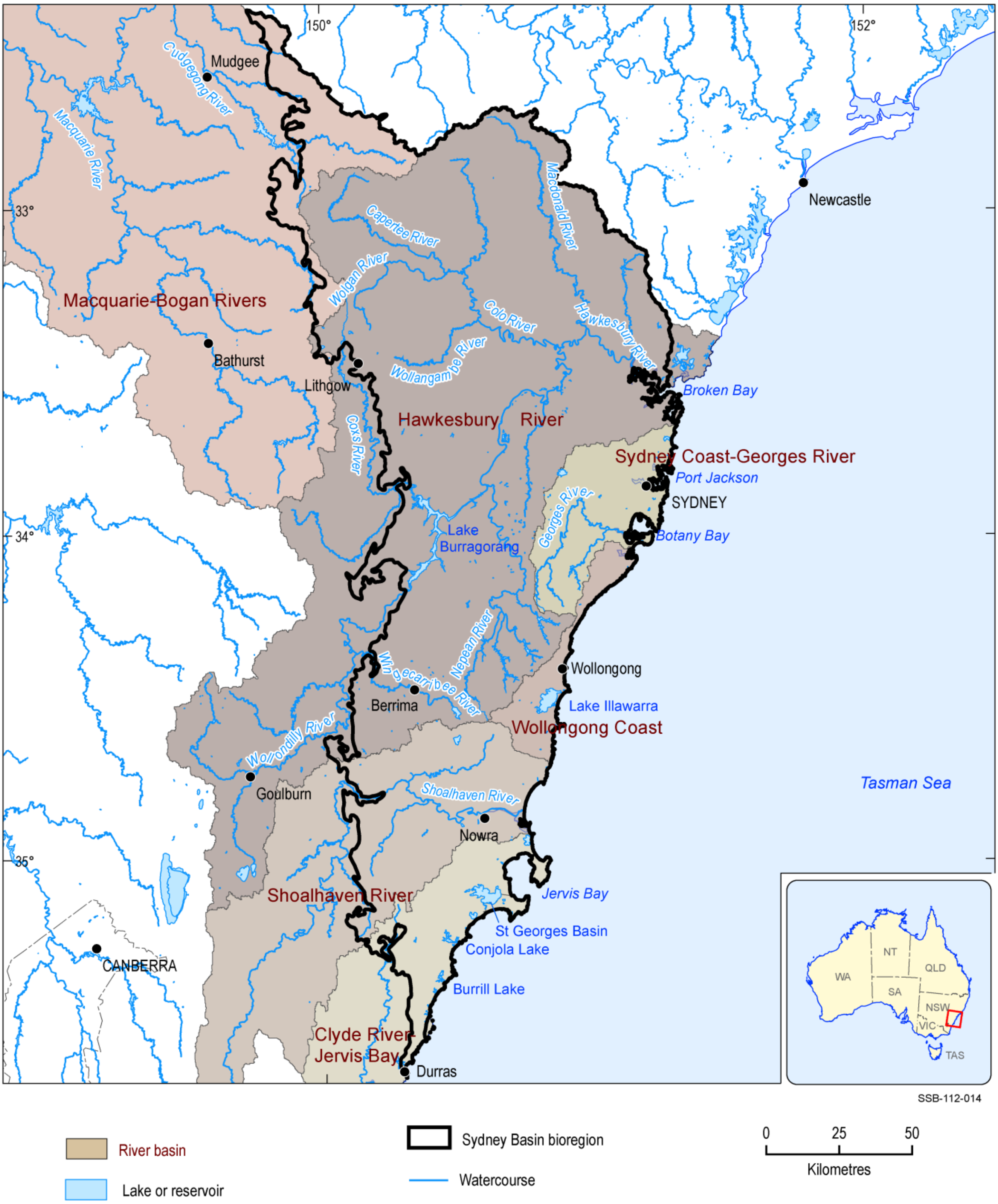

Figure 10 Major river basins and selected surface water bodies of the Sydney Basin bioregion

Data: Bureau of Meteorology (Dataset 5); Bioregional Assessment Programme (Dataset 6)

1.1.2.1.1 Physiography and soils

The Sydney Basin bioregion is comprised of four physiographic regions of the Australian Soil Resource Information System (ASRIS) (Figure 11). Physiographic regions are defined by an internal coherence of their landform characteristics and underlying geology (Jennings and Mabbutt, 1986). They are considered to be areas of similar landform evolutionary history, which have given rise to similar groups of regolith materials, such that the resultant mapped units can be described in terms of landform, underlying geology, regolith and soils (Pain et al., 2011). The main ASRIS classes are (i) Hawkesbury-Shoalhaven Plateaus, (ii) Bathurst Tablelands, (iii) Cumberland Lowland and (iv) Monaro Fall. Figure 11 shows a tiny intersect with the Goulburn Corridor in the north, which likely reflects scale of mapping. It is not included in Table 6. The Interim Biogeographic Regionalisation for Australia (IBRA) subregions shown in Figure 6 of Section 1.1.1 broadly conform to these physiographic regions (Table 6). Table 7 summarises the IBRA subregions by geology, landform and soils.

Table 6 Australian Soil Resource Information System physiographic classes in the Sydney Basin bioregion and corresponding Interim Biogeographic Regionalisation for Australia subregions

Code	ASRIS[a] class name	Area in bioregion (km^2) (%)	Corresponding IBRA[b] subregions
10607	Hawkesbury-Shoalhaven Plateaus	18,634 (76%)	Wollemi, Yengo, Pittwater, Burragorang, Sydney Cataract, Moss Vale, Illawarra, Ettrema
10606	Bathurst Tablelands	2,435 (10%)	Capertee Valley, Capertee Uplands
10608	Cumberland Lowland	2,110 (9%)	Cumberland
10705	Monaro Fall	1,390 (6%)	Jervis

[a] Australian Soil Resource Information System
[b] Interim Biogeographic Regionalisation for Australia
Data: CSIRO (Dataset 7)

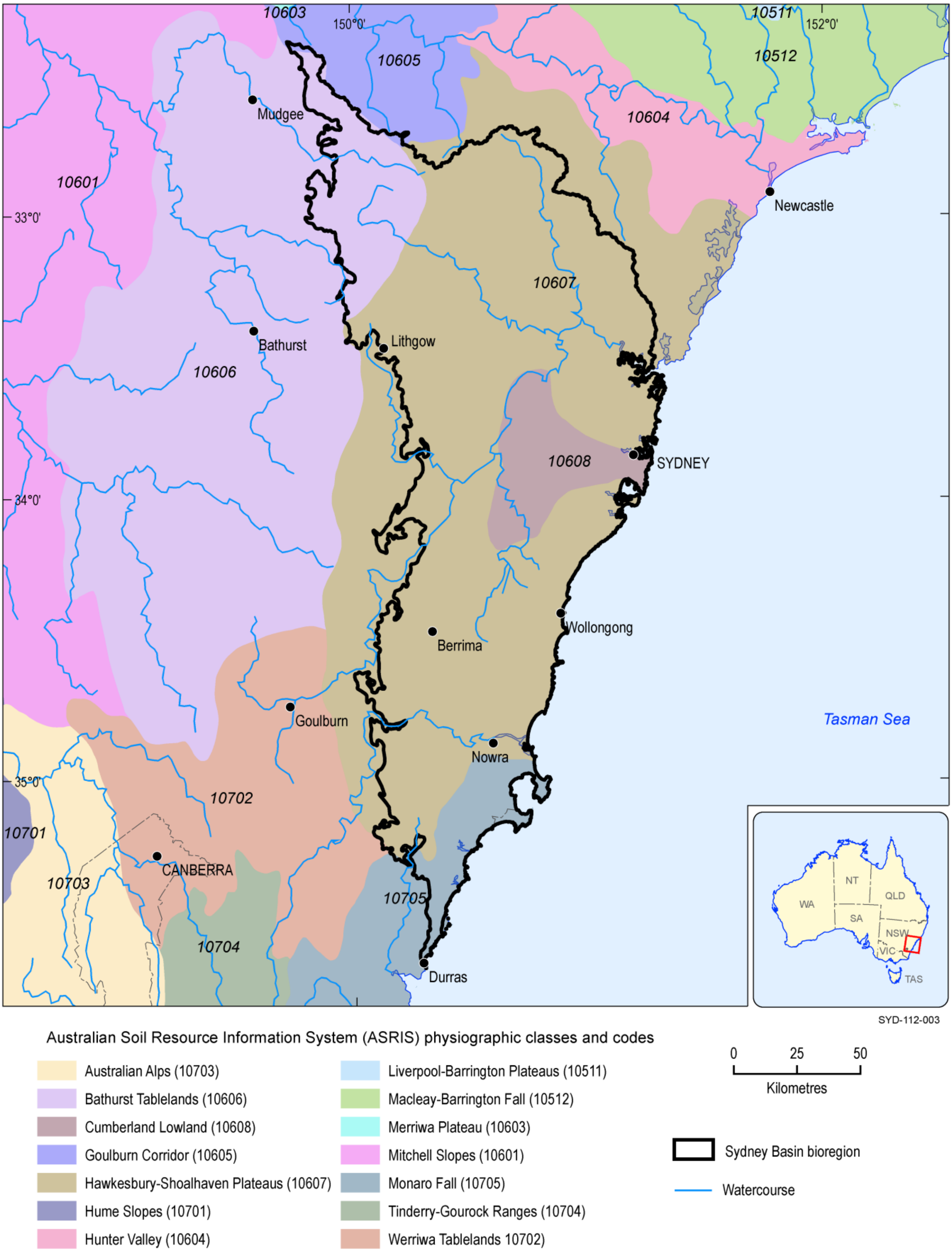

Figure 11 Australian Soil Resource Information System (ASRIS) physiographic classes and codes in the Sydney Basin bioregion

Data: CSIRO (Dataset 7)

Table 7 Geology, landforms and typical soils of the main Interim Biogeographic Regionalisation for Australia subregions in the Sydney Basin subregion

IBRA[a] subregion	Geology	Characteristic landforms	Typical soils
Wollemi	Hawkesbury Sandstone and equivalent quartz sandstones of Narrabeen Group, subhorizontal bedding, strong vertical joint patterns. A few volcanic necks.	Highest part of the Blue Mountains. Sandstone plateau with benched rock outcrops. Creek directions controlled by jointing deep gorge of the Capertee and Wolgan rivers.	Thin sands or deep yellow earths on plateau, thin texture contrast soils on shale benches. Organic sands in swamps and joint crevices, bouldery slope debris below cliffs, sandy alluvium in pockets along the streams. Red brown structured loams on basalts.
Yengo	Hawkesbury Sandstone, valleys incised to Narrabeen Group sandstone, a few volcanic necks and basalt caps, Quaternary sandy alluvium and high level sands on Mellong Range and Maroota. Quaternary muddy sands in Hawkesbury upper estuary.	Benched sandstone plateau with steep slopes into narrow valleys with low cliff lines on Narrabeen sandstone. Structurally controlled subrectangular drainage pattern. Northern end of Lapstone monocline controls Mellong Range. Hawkesbury River gorge cuts across the subregion, tributary streams dammed by levees form freshwater swamps adjacent to the river.	Shallow quartz sands on plateau, some areas of deep yellow earth and patches of Podosol development on sandstone benches and in all Cenozoic and Quaternary high-level sands. Texture contrast soils on shales, deep clean sands in alluvium. Red brown structured loams and clay loams on basalt.
Pittwater	Hawkesbury Sandstone with thin ridge cappings of Ashfield Shale. Narrabeen Group sandstones exposed in valleys and along the coast. Quaternary coastal sands.	Hornsby plateau of quartz sandstone with occasional shale caps. Small beach, dune and lagoon barrier systems. Steep coastal cliffs and rock platforms.	Deep yellow earths or rocky outcrop on plateau tops. Uniform and texture contrast soils on sandstones and shale slopes. Loamy sands in alluvium along creeks, clean quartz sands with moderate shell content on beaches and frontal dunes. Organic sands and muds in estuaries.
Burragorang	Permian and Triassic sandstones and shales on the western edge of the Basin. Limited basalt caps.	Rolling hills on a sandstone plateau with deep gorges and sandstone cliffs in Burragorang valley.	Rocky outcrops, texture contrast soils and uniform sands on sandstone. Bouldery debris with sandy clay matrix below cliffs. Rich loams in alluvium.
Cataract	Hawkesbury Sandstone on the coastal edge of the Basin above the Illawarra escarpment. Quaternary sands and muds in Georges River and Botany Bay.	Sandstone plateau with shallow creeks flowing through hanging swamps in the highest parts ramping down to low hills in the Georges River and Botany Bay. Coastal cliffs north of the Illawarra. Large barrier system with beach, dunes, swamps, and estuary at Kurnell.	Deep sands and clayey sands with peat in hanging swamps, yellow earths on better drained sandstone ridges. Siliceous sands in younger dunes and well-developed podzols in older dunes. Organic sands in swamps and estuary.

IBRA[a] subregion	Geology	Characteristic landforms	Typical soils
Moss Vale	Triassic Wianamatta Group shales, Paleogene and Neogene basalts and trachyte intrusions, large Quaternary peat swamp.	Shale and basalt plateau with rolling hills and shallow valleys. Very large peat swamp at Wingecarribee.	Structured red and red brown clay loams and loams, and loamy alluvium with high fertility. Areas of sandstone at the margins thin, waterlogged sandy soils. Organic peat in swamps. Stony slope debris on larger intrusions.
Illawarra	Permian siltstones, shale, sandstones and interbedded volcanics on and below the coastal escarpment. Quaternary alluvium and coastal sands.	Vegetated cliff faces on coastal escarpment with waterfalls and steep streams. Bouldery debris slopes with sandy clay matrix and low hills and alluvial valleys on coastal ramp. Barrier systems at Lake Illawarra and Nowra.	Structured red and red brown loams and clay loams with some areas of mellow texture contrast soils. Fertility high and good water holding capacity. Siliceous sands on beaches and dunes, podzol profiles in older dunes, peaty sands and organic silts in swamps and estuaries.
Ettrema	Permian horizontal quartz sandstone alternating with shales. Deep gorges expose Silurian volcanics and Carboniferous granite in underlying Lachlan Fold Belt. Limited Paleogene and Neogene basalt with river gravels.	Low stepped hills on plateau with deeply incised streams off plateau edge below waterfalls on the escarpment.	Alternating sandstone and shale create bare rock benches and soil benches with shallow, often saturated sand. Structured red brown clay loams on basalt.
Capertee[b]	Permian Shoalhaven Group conglomerates, sandstones, and shales with coal at the base of the Sydney Basin and exposure of underlying Devonian shale, siltstone or quartzite. Eastern margin of Narrabeen Group sandstone in cliffs. Small areas of hill top Paleogene and Neogene basalt.	Wide valleys, low-rolling hills below sandstone cliffs, Isolated flat top mountains in the valleys formed as pinnacles or remnant pieces of plateau. Steep, bouldery debris slope below cliffs. Shoulder slopes with stone pillars or "pagodas" above steep canyons on tributary streams falling into gorges. Low gradient swampy stream lines.	Shallow stony texture contrast profiles, usually with gritty well drained A horizons, over tough yellow or grey poorly drained clays. Bouldery debris with clay matrix below cliffs (talus). Organic sands in swamps. Red brown structured loams on basalts.
Cumberland	Triassic Wianamatta Group shales and sandstones. A downwarped block on the coastal side of the Lapstone monocline. Intruded by a small number of volcanic vents and partly covered by Paleogene and Neogene river gravels and sands. Quaternary alluvium along the mains streams.	Low rolling hills and wide valleys in a rain shadow area below the Blue Mountains. At least three terrace levels evident in the gravel splays. Volcanics from low hills in the shale landscapes. Swamps and lagoons on the floodplain of the Nepean River.	Red and yellow texture contrast soils on slopes, becoming harsher and sometimes affected by salt in tributary valley floors. Pedal uniform red to brown clays on volcanics. Poor uniform stony soils, often with texture contrast profiles on older gravels, high quality loams on modern floodplain alluvium.

IBRA[a] subregion	Geology	Characteristic landforms	Typical soils
Jervis	Permian quartz sandstone and mixed shale and lithic sandstones. Paleogene and Neogene trachyte intrusives at Milton. Limited Paleogene and Neogene sands and more extensive Quaternary coastal sands.	Escarpment faces west and south and sandstone plateau rises to small peaks like Pigeon House. Waterfalls and gorges off the escarpment but low hills and coastal ramp on siltstones to Jervis Bay. Well-developed coastal barrier with Jervis Bay enclosed by tied islands. Pleistocene cliff top dunes on the peninsula with fresh lakes created by watertable windows.	Poor shallow sands on quartz sandstone plateau similar to Ettrema. Deep texture contrast soils with loam topsoils on coastal shales, moderate fertility but waterlogged valley floors. Coastal barriers extend from clean dune sands to deep podzols in Pleistocene dunes. Organic sands and muds in swamps and estuary.

[a]Interim Biogeographic Regionalisation for Australia (SEWPaC, 2012)
[b]source document does not differentiate between Capertee Upland and Capertee Valley
Data: NSW National Parks and Wildlife Service (2003)

Soils of the Sydney Basin bioregion can be classed into seven main Australian Soil Classification (Isbell, 2002) soil types (Figure 12): Tenosols (25%), Kurosols (22%), Kandosols (16%), Rudosols (15%), Dermosols (10%), Sodosols (6%) and Chromosols (4.0 %). Localised occurrences of Ferrosols, Hydrosols, Podosols and Organosols have also been mapped. The Hawkesbury-Shoalhaven physiograpic province is dominated by Tenosols, Dermosols and Kandosols in the north and west, with Kurosols, Rudosols and Ferrosols becoming more important to the south; the Cumberland Lowland province is characterised by Sodosols and Kurosols; that part of the Monaro Fall province that lies within the Sydney Basin bioregion is dominated by Kurosols; and the Bathurst Tablelands province, which includes the Capertee Uplands and Capertee Valley IBRA subregions, has a wide mix of soil types, including significant areas of Chromosols and Sodosols. Characteristics of the main soil types are summarised below, ordered by descending area.

Tenosols are soils which are young, typically very sandy and exhibit a weakly developed soil profile, except perhaps for the A horizon. They generally have low agricultural potential due to low chemical fertility, poor structure and low water holding capacity.

Kurosols tend to develop in mid- and lower slope positions. They are characterised by a clear, sharp textural boundary between coarser textured A horizons (e.g. sands or loams) and finer textured (i.e. clayey) B horizons (Isbell, 2002). The surface of the soils is often acidic (pH <5.5). These soils are found predominantly in the Cumberland and Monaro Fall IBRA subregions.

Kandosols do not exhibit strong texture contrast between the A and B horizons. Instead the B horizon tends to have a massive or weakly developed structure. They have moderate chemical fertility and water holding capacity.

Rudosols are generally associated with upper slopes, ridges and crests. These soils are poorly developed and typically young, so have had little time to develop structure. They may be deep or shallow, and either clayey, or loamy or sandy throughout the profile. Rudosols may also be stony.

Dermosols are likely to be dominated by clay that is near uniform to slowly changing in texture in the profile (Isbell, 2002). These are well-structured soils and generally more clayey in the floodplains, where the deepest soils in the Sydney Basin bioregion are likely to be found. They occur in the lower lying parts of the Hawkesbury-Shoalhaven Plateau, north and east of Lithgow, and along the coast to the south of Wollongong.

Sodosols generally develop on lower hillslopes or in perched upper slope locations. They are often associated with salinity (e.g. at seeps or where drainage is poor). Soils exhibit a strong contrast in textures between topsoil and poorly structured, dispersible clay subsoils. Agriculture can be a challenge due to structural issues (caused by excessive sodium ions) and salinity. In the Sydney Basin bioregion, Sodosols occur in the western parts of the Cumberland IBRA subregion, east of the Nepean River and in the north-west corner of the Capertee Valley and Capertee Uplands IBRA subregions.

Chromosols have a strong texture contrast and form from quartz-rich parent material. In the Sydney Basin bioregion, they are found in the upper Capertee river basin and in the Nepean river basin in the south of the Cumberland Lowlands physiographic province.

Organic rich soils are typical of the bioregion’s many swamps and estuarine areas.

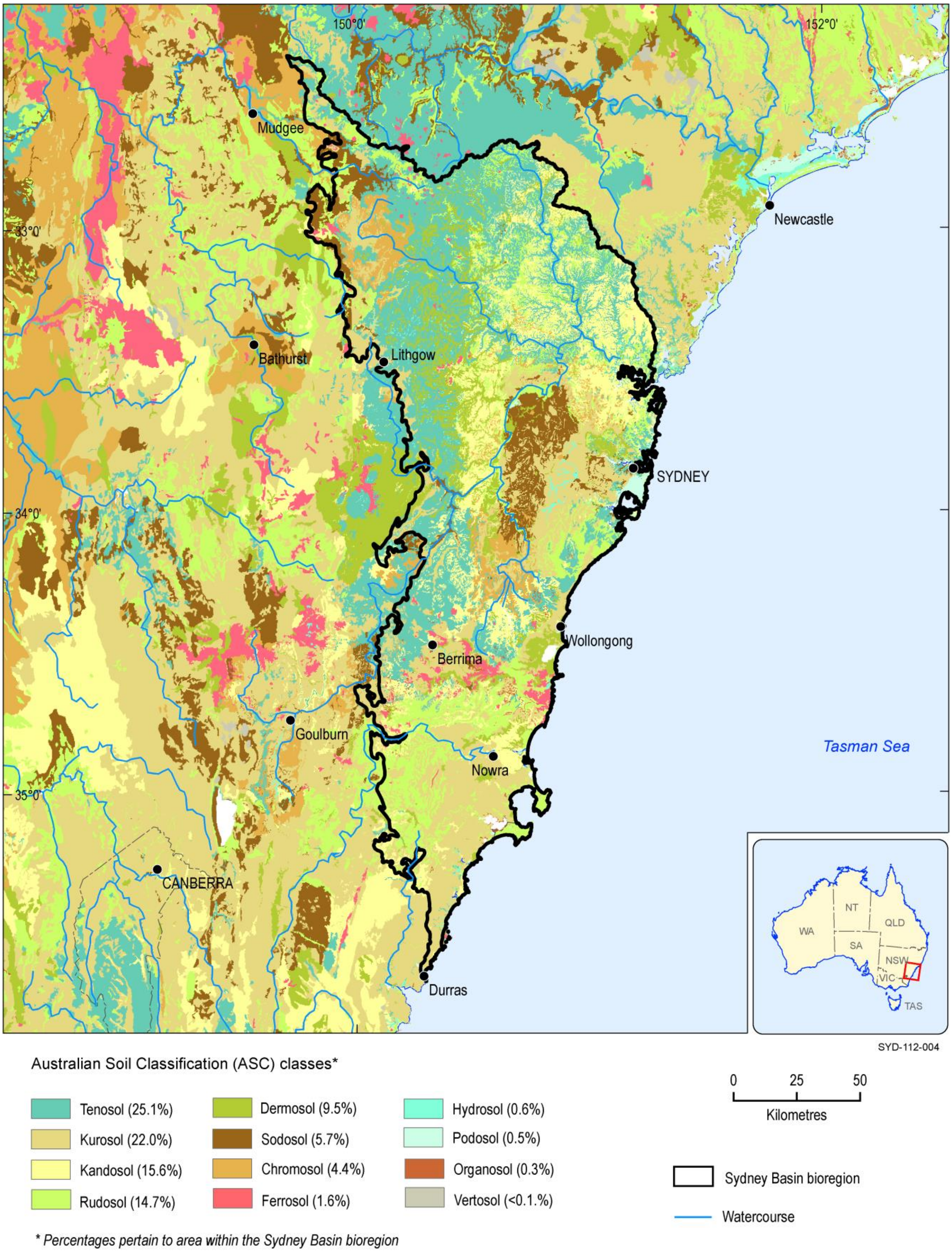

Figure 12 Australian Soil Classification (ASC) classes for the Sydney Basin bioregion

Data: CSIRO (Dataset 8)

1.1.2.1.2 Vegetation cover

Figure 13 shows the land cover in the Sydney Basin bioregion in 2008, based on remotely sensed data that are post-processed to convert vegetation greenness to a land cover type (Geoscience Australia, Dataset 9). The bioregion is overwhelmingly dominated by trees, reflecting (i) good rainfall, (ii) the rugged topography (i.e. difficult to develop) of the deeply incised sandstone country of the Blue Mountains and Illawarra and Southern Highlands escarpments, and (iii) the associated conservation status of significant tracts of the bioregion and the protected area status of much of the water supply catchments around Sydney and Wollongong (see also Figure 15). Major vegetation type mapping of the bioregion (Figure 48 in Section 1.1.7) indicates that these treed areas are mostly different eucalypt forest and woodland types, but that the lower density treed areas of the Cumberland IBRA subregion around Sydney include cleared, non-native vegetation and buildings. Areas of irrigated pasture are evident along the coastal zone between Wollongong and Nowra, with much of the rest of the land cover being classed as rainfed pasture.

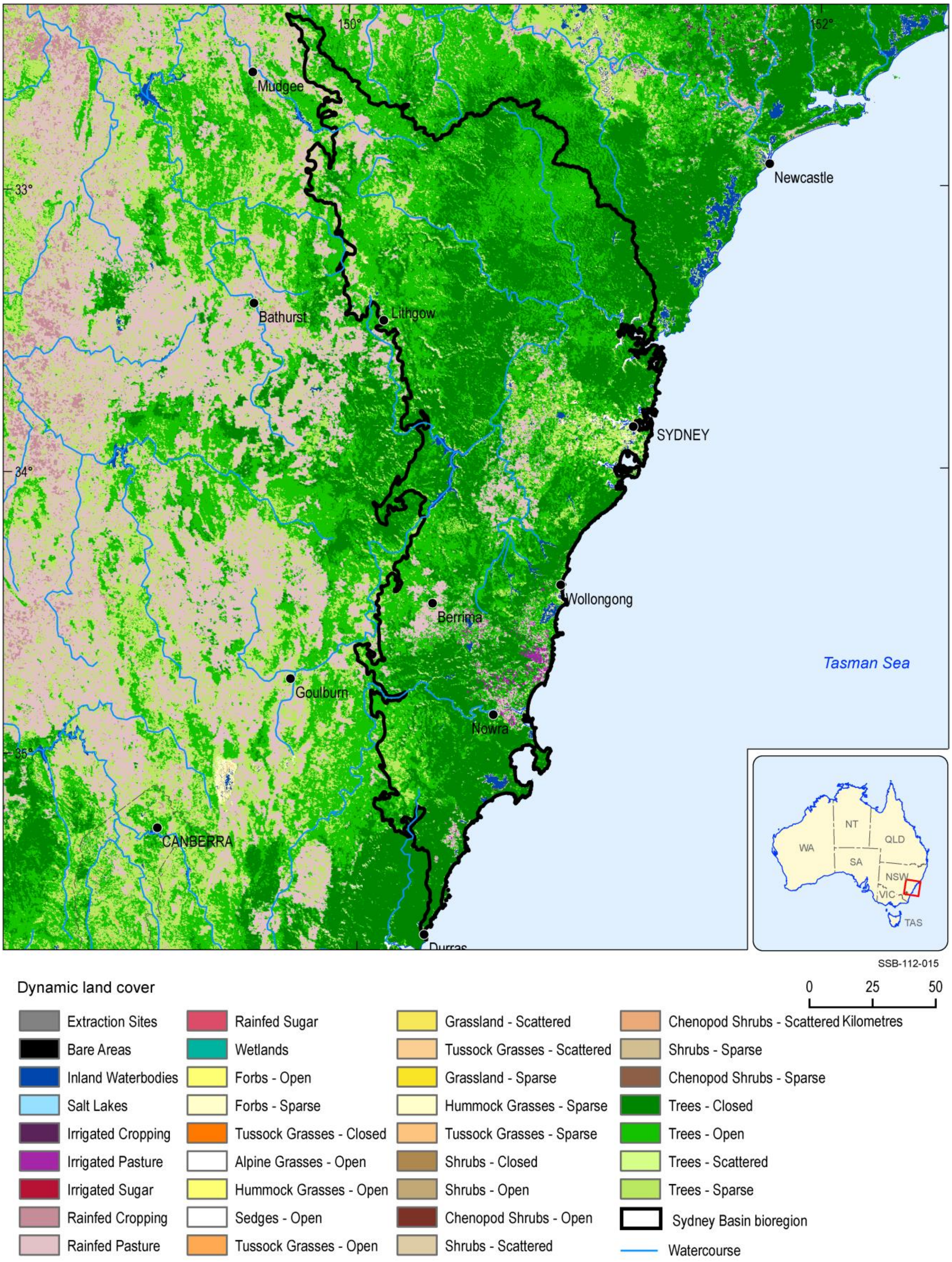

Figure 13 Vegetation cover of the Sydney Basin bioregion

Data: Geoscience Australia (Dataset 9)

1.1.2.2 *Human geography*

The population of the Sydney Basin bioregion is concentrated within the area occupied by the Greater Sydney region. The estimated resident population of the area known and reported by the Australian Bureau of Statistics as the Greater Sydney Greater Capital City Statistical Area (GCCSA) at 30 June 2014 was 4.84 million, which is about two-thirds of the total population of NSW (Australian Bureau of Statistics, 2015). This area includes Central Coast and Blue Mountains. The Central Coast is not within the bioregion, so the number represents a slight overestimate. The Illawarra and Southern Highlands and Shoalhaven statistical local areas (ABS SA4 level) were estimated to have 296,845 and 146,388 residents in 2014 (Australian Bureau of Statistics, 2015), putting the total for the Sydney Basin bioregion at around 5 million.

After Sydney, Wollongong is the next largest settlement in the Sydney Basin bioregion. The combined populations of the Southern Highlands towns, including Mittagong, Bowral and Moss Vale, constitute the next largest population centre, followed by Nowra. Table 8 provides the 2014 populations for the five main urban centres within the bioregion. Figure 14 illustrates the population density distribution with major concentrations around Sydney and Wollongong and along a corridor west of Sydney to the Blue Mountains. Most of the coastal zone is well developed, as is the corridor from Sydney through the Southern Highlands towns around Berrima and onto Goulburn.

Table 8 Major population centres of the Sydney Basin bioregion and their 2014 populations

Urban centre	Population
Sydney	4,451,841
Wollongong	289,236
Bowral-Mittagong	37,495
Nowra	35,383
Lithgow	12,989

Data: Australian Bureau of Statistics (2015)

Figure 15 shows the pattern of land use across the Sydney Basin bioregion. The bioregion is distinctive because of (i) the very large area of urban (intensive) land (14% of the bioregion), (ii) the very extensive areas of land used for nature conservation (41%) and (iii) other minimal uses (almost 16%). The bioregion has a large number of national parks, including (i) the Blue Mountains National Park, Wollemi National Park, Yengo National Park and Kanangra-Boyd National Park in the north and west, (ii) the Kuring-gai Chase National Park and Royal National Park, directly to the north and south of Sydney, respectively and (iii) the linked Morton National Park and Budawang National Park, which extend from inland of Kiama to inland of Durras at the southern end of the bioregion. Other smaller, less well known national parks and conservation areas are located throughout the bioregion, some of them contiguous with the aforementioned parks.

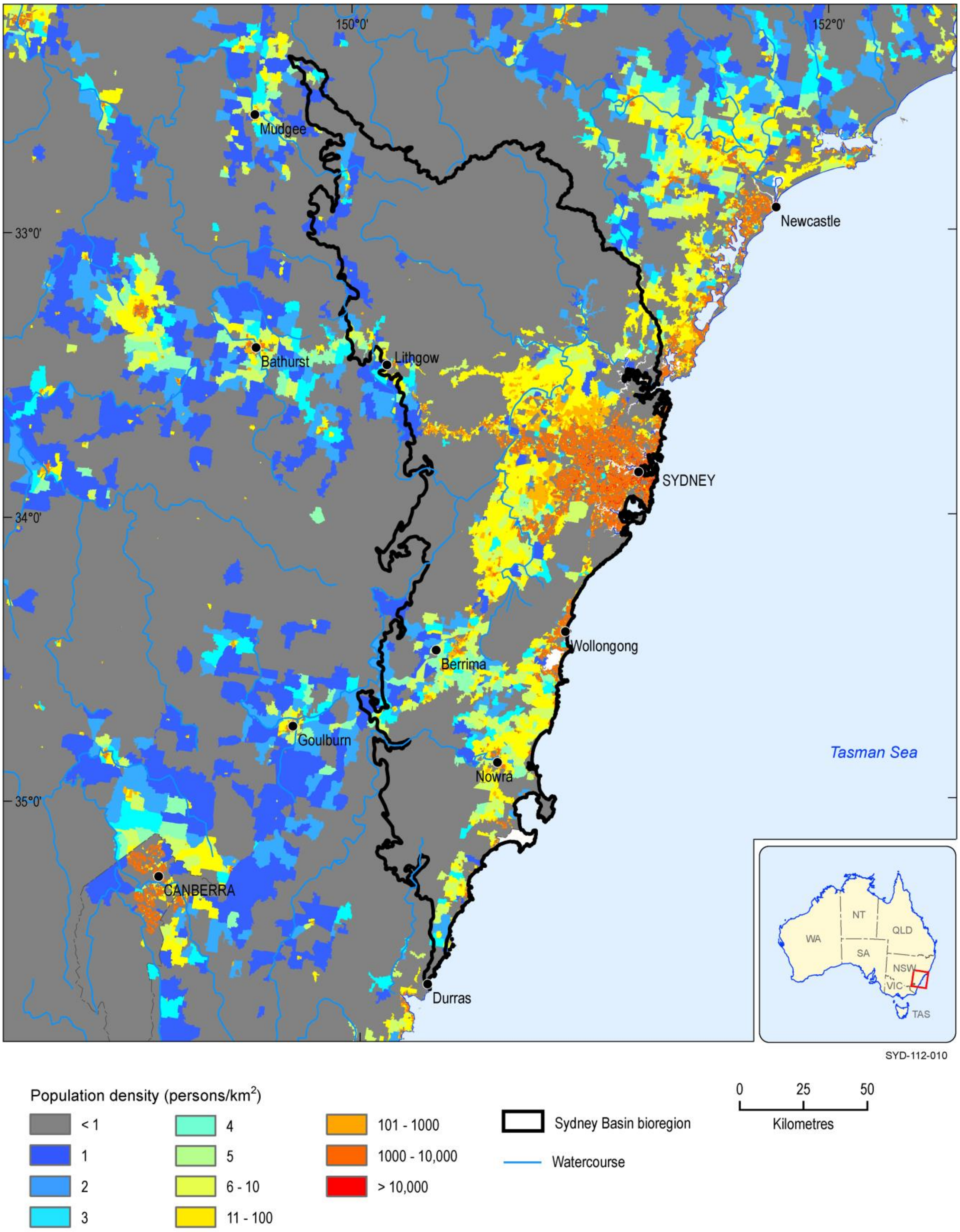

Figure 14 Population density of the Sydney Basin bioregion

Data: Australian Bureau of Statistics (Dataset 10)

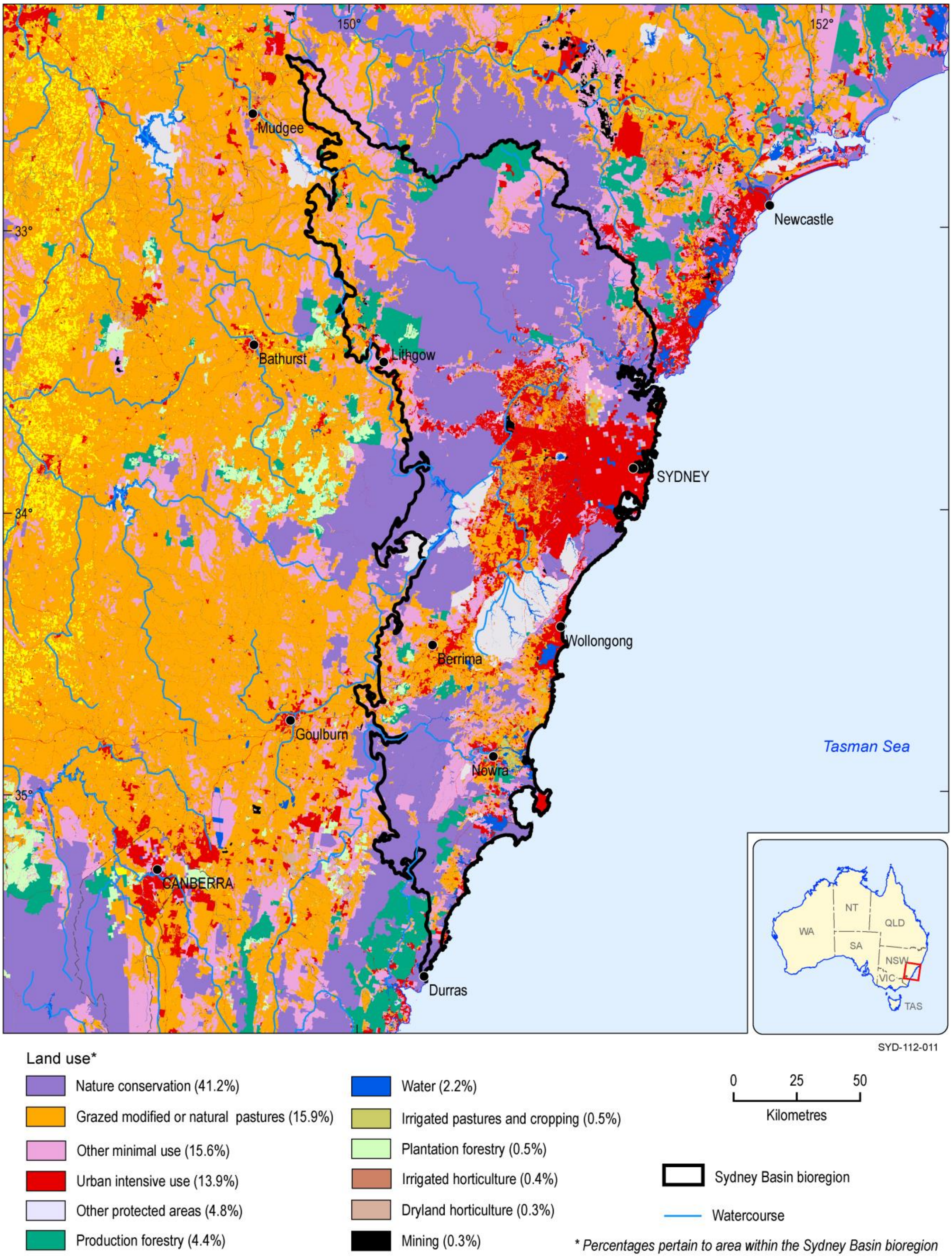

Figure 15 Land use in the Sydney Basin bioregion

Data: Australian Bureau of Agricultural and Resource Economics and Sciences (Dataset 11)

A number of small, but significant protected areas can be seen to the south-west of Sydney in Figure 15. These protected areas are owned and managed by WaterNSW as part of Sydney's main water supply catchments. In Figure 16, it can be seen that they encompass the catchments contributing to the Cordeaux, Cataract, Avon and Nepean reservoirs (the Metropolitan Special Area), to the Woronora Reservoir (the Woronora Special Area) and parts of the contributing area to Warragamba Dam and the Warragamba River downstream of the dam wall (Warragamba Special Area). In addition to their value for a clean, reliable water supply, some of these areas are environmentally significant because they contain many relatively undisturbed, regionally significant vegetation communities, including upland swamps (see Section 1.1.7). The Metropolitan and Woronora special areas are also economically significant because of the underlying coal seams of the Southern Coalfield, and existing mining leases extend well into the protection areas (shown in Figure 16). Longwall mining is currently undertaken under the Metropolitan and Woronora special areas, and there are proposals to expand further into these areas (see the coal and coal seam gas resource assessment in companion product 1.2 for the Sydney Basin bioregion (Hodgkinson et al., 2018)). Public concern about the potential loss of streamflow, and associated loss of habitat, have made this a particularly controversial issue. Loss of flow along a 2 km reach of the Waratah Rivulet, an important tributary to the Woronora Reservoir, following the collapse of longwall panels beneath the streambed in 2006, and degradation of some upland swamps are well documented (e.g. NSW Chief Scientist and Engineer, 2014; Rivers SOS, 2016; NSW Office of Environment and Heritage, 2011)). In March 2016, the Planning and Assessment Commission rejected a proposal from Russell Vale mine to expand into the Special Area on the grounds of potential water losses (as much as 2.6 GL/year) from WaterNSW reservoirs (NSW Planning and Assessment Commission, 2016). Concerns that the mines could potentially drain two upland swamps also formed part of the decision.

There are pockets of production forestry throughout the bioregion, including north of Wollemi National Park, north of Lithgow, in the Southern Highlands near Berrima and to the south of Nowra (Figure 16). Grazing of natural and modified pastures occurs at the western margins of Sydney, along the coastal zone and in the Southern Highlands near Berrima. Mining accounts for 0.3% of the mapped land uses in the bioregion (Figure 15).

In October 2013, the NSW Government introduced coal seam gas (CSG) exclusion zones for existing residential zones in all local government areas in NSW (NSW Government, 2015). In January 2014, 'future residential growth areas' were added to the CSG exclusion area in the Sydney Basin bioregion. The exclusion zones ban new CSG activity inside and within a 2 km buffer around existing and future residential areas. Together, these areas total 5748 km^2 or 23.3% of the bioregion. Also in January 2014, areas of 'biophysical strategic agricultural land' were identified across NSW that were deemed necessary to support the state's $12 billion/year agricultural industry (NSW Government, 2014). These areas correspond to land having high quality soil and water resources capable of supporting high levels of agricultural production. Areas of biophysical strategic agricultural land cover 36.5 km^2 (1.5%) of the bioregion. The three types of exclusion zone are shown in Figure 17. There is some overlap between these zones, which means a total area of 5942 km^2 or 24.1% of the bioregion is excluded from CSG development. The CSG exclusion zones do not affect the existing arrangements for non-CSG types of mining and petroleum activity. In addition to the exclusion zones, mining and petroleum production are generally prohibited in areas designated as conservation zones (i.e. national parks and other reserves) and in some land zoned for environmental protection within NSW, which together represent 46% of the bioregion. The exclusion zones relate to both the land surface and all geological strata below, this means no CSG can be extracted using horizontal wells located below the exclusion zones.

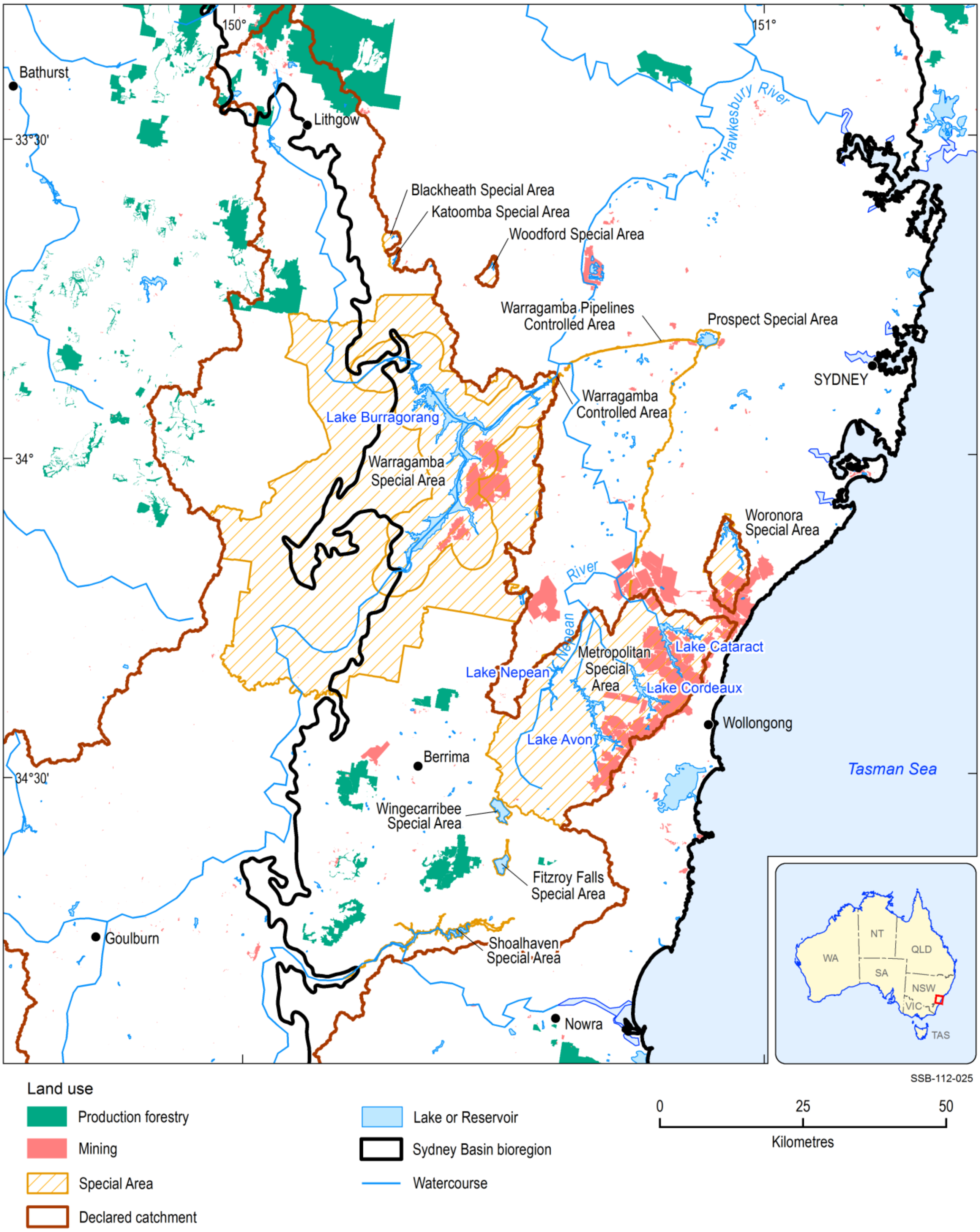

Figure 16 Special areas of the Sydney water supply catchment and mining areas close to and within

Data: Australian Bureau of Agricultural and Resource Economics and Sciences (Dataset 11); WaterNSW (Dataset 12, Dataset 13)

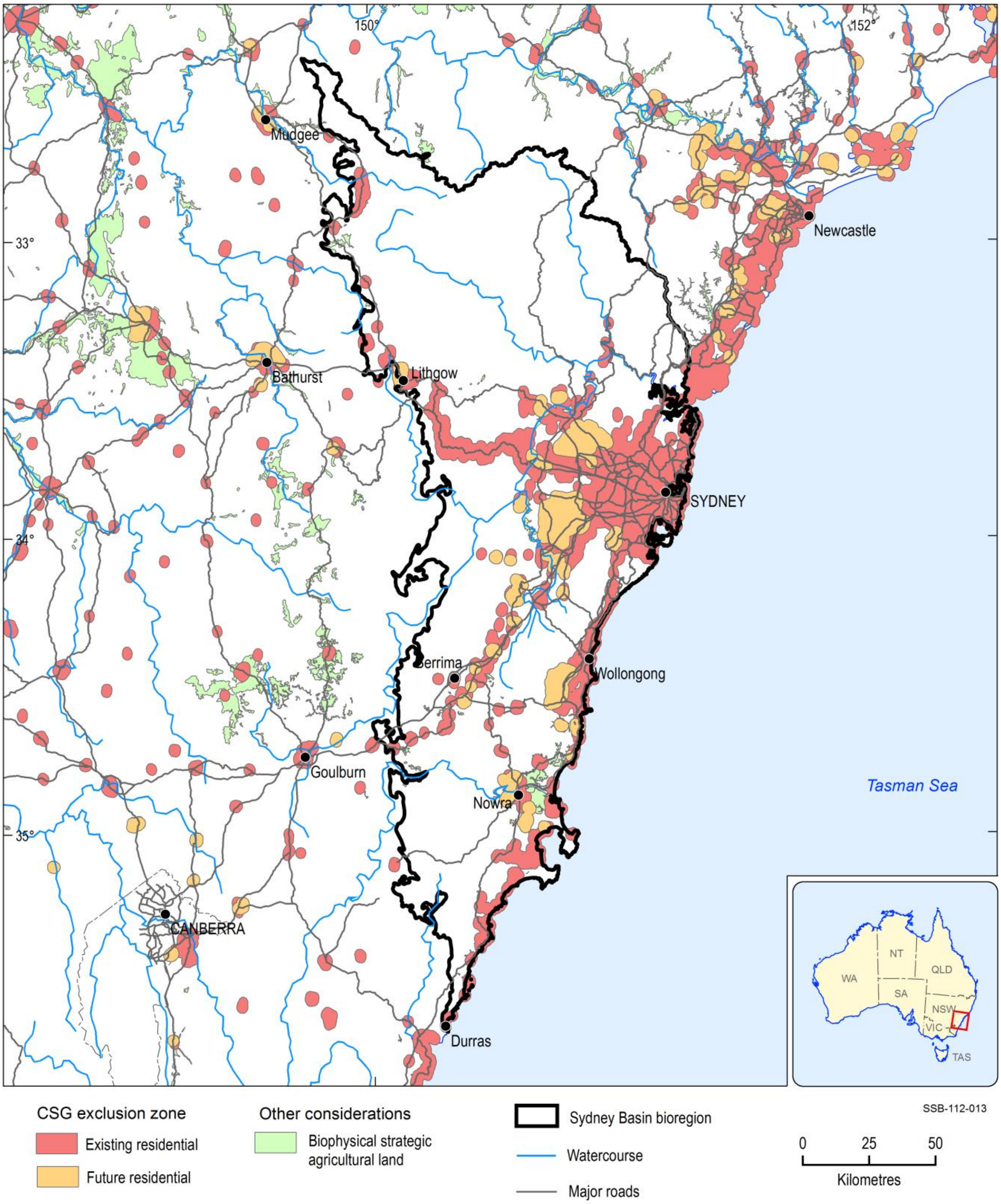

Figure 17 Coal seam gas exclusion zones and biophysical strategic agricultural land in the Sydney Basin bioregion

Data: NSW Department of Planning and Infrastructure (Dataset 14); Bioregional Assessment Programme (Dataset 15)

1.1.2.3 Climate

The Sydney Basin bioregion has a temperate climate, which means that temperatures are on average relatively moderate and not characterised by extremes of hot and cold or dramatic changes between summer and winter. The mean monthly temperatures for June, July and August are below 10 °C and for December to February are around 20 °C, but parts of the region are characterised by hot summers, particularly along the coast and at lower elevations, grading to warm summers at higher elevations.

The bioregion does not have a dry season, but the temporal pattern indicates summer dominant rainfall with December to March averaging 90 to 120 mm/month, while July to October averages about 60 mm/month (Figure 18). The long-term (1900 to 2012) mean precipitation (P) is 951 mm/year but, as for much of Australia, there is considerable inter-annual variability (Figure 19). The maximum annual P over this period was 2000 mm in 1950, while 1944 recorded a minimum of 400 mm/year over this period. Figure 19 highlights longer term trends within the record, such as a relatively dry period between 1900 and 1949 when mean annual P was less than 900 mm/year and there was only one year when the annual total exceeded 1200 mm, followed by a generally wetter period through to the 1990s when mean P exceeded 1000 mm/year and there were 16 years with annual totals at and above 1200 mm.

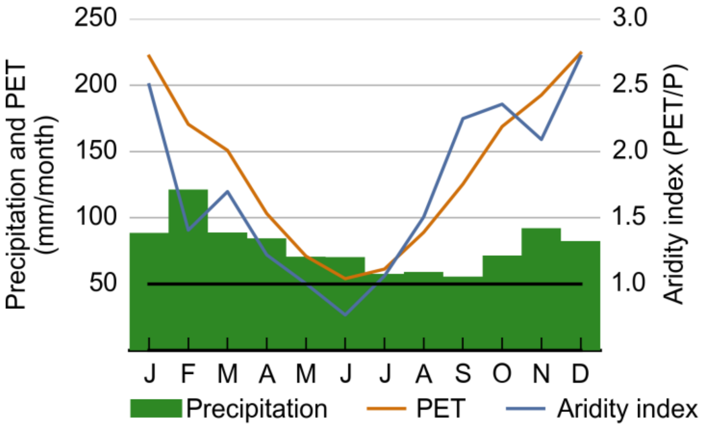

Figure 18 Mean monthly precipitation (P), potential evapotranspiration (PET) and aridity index for the Sydney Basin bioregion

Data: Bioregional Assessment Programme (Dataset 16)

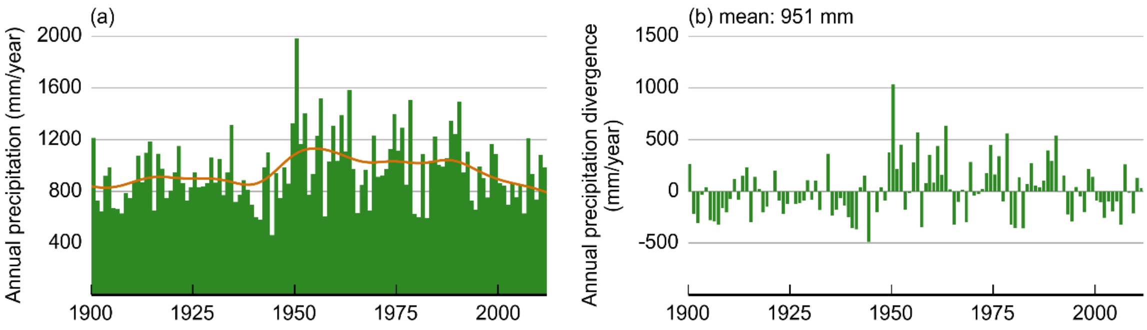

Figure 19 Temporal characteristics of annual precipitation for the Sydney Basin bioregion

(a) bioregion-averaged annual precipitation with smoothed rolling average (orange line) and (b) annual precipitation divergence from the long-term (1900 to 2012)
Data: Bioregional Assessment Programme (Dataset 16)

The spatial distribution of rainfall varies significantly, with rainfall generally decreasing with distance from the coast, but increasing with elevation. Figure 20a highlights the higher rainfall areas along the coast and in the upland areas associated with the Blue Mountains and the Southern Highlands between Wollongong, Nowra and Berrima. Mean annual P varies from 610 mm/year in the north-west of the region to 1530 mm to the north of Nowra.

Potential evapotranspiration (PET), which is a measure of the atmosphere's 'drying power', is a function of surface and air temperatures, radiation and wind. The PET data presented here have been calculated using the approach of Donohue et al. (2010) based on the Penman formulation, using meteorological data from the Bureau of Meteorology (Jones et al., 2009) and daily mean wind speed from CSIRO (McVicar et al., 2008). PET exhibits a strongly seasonal pattern with winters characterised by low evaporative demand and summers by high evaporative demand. For the Sydney Basin bioregion, mean annual PET exceeds 200 mm/month from December to February, but is in the range of 50 to 70 mm/month through June, July and August (Figure 18). For most of the year, P is below PET. The aridity index, which is calculated as PET/P, provides an indication of the limiting condition on actual evapotranspiration (AET). When the aridity index is greater than 1.0, as it is on average for 9 to 10 months in the bioregion, the availability of water places a limit on AET; when the aridity index is below 1.0, as it is on average from May to July in the bioregion, AET is energy-limited (Figure 18).

As for P, the spatial pattern of potential evapotranspiration (Figure 20b) is variable across the bioregion, but with a contrasting pattern to P (Figure 20a). The lower rainfall areas are associated with higher PET, reflecting generally warmer temperatures and less cloud cover. The higher rainfall areas are on average cloudier and cooler and therefore associated with lower evaporative demand.

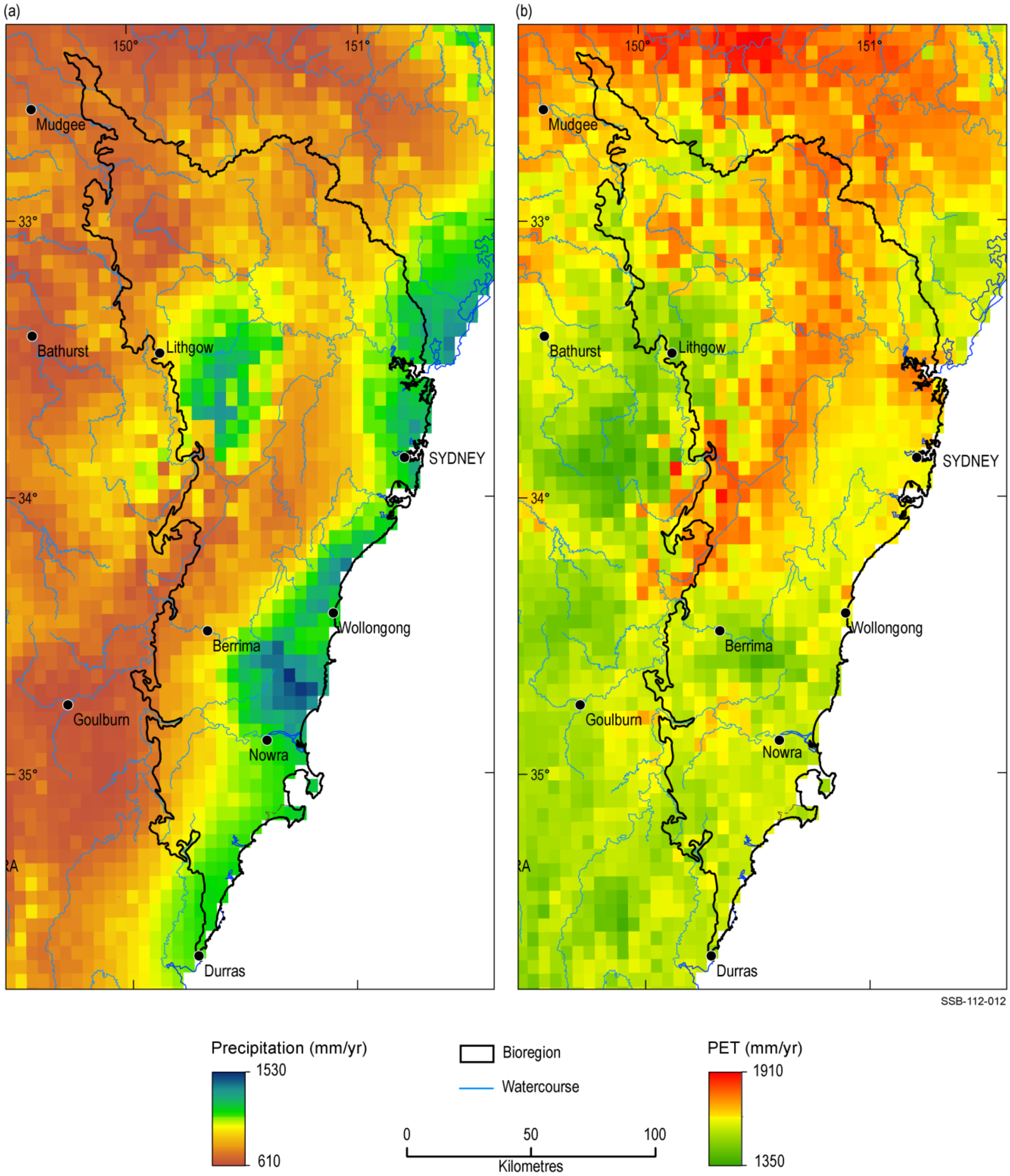

Figure 20 Spatial distribution of (a) mean annual precipitation and (b) potential evapotranspiration (PET) in mm/year across the Sydney Basin bioregion for the years 1982 to 2012

Data: Bioregional Assessment Programme (Dataset 17)

Figure 21 shows the inter and intra-variability in monthly P, PET and the climate factors (primarily air temperature, vapour pressure deficit (VPD), net radiation and wind speed) that govern PET for the 30 years from 1982 to 2012. While there is on average relatively low variability in P between months, in any given month, there is marked variability in monthly totals over the 30-year period (Figure 21a). Wind speed shows a strong seasonal signal, with a lot of intra-month variability.

Other climate variables also show marked seasonal variability, but little variation between years in any given month.

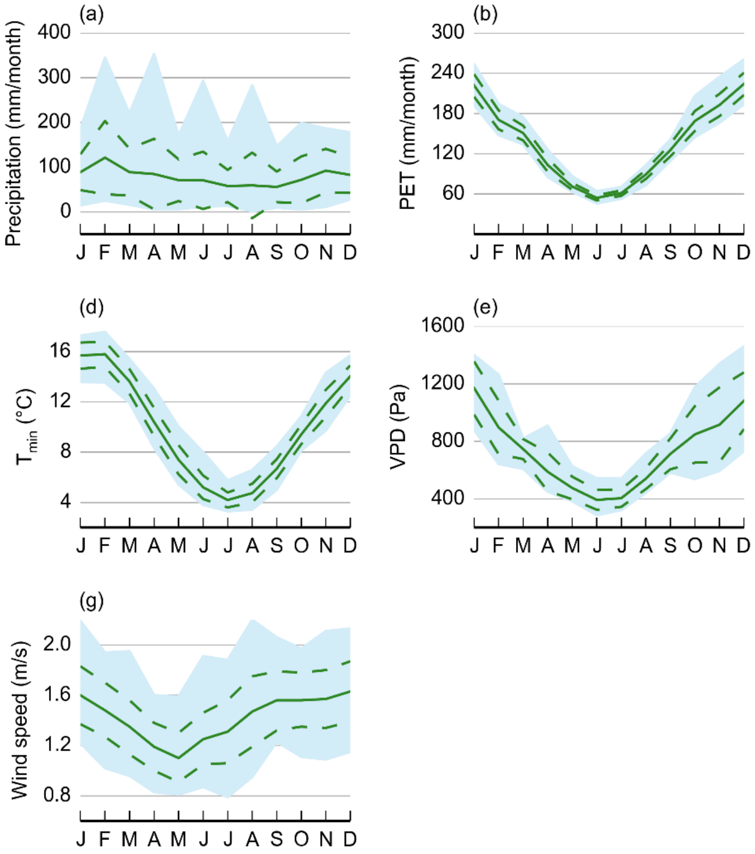

Figure 21 Monthly climate variables for the Sydney Basin bioregion

Charts show: (a) precipitation (P), (b) potential evapotranspiration (PET), (c) maximum temperature (Tmax), (d) minimum temperature (Tmin), (e) vapour pressure deficit (VPD), (f) net radiation (Rn), and (g) wind speed for the Sydney Basin bioregion. The mean (solid line), ± 1 standard deviation (dashed lines) and the minimum to maximum range (blue shaded area) are shown. Values were calculated over the years 1982 to 2012 (inclusive)
Data: Bioregional Assessment Programme (Dataset 16)

Monthly trends of P, PET and the other variables that drive PET are shown in Figure 22. The monthly trends for P straddle the no trend (i.e. zero mm/month/year) line, whereas PET, even in the face of warming air temperatures is mainly declining. Declining rates of PET are due to declining rates of wind speed (in all months) and declining amounts of net radiation and VPD (in most months), which together result in a larger change than the PET increases associated solely with increasing air temperature. Similar findings were reported for other areas of south-east of Australia (Donohue et al., 2010, 2011; McVicar et al., 2012a).

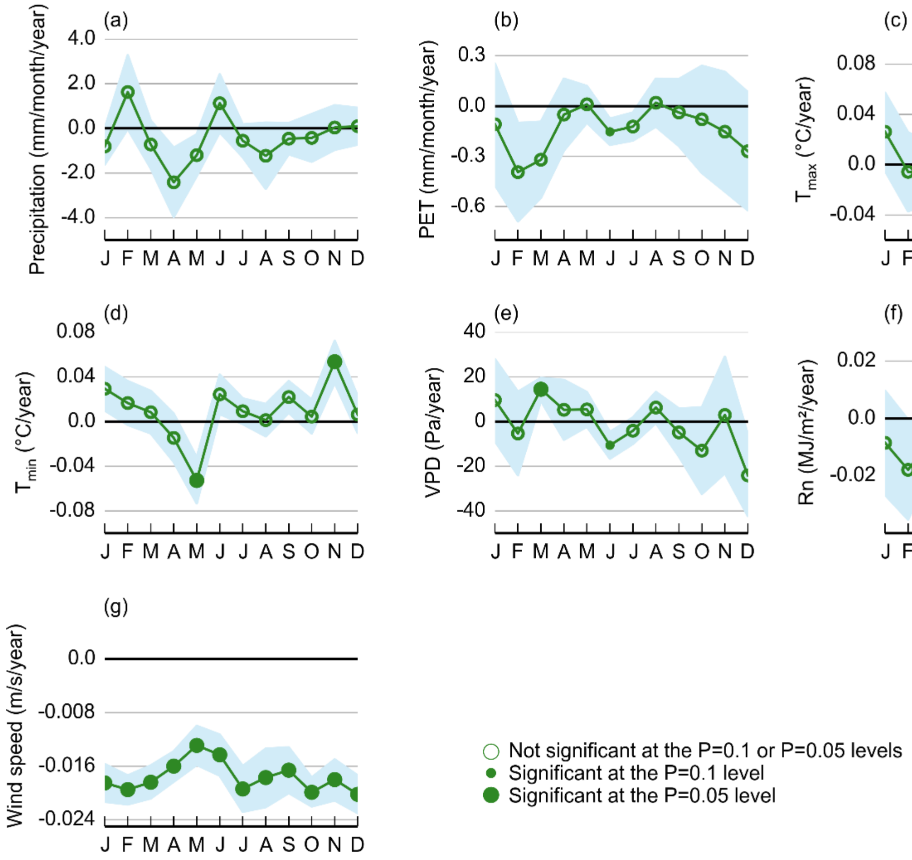

Figure 22 Annual trends by month of precipitation, potential evapotranspiration and other climate factors for the Sydney Basin bioregion

Charts show: (a) precipitation (P), (b) potential evapotranspiration (PET), (c) maximum temperature (Tmax), (d) minimum temperature (Tmin), (e) vapour pressure deficit (VPD), (f) net radiation (Rn), and (g) wind speed for the Sydney Basin bioregion. The trend (line), ± 1 standard error (blue shaded area) and trend significance (markers) are shown. Values were calculated over the years 1982 to 2012 (inclusive). Trends are obtained from ordinary linear regression (a parametric test) of the monthly time series and significance was calculated using 2-sided T-test (another parametric test)
Data: Bioregional Assessment Programme (Dataset 16)

Using 15 global climate models (GCMs) from the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007, hereafter referred to as IPCC AR4), Post et al. (2012) used the IPCC A1B global warming scenario output to transform historical daily climate records into future daily climate projections of P and PET for use in rainfall-runoff models. Under the IPCC A1B scenario, the mean global temperature is predicted to rise by 1 °C by 2030 and 2 °C by 2070, relative to the global mean temperature in 1990. This scenario is based upon (i) very rapid economic growth, (ii) with global populations peaking mid-century and declining thereafter, and (iii) the rapid introduction of new and more efficient technologies with a balance across all energy sources (IPCC, 2007). Full details of the transformation of historical daily climate records using IPCC AR4 output are reported in Chiew et al. (2009) and Li et al. (2009).

Post et al. (2012) assessed the changes in P from the 15 GCMs and reported changes for large river basins including the Hawkesbury, Shoalhaven, Sydney Coast-St Georges River, Wollongong Coast and Clyde River-Jervis Bay and Macquarie-Castlereagh river basins, which make up the Sydney Basin bioregion (see Figure 37 in Section 1.1.5). Table 9 shows that for all river basins, between 9 and 11 of the GCMs selected predict some decline in P. Taking into account the range of projections that may occur for a 1 °C rise in temperatures (associated with 2030), there is approximately a –7%, –2% and 4% change in P projected for the dry extreme, median and wet extreme, respectively. For a 2 °C rise in temperatures (associated with 2070), these values are approximately –15%, –5% and 8%, respectively (Table 9).

Table 9 Summary of projected impacts of climate change on rainfall for the broad vicinity of the Sydney Basin bioregion

River basin	Historical precipitation (mm/year)	Number (out of 15) of global climate models projecting a decrease in future precipitation	1 °C of global warming			2 °C of global warming		
			Dry extreme	Median	Wet extreme	Dry extreme	Median	Wet extreme
Hawkesbury River	870	9	–8%	–2%	4%	–16%	–5%	8%
Shoalhaven River	892	10	–7%	–3%	4%	–15%	–6%	7%
Sydney Coast-Georges River	1017	10	–7%	–2%	5%	–15%	–5%	9%
Wollongong Coast	1250	10	–7%	–2%	5%	–13%	–5%	9%
Clyde River-Jervis Bay	1076	11	–7%	–3%	4%	–15%	–6%	7%
Macquarie-Castlereagh	544	9	–9%	–2%	4%	17%	–5%	8%

Data: Table 2 in Post et al. (2012)

To model future runoff (Q), Post et al. (2012) used the future projections of daily P, along with a form of PET (specifically Morton's wet environment areal formulation) as input to a lumped conceptual rainfall-runoff model called SIMHYD which utilises the Muskingum routing method (Chiew et al., 2009). The Post et al. (2012) modelling results suggest for a 1 °C rise in temperatures (associated with 2030) there is potentially a –20%, –6% and 8% change in Q projected for the dry extreme, median and wet extreme, respectively (Table 10). For a 2 °C rise in temperatures (associated with 2070), these values are approximately –32%, –11% and 16%, respectively (Table 10). Estimates of both P and PET are important for future projections of Q (McVicar et al., 2012b). As Morton's wet environment areal formulation of PET does not include wind speed in its formulation, the impact of declining rates of observed wind speed, which acts to offset the PET enhancement from increasing air temperature (Donohue et al., 2010; McVicar et al., 2012a; McVicar et al., 2012b), is not factored into these estimates of runoff change.

Table 10 Summary of projected impacts of climate change on runoff for the broad vicinity of the Sydney Basin bioregion

River basin	Historical runoff (mm/year)	Number (out of 15) of global climate models projecting a decrease in future precipitation	1 °C of global warming			2 °C of global warming		
			Dry extreme	Median	Wet extreme	Dry extreme	Median	Wet extreme
Hawkesbury River	135	11	–20%	–6%	8%	–36%	–10%	17%
Shoalhaven River	237	12	–16%	–5%	7%	–30%	–9%	13%
Sydney Coast – Georges River	182	12	–20%	–7%	9%	–36%	–13%	19%
Wollongong Coast	342	12	–15%	–6%	8%	–29%	–11%	17%
Clyde River-Jervis Bay	351	12	–15%	–5%	6%	–28%	–8%	12%
Macquarie-Castlereagh	33	12	–25%	–8%	5%	–42%	–12%	13%

Data: Table 3 in Post et al. (2012)

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Dataset 6 Bioregional Assessment Programme (2016) BA SYD selected GA TOPO 250K data plus added map features. Bioregional Assessment Derived Dataset. Viewed 22 January 2016, http://data.bioregionalassessments.gov.au/dataset/ba5feac2-b35a-4611-82da-5b6213777069.

Dataset 7 CSIRO (2011) Physiographic Regions of Australia. Bioregional Assessment Source Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/a0f3edb6-6afd-4eb9-a9be-e815f8ec4eab.

Dataset 8 CSIRO (2012) ASRIS Australian Soil Classification - Dominant Soil Order (250m raster). Bioregional Assessment Source Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/d6b0c5c7-37d0-4832-b5b1-53cb7eeb3cd7.

Dataset 9 Geoscience Australia (2013) The Dynamic Landcover Dataset of Australia. Bioregional Assessment Source Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/b85713ee-5fa3-44a5-b145-25b01efa3e31.

Dataset 10 Australian Bureau of Statistics (2014) NSW 2011 Census Population Counts and Density (Spatial). Bioregional Assessment Source Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/90662127-a559-493b-9d65-df44270aeb0a.

Dataset 11 Australian Bureau of Agricultural and Resource Economics and Sciences (2014) Catchment Scale Land Use of Australia - 2014. Bioregional Assessment Source Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/6f72f73c-8a61-4ae9-b8b5-3f67ec918826.

Dataset 12 Water NSW (2015) SSB SW Special Areas v01. Bioregional Assessment Source Dataset. Viewed 12 July 2016, http://data.bioregionalassessments.gov.au/dataset/84d1a125-2ce7-4cd5-8324-d1c1ce959b7a.

Dataset 13 Water NSW (2016) SSB Mines Footprint WaterNSW May2016. Bioregional Assessment Source Dataset. Viewed 12 July 2016, http://data.bioregionalassessments.gov.au/dataset/03aadb19-63ef-440f-ba8d-1da7e3fa75bb.

Dataset 14 NSW Department of Planning and Infrastructure (2013) Strategic Agricultural Lands (SAL) Biophysical. Bioregional Assessment Source Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/42e2a51d-3c11-431f-ac62-f8511c859516.

Dataset 15 Bioregional Assessment Programme (2015) NSW CSG Exclusion Zone - Future Residential Growth Area V2 20140509. Bioregional Assessment Derived Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/0ff279d0-7381-4f44-9a37-28e926f14189.

Dataset 16 Bioregional Assessment Programme (2014) Charts of climate statistics and MODIS data for all Bioregional Assessment subregions. Bioregional Assessment Derived Dataset. Viewed 29 January 2016, http://data.bioregionalassessments.gov.au/dataset/8a1c5f43-b150-4357-aa25-5f301b1a02e1.

Dataset 17 Bioregional Assessment Programme (2013) Bioregional Assessment Programme (2016) Mean annual climate data clipped to BA_SYD extent. Bioregional Assessment Derived Dataset. Viewed 03 February 2016, http://data.bioregionalassessments.gov.au/dataset/a8393a45-5e86-431b-b504-c0b2953296f4.

1.1.3 Geology

Summary

The Sydney Basin bioregion is within the geological Sydney Basin (simply referred to henceforth throughout this section as the Sydney Basin), part of the greater Sydney-Gunnedah-Bowen Basin complex (SGBB). The Sydney Basin extends offshore to the continental shelf, which marks its easternmost boundary. It is further bounded by older rocks of the Lachlan Fold Belt to the south and west, the Mount Coricudgy Anticline to the north-west – across which is the Gunnedah Basin – and the New England Fold Belt to the north and west. The Sydney Basin bioregion abuts the Hunter subregion of the Northern Sydney Basin bioregion to the north. The rocks of the SGBB complex are of Carboniferous to Triassic age, and about 325 to 230 million years old.

The evolution of the Sydney Basin – and the wider SGBB – began during the orogenic phase that built the Tasman Fold Belt, initially during the Devonian and continued intermittently until the Cretaceous, when major tectonic activity ceased. The stratigraphic record preserved within the basin reveals an active depositional history from the Carboniferous to the Triassic, although Jurassic and Cretaceous rocks were likely to have been present at some stage (and have since been eroded). Sedimentation took place across the SGBB as a zone of crustal depression was gradually infilled by sediment supplied from the nearby New England and Lachlan fold belts. The dominant control on this deposition was the cyclic nature of marine transgression and regression. The major coal-bearing units were deposited from the latest early Permian to the earliest middle Permian, and again from the latest middle Permian to the end of the Permian. These coal-rich stratigraphic units are known as the Greta, Clyde, Illawarra, Wittingham, Tomago and Newcastle coal measures. The Sydney Basin is divided into five coalfields, namely the Hunter, Newcastle, Western, Central and Southern coalfields, based largely upon variations in stratigraphy, including the specific coal measures.

In the Sydney Basin bioregion, the main coalfields are the Western, Central and Southern coalfields. The most economically important coal-bearing unit in each of these areas is the Illawarra Coal Measures, although lesser coal units also occur.

1.1.3.1 Geological structural framework

The Sydney Basin bioregion covers the central, western and southern portions of the geological Sydney Basin (simply referred to henceforth throughout this section as the Sydney Basin) (Figure 23). The Hunter subregion of the Northern Sydney Basin bioregion (see Section 1.1.3 of companion product 1.1 for the Hunter subregion (McVicar et al., 2015)) abuts the Sydney Basin bioregion to the north, and corresponds to the northern part of the Sydney Basin. The Sydney Basin bioregion covers the full extent of the Southern and Central coalfields of the Sydney Basin, as well as most of the Western Coalfield (Figure 23). While the southernmost extents of the Hunter and Newcastle coalfields also intersect the Sydney Basin bioregion (Figure 23), resource prospects are considered limited in this part of the bioregion and they are not discussed in detail here. The Central Coalfield, which historically has been mined (e.g. Sydney Harbour Colliery at

Balmain between 1897 and 1931; NSW DPI (2007)), is also not discussed in detail here as there is currently no future planned coal resource development. Consequently, Southern and Western coalfields are the main focus of this section, with rock and stratigraphy descriptions for the Hunter and Newcastle coalfields presented in product 1.1 for the Hunter subregion (not discussed in this product). As can be seen in Figure 24, the surface geology of the Sydney Basin bioregion is dominantly Permian to Triassic, with some older rocks and younger Cenozoic alluvium.

The Sydney Basin contains rocks of Late Carboniferous to Middle Triassic age (Geoscience Australia, 2015a). These rocks are a mixed assemblage of marine and non-marine sedimentary rocks, predominantly siliclastics and coals. The maximum thickness of the basin's entire sedimentary sequence varies between 4.5 and 6 km. The Sydney Basin initially formed as a rift basin, and subsequently experienced thermal subsidence and foreland basin development stages (Ward and Kelly, 2013). The basin spans approximately 20% of the NSW coastline, covering approximately 400 km from just south of Durras in the south to just north of Newcastle (Cadman et al., 1998, p. 141; Ward and Kelly, 2013). The basin occurs both onshore and offshore (see Figure 23; Cadman et al., 1998, p. 141; Geoscience Australia, 2015a), with approximately 36,000 km^2 onshore and 28,000 km^2 offshore (Stewart and Alder, 1995; Ward and Kelly, 2013; Geoscience Australia, 2015a). The Sydney Basin forms part of a much greater late Paleozoic to early Mesozoic sedimentary basin complex known as the Sydney-Gunnedah-Bowen Basin (SGBB) (Figure 23, Figure 25).

This so-called 'super basin' spans from central Queensland in the north to the NSW central coast, with the Sydney Basin forming the southernmost portion (Figure 25; Brakel, 1991, p. 10; Cadman et al., 1998, p. 141; Haworth, 2003; Ward and Kelly, 2013; Geoscience Australia, 2015a). Throughout much of its development, the SGBB formed in a back-arc tectonic setting, adjacent to a subduction zone (Bray et al., 2010). Korsch and Totterdell (2009) identified three dominant phases of basin development: early Permian extension, thermal subsidence in the middle Permian and later foreland loading during the late Permian, which continued into the Middle Triassic.

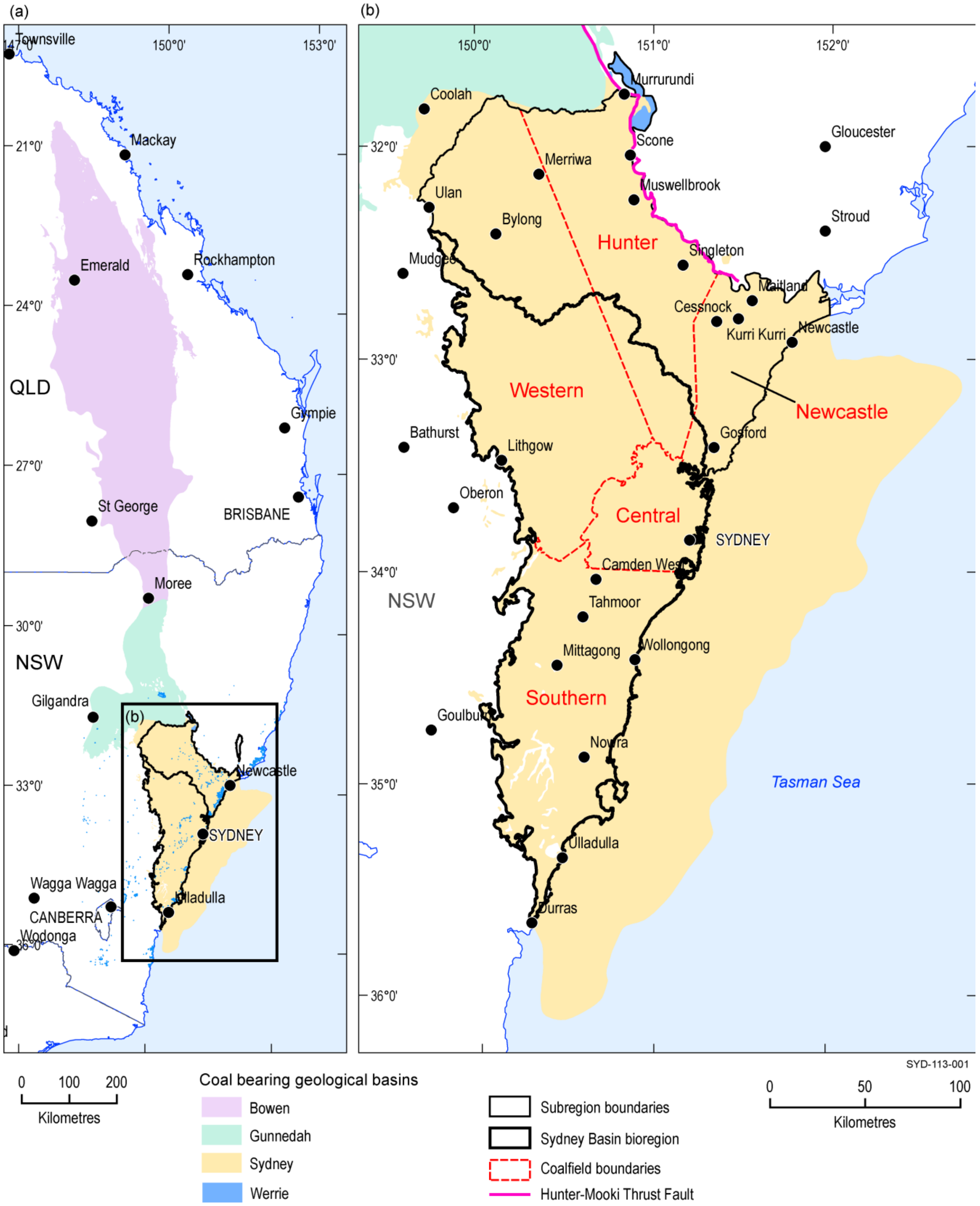


Figure 23 Geological basins and coalfields of the Sydney Basin bioregion

(a) Location of the geological Sydney Basin on the coast of eastern Australia and (b) the five coalfields of the onshore geological Sydney Basin
Data: NSW Trade and Investment (Dataset 1); Geoscience Australia (Dataset 2)

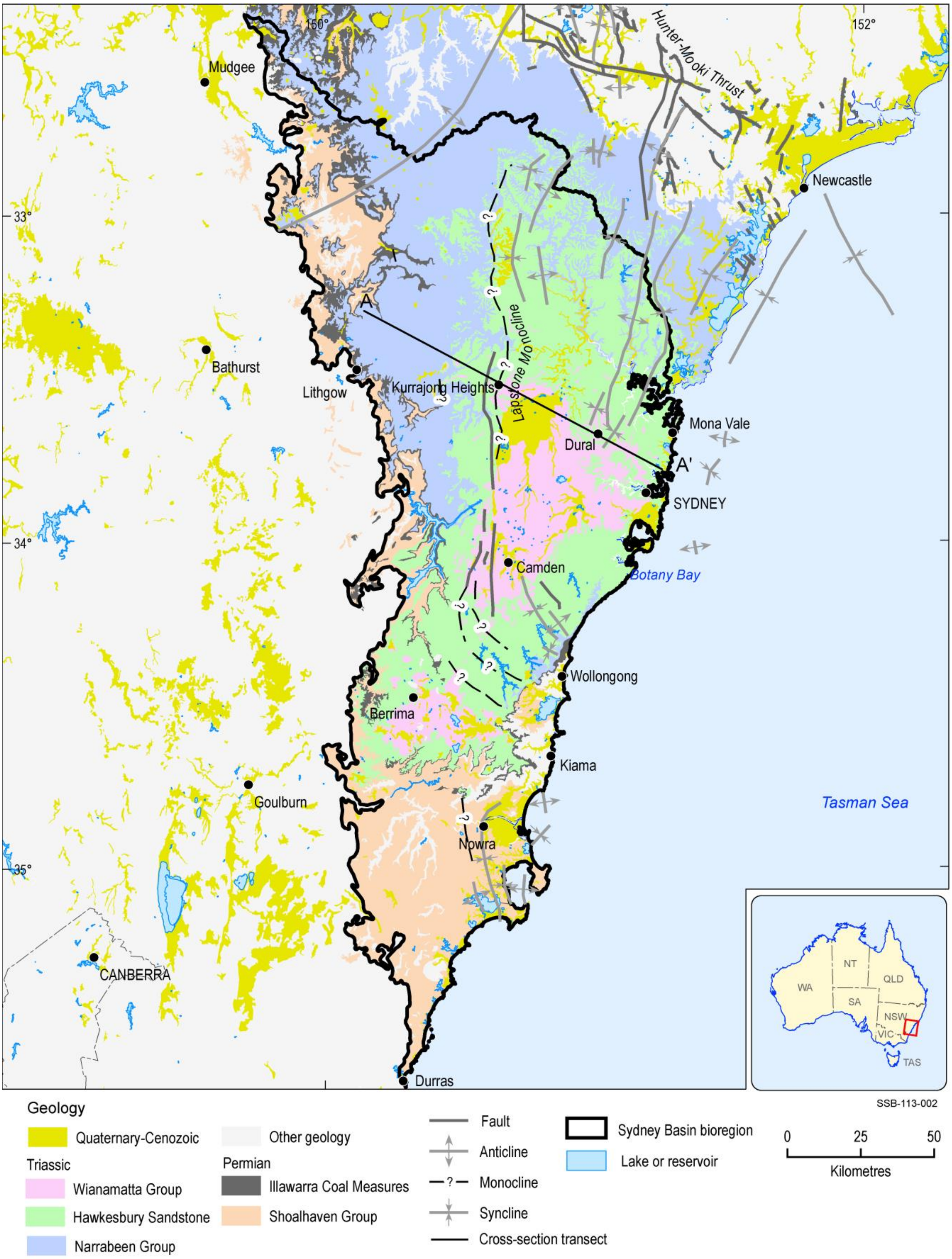


Figure 24 Surface geology of the Sydney Basin bioregion. A-A' shows approximate location of the cross-section in Figure 26

Data: Geoscience Australia (Dataset 3), Stewart and Alder (1995)

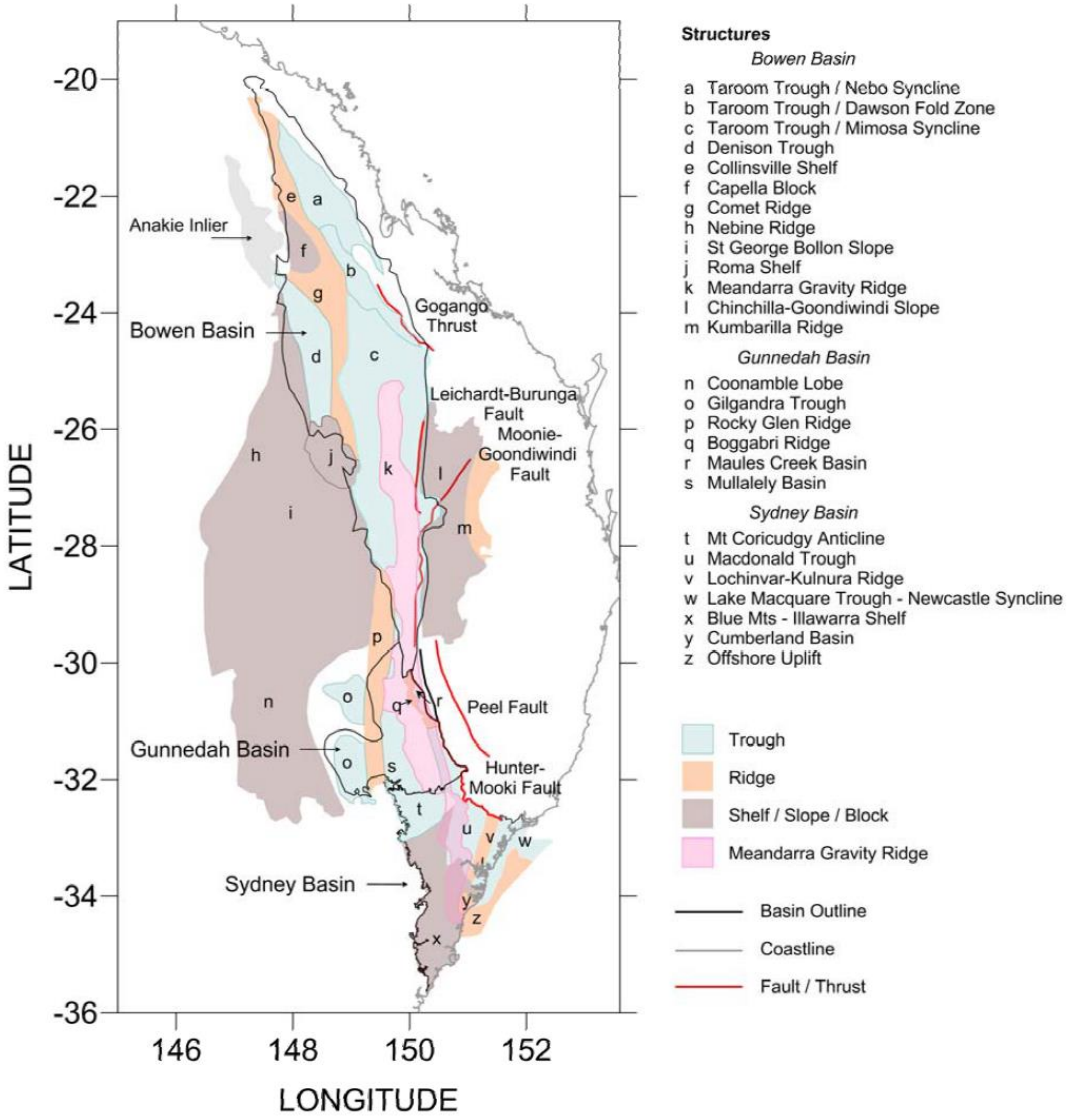


Figure 25 Major structural elements of the Sydney-Gunnedah-Bowen Basin complex

Source: O’Neill and Danis (2013, p. 16)

To the north of the Sydney Basin the Gunnedah Basin sits on the north-western side of the Liverpool Range where recognisable differences in basin stratigraphy have been defined (Brakel, 1991, p. 10; Stewart and Alder, 1995; Cadman et al., 1998, p. 143). Earlier work on the Sydney and Gunnedah basins had placed this basin divide further to the south-east at the Mount Coricudgy Anticline where basin strata are thinner (Brakel, 1991, p. 10; Tadros 1993; Cadman et al., 1998, p. 141). The Sydney Basin extends easterly to the continental shelf (Brakel, 1991, p. 10; Haworth, 2003), and to the north the basin terminates at the Hunter-Mooki Thrust Fault (Brakel, 1991, p. 10). To the west, much of the basin has been eroded, and now terminates where it abuts the older rocks of the Lachlan Fold Belt (Brakel, 1991, p. 11).

The older (prior to late Permian) sedimentary rocks of the Sydney Basin were originally deposited due to glacially influenced marine sedimentation, with some volcanic influence and minor terrestrial deposition (Brakel, 1991, p. 14; Ward and Kelly, 2013). These terrestrial units are more common in the north of the Sydney Basin and are generally considered coal-bearing (Ward and Kelly, 2013). Younger sediments (late Permian and younger) are dominantly terrestrial and more coal-rich (Brakel, 1991, p. 14; Ward and Kelly, 2013) and are considered to be of greatest economic importance in the Sydney Basin (Ward and Kelly, 2013). There are notable differences in rock types across the basin (Ward and Kelly, 2013) and, as such, stratigraphic divisions are made separately for the five coalfields. Sedimentation in the Late Carboniferous and early Permian formed the oldest preserved units, and probably continued without significant disruption into the Jurassic, although subsequent widespread erosion has removed all traces of strata from the Middle Triassic to the Jurassic – hence the existence of these rocks is speculative (Philp and Saxby, 1980). Early Permian marine transgression over much of the basin was followed by a late Permian regression; with the lower Permian marine sequences overlain by widespread coal-bearing units (Brakel, 1991, pp. 14–21). The main exception to this occurred in the northern-most portion of the basin where a middle Permian regression locally formed the Greta Coal Measures (Brakel, 1991, pp. 14–21). The lower Permian strata thicken to the north of the basin whereas the late Permian and Triassic strata thin northwards (Philp and Saxby, 1980). All strata thin over the western margin of the basin where the basement rock is topographically higher, Figure 26.

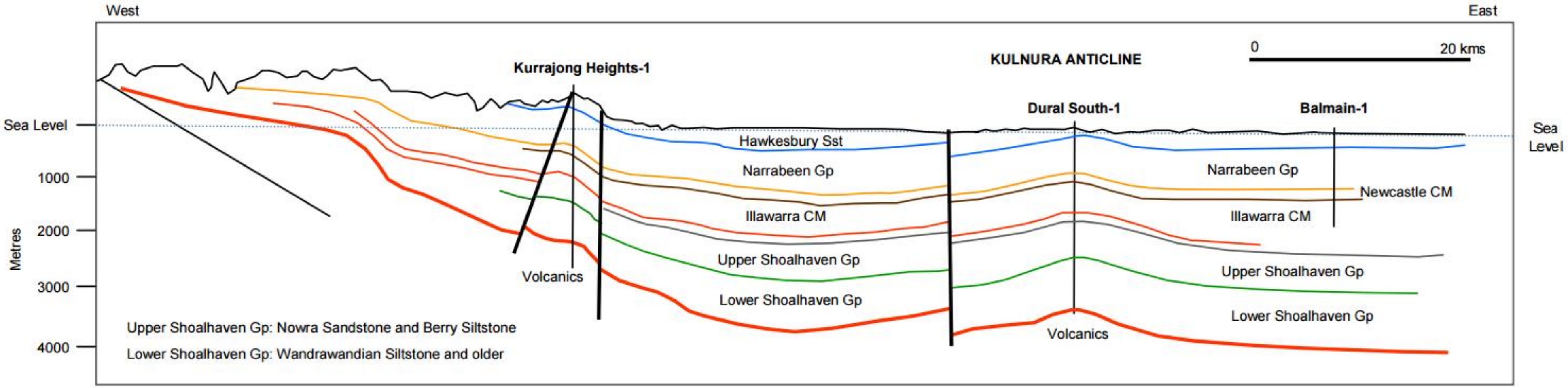


Figure 26 Schematic west to east geological cross-section of the southern Sydney Basin, showing three conventional hydrocarbon wells

Source: Blevin et al. (2007) for NSW Department of Industry

The Sydney Basin is divided into several major structural zones, including a series of north to north-east trending ridges and troughs in the north-east of the basin (Figure 27). The central Sydney Basin, commonly referred to as the Inner Sydney or Cumberland Basin (Bembrick et al., 1973; Jones and Clark, 1991; Haworth, 2003; Branagan, 2009; Bray et al., 2010) is a structural low, reflected in the topography, surrounded by a series of elevated plateaux (Figure 27; Haworth, 2003). This particular sub-basin is largely urbanised and is described as the lowest lying structural feature of the Sydney Basin (Ward and Kelly, 2013). The surrounding topographic highs (including the Woronora, Blue Mountains and Hornsby plateaux) form structural barriers that isolate the central basin (Ward and Kelly, 2013).

The Cranky Corner, Gloucester and Myall basins sit outside the northern boundary of the Sydney Basin, but have at times been referred to as detached pockets of remnant Sydney Basin (Korsch et al., 2009; Ward and Kelly, 2013; Brakel, 1991, p. 10). Geoscience Australia (2015b) refers to the Myall Basin (also referred to as Myall Syncline) as an outlier of the Sydney Basin. The Cranky Corner and Gloucester basins are currently recognised as separate basins containing stratigraphy of a similar age to the Sydney Basin. The hydrogeological Botany Basin is also of note due to its importance to hydrology (Griffin, 1963, p. 6) though it has had limited use throughout geological literature. In terms of location, the Botany Basin sits to the immediate south of the City of Sydney, encompassing part of Sydney itself and the suburbs of Marrickville, Botany, Randwick, Rockdale and Sutherland Shire (Griffin, 1963, p. 8) and extends into Botany Bay. The basin is approximately 8 x 8 km at its maximum width and length. The geology of the Botany Basin is that of a trough feature, largely filled with Triassic aged deposition (Douglas Partners, 2007, p. 5).

The Lapstone Monocline, Kurrajong Fault, Lochinvar Anticline, Kulnura Anticline and Lake Macquarie Syncline form the dominant north-trending basin structures (Ward and Kelly, 2013). These structures are the result of either tectonic movement during the Permian and Triassic or the reactivation of older basement structures (Stewart and Alder, 1995; Belvin et al., 2007; Ward and Kelly, 2013). In the southern part of the Sydney Basin there are also some synclines, anticlines and faults that trend north-westerly (Ward and Kelly, 2013). The Blue Mountains Shelf and the Illawarra Shelf are separated from the rest of the basin by a series of faults and monoclines thought to represent a possible older basement structural feature (Harrington and Brakel, 1981, p. 10; Brakel, 1991, pp. 11–12). The remaining Sydney Basin can be thought of as a series of troughs and ridges (Brakel, 1991, p. 11). During the Permian, when coals were being deposited, the Dome Belt (a series of anticlines and dome structures) of the Hunter Valley region is interpreted to have been forming (Brakel, 1991, p. 12).

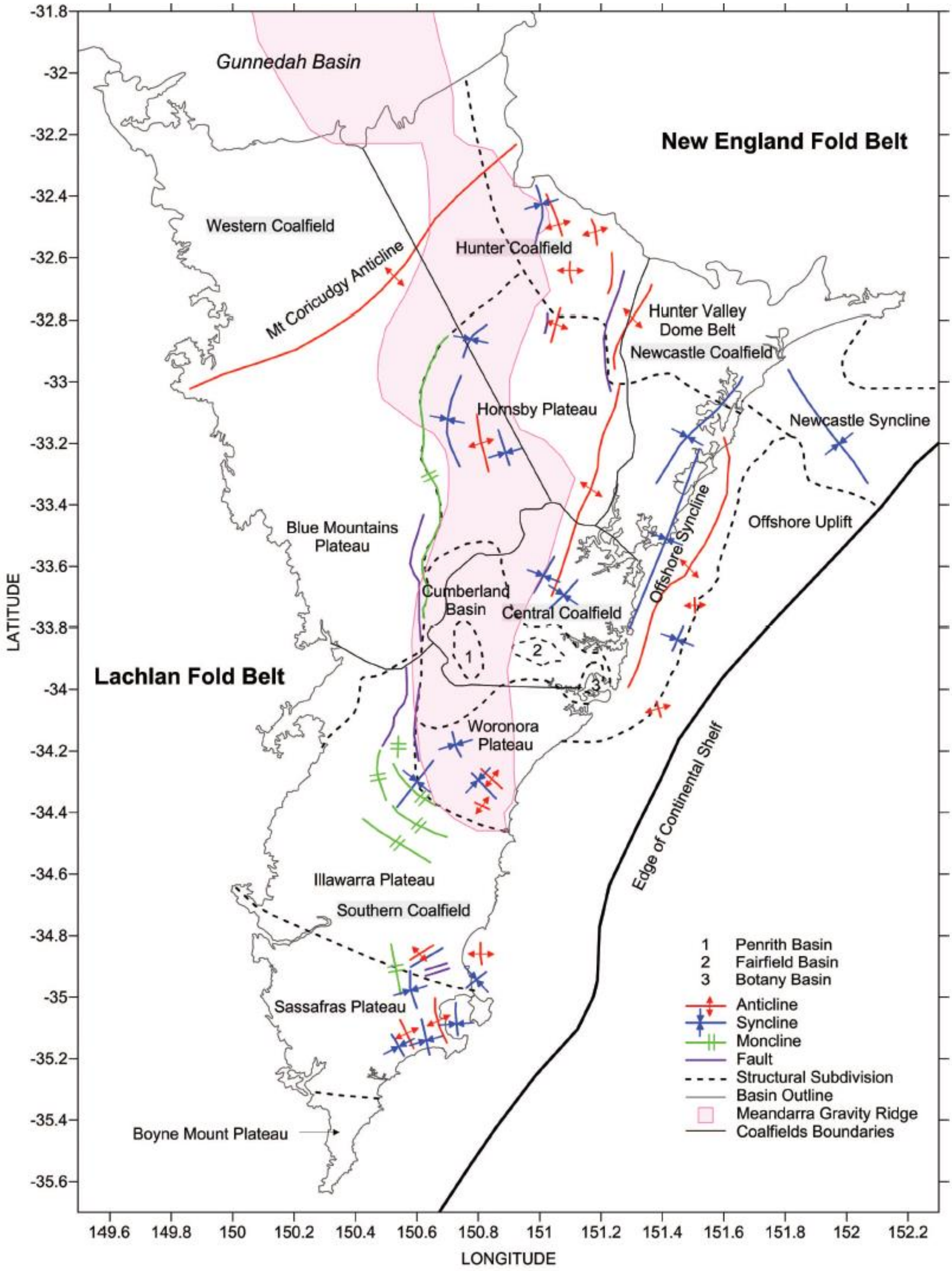


Figure 27 Modern divisions of the onshore geological Sydney Basin

Source: Danis et al. (2011). Deep 3D structure of the Sydney Basin using gravity modelling, Danis et. al., Australian Journal of Earth Sciences. Copyright © Geological Society of Australia, reprinted by permission of Taylor & Francis Ltd, www.tandfonline.com on behalf of Geological Society of Australia. This figure may not be reproduced without the express permission of Australian Journal of Earth Sciences, http://www.tandfonline.com/toc/taje20/current.

1.1.3.1.1 Structure of the Southern Coalfield

The Southern Coalfield is a large syncline feature at the southernmost end of the Sydney Basin (Hutton, 2009, p. 44). Strata within the coalfield mostly dip between 2 and 5 degrees, although dips of less than 2 degrees also occur (Hutton, 2009, p. 44). Internal to the Southern Coalfield's synclinal structure, anticlines and synclines are noted, with the two largest forming the Camden Syncline and the Woronora Ridge; the latter of which is technically a series of anticlines and synclines (Hutton, 2009, p. 44). Although internal anticline and syncline structures are recognised, the dominant structural feature within the coalfield consists of a series of north-west to north-east trending faults (Hutton, 2009, p. 44). The north-westerly faults have throws of up to 90 m whereas the north-easterly en-echelon faults have throws of up to 15 m (Hutton, 2009, p. 44). Internal divisions within the Southern Coalfield have been proposed by several authors (Bembrick et al., 1973; Scheibner, 1999) focusing on the magnetic lineaments of the major faults such as the Lapstone Monocline Fault System, the Nepean Fault Zone, the Oakdale Fault System and the Bargo Fault (Hutton, 2009, p. 44). Most faulting in this coalfield is considered to be normal, with strike-slip, reverse and high angle faults (less commonly) documented (Hutton, 2009, p. 44). Jointing and doming related to igneous features also occur (Hutton, 2009, p. 44).

1.1.3.1.2 Structure of the Western Coalfield

The Western Coalfield is marked by a series of north-trending monoclines that form the dominant structural features of the basin, with some associated faulting (Hutton, 2009, p. 51). The Mount Tomah Monocline is the dominant structural feature of the Western Coalfield and separates the Wollar and Blue Mountains shelves from the Murrurundi Trough and the Macdonald Trough (Yoo et al., 2001, p. 57). The Mount Coricudgy Anticline is a basement growth structure sitting 2 km above the base of the Macdonald Trough (Yoo et al., 2001, p. 57). The other prominent structural feature is the Lapstone Structural Complex, a north-trending monocline and fault system within the Macdonald Trough (McVicar et al., 2015). The Kurrajong Fault is a major high-angle reverse fault within the coalfield which dips eastwards (McVicar et al., 2015). Localised small throw faults are evident in some locations (Hutton, 2009, p. 51).

1.1.3.2 Stratigraphy and rock type

In this section, the stratigraphy and rock types of the Southern and Western coalfields (Figure 28) are presented, with a focus on the coal-bearing stratigraphic units and main non-coal units. For reasons identified in Section 1.1.3.1, the Central Coalfield is not specifically dealt with here, but the available data indicates that the stratigraphy of the Central Coalfield closely mirrors that of the Southern Coalfield (Haworth, 2003). A detailed analysis of all stratigraphic units recognised in the Australian Stratigraphic Units Database (Geoscience Australia and Australian Stratigraphy Commission, 2016) is not included here. Further information about the coal-bearing units, current mining operations and proposed development in this bioregion is provided in companion product 1.2 for the Sydney Basin bioregion.

1.1.3.2.1 Permian sedimentary rocks

Talaterang Group

Known from the southern part of the Sydney Basin (Southern Coalfield), the Talaterang Group was deposited in the early Permian through fluvial transport within deeply incised valleys. These are thought to be remnant glacial features located within early formed north-trending fault-bound sub-basins (Herbert, 1972; Brakel, 1991, p. 14; Tye et al., 1996) which rest directly on the underlying basement rocks (Ward and Kelly, 2013; Tye et al., 1996). The Talaterang Group is composed of the Badgerys Breccia, Clyde Coal Measures, Pigeon House Creek Siltstone and Wasp Head Formation (Figure 28; Geoscience Australia and Australian Stratigraphy Commission, 2016). The Clyde Coal Measures formed in a transgressive depositional cycle in the south of the Sydney Basin, with marine transgression moving across the basin from the east to the west (Brakel, 1991, p. 15). The formation of the Clyde Coal Measures has been attributed to the marshlands of a delta complex (Evans et al., 1983), where the mud-rich sediment was deposited in northerly flowing channels (Tye et al., 1996). As the rising ocean moved westward across the Sydney Basin the Clyde Coal Measures were deposited in paralic zones, forming lenses of coal (Evans et al., 1983; Brakel, 1991, p. 15). The Talaterang Group contains limited economic coal resources due to the thin nature of coal seams within the Clyde Coal Measures (Hutton, 2009, p. 43), although some mining has occurred historically.

Shoalhaven Group

Coincident with the early Permian marine transgression was the deposition of thick sand and silt units of the Shoalhaven Group (Figure 28) across the Southern and Western Coalfields. These were deposited in variably low to high energy, fluvial to marine (shelf) environments (Brakel, 1991, p. 15; Tye et al., 1996) and mainly comprise sandstone with interbedded shale and mudstone (Hutton, 2009, p. 43). The shale and mudstone units represent marine influenced deposition, whereas the sandstone units are fluvial to terrestrial in origin (Hutton, 2009, p. 43). The Shoalhaven Group consists of the Pebbley Beach Formation, Snapper Point Formation, Wandrawandian Siltstone, Nowra Sandstone, Berry Siltstone and Broughton Formation (Geoscience Australia and Australian Stratigraphy Commission, 2016). The Shoalhaven Group also contains a coal-bearing unit of low economic importance, the Yarrunga Coal Measures (Yoo et al., 2001, p. 9; Hutton, 2009, p. 43). In the Southern Coalfield the Shoalhaven Group overlies the Talaterang Group. Within the Western Coalfield the Shoalhaven Group is divided into the sandstone rich Snapper Point Formation and the Berry Siltstone which are separated by an unconformity relating to depositional hiatus (Yoo et al., 2001, p. 10).

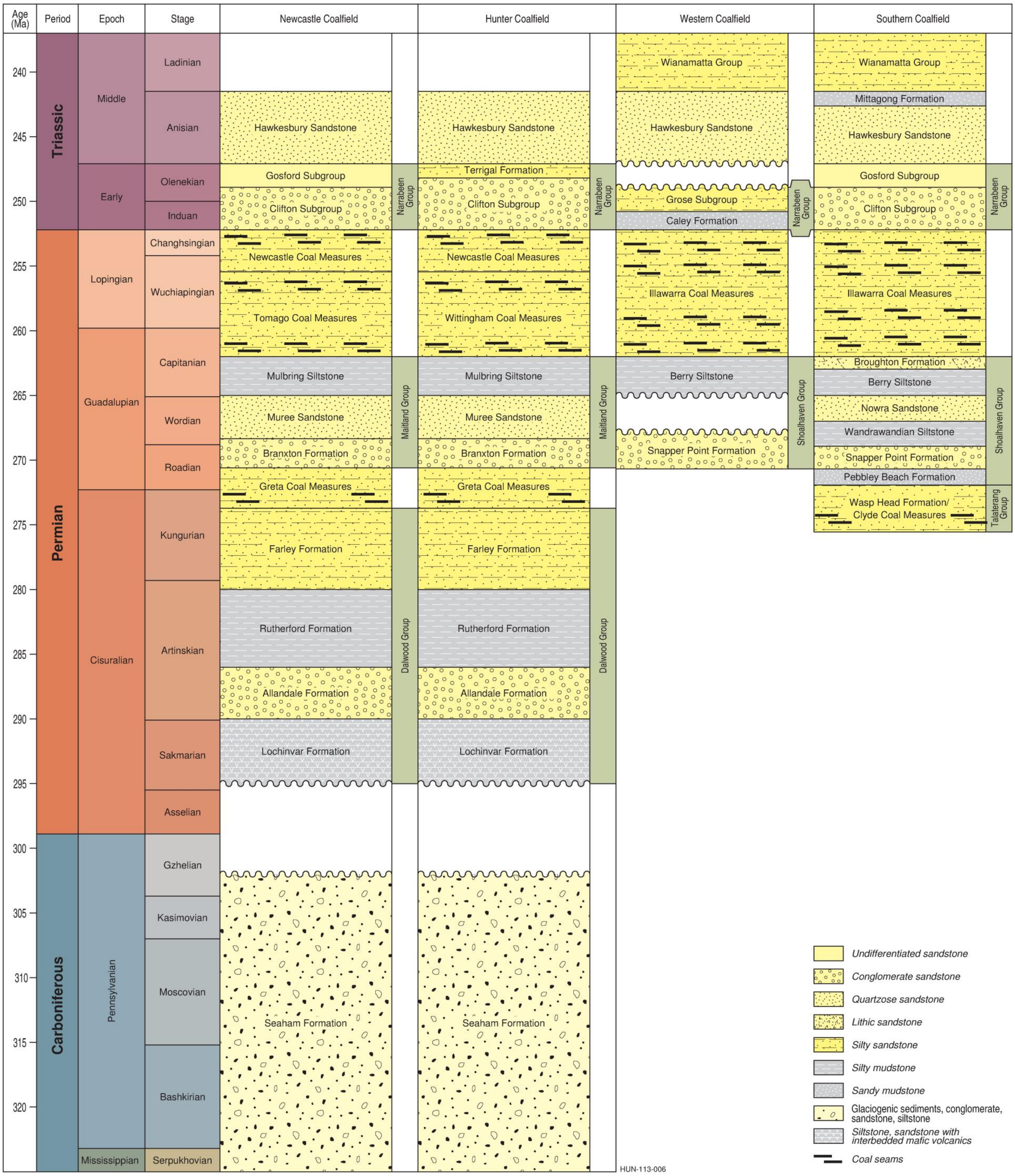


Figure 28 Generalised stratigraphic column for the geological Sydney Basin showing the main formations and coal measures and how these are correlated across the basin

Data: produced for Bioregional Assessment Programme based on stratigraphic unit information from Geoscience Australia and Australian Stratigraphy Commission (2016)

This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

Illawarra Coal Measures

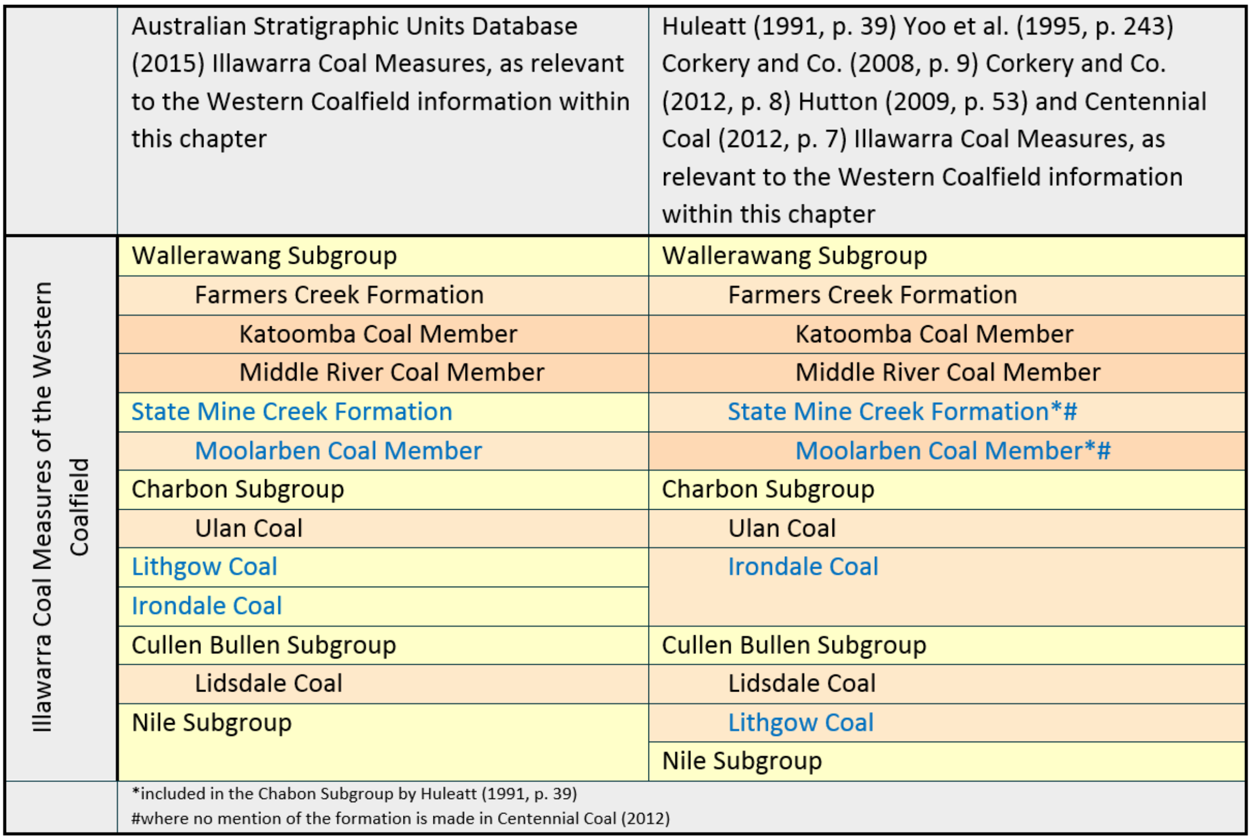
Considered to be an approximate equivalent of the Tomago, Newcastle and Wittingham coal measures in the Newcastle and Hunter Coalfields (Ward and Kelly, 2013), the Illawarra Coal Measures are composed of sandstone, siltstone, claystone and coal. There are also some minor tuff and conglomerate layers, with rare basalt noted within the Southern Coalfield only (Bamberry, 1991, pp. 52–79; Ward and Kelly, 2013). The formation of these coal measures occurred in lower delta plain to alluvial fan environments (Bamberry, 1991, p. 47). The Illawarra Coal Measures reach a maximum thickness in the north of the Southern Coalfield (over 500 m of vertical succession) and are thinnest (less than 100 m) to the south-east of the same coalfield (Bamberry, 1991, p. 47; Ward and Kelly, 2013). In the Southern Coalfield the Illawarra Coal Measures are divided into two subgroups, the Cumberland Subgroup (the basal section) and the Sydney Subgroup (Bamberry, 1991, p. 47; Hutton, 2009, p. 44). The Cumberland Subgroup is considered to contain limited coal and in low quantities that make it economically unimportant (Bamberry, 1991, p. 47). This subgroup contains marine, marginal marine and volcanic latite facies (Bamberry, 1991, p. 47). In the Southern Coalfield, the Sydney Subgroup contains all of the economic coal reserves of the Illawarra Coal Measures (Bamberry, 1991, p. 48). It is composed of conglomerate, sandstone, conglomeratic sandstone, coal, claystone, siltstone and some tuff (Bamberry, 1991, p. 48). Coal is mined from a wide range of depths within the Southern Coalfield from open-cut mines and underground mines. The two most productive coal-bearing units in the Southern Coalfield are:

- The Bulli Coal which varies in depth from surface (open-cut mining in the Wollongong-Coalcliff region) down to about 850 metres in the north-west of the Southern Coalfield (Moffitt, 2000).
- The Wongawilli Coal which varies in depth from near surface to 900 metres (Moffitt, 2000).

The Illawarra Coal Measures of the Western Coalfield are subdivided into seven main constituent units (Australian Stratigraphic Database, 2015). These are the Nile, Cullen Bullen, Charbon and Wallerawang subgroups and State Mine Creek Formation, the Lithgow Coal and the Irondale Coal (Australian Stratigraphic Database, 2015). Further internal divisions of the Cullen Bullen, Charbon and Wallerawang subgroups and State Mine Creek Formation are shown in Figure 29, relevant to the Western Coalfield (Australian Stratigraphic Database, 2015). However due to differences in the stratigraphic hierarchy between authors, industry and governing bodies, the coal of the Western Coalfield is at times divided into four main intervals (Figure 29) where the State Mine Creek Formation, Lithgow and Irondale coals are placed within other subgroups (Huleatt, 1991, p. 39; Yoo et al., 1995, p. 243; Corkery and Co., 2008, p. 9; Corkery and Co., 2012, p. 8; Hutton 2009, p. 53; Centennial Coal, 2012, p. 7).

The Nile Subgroup was formed in a prodelta to lower delta plain environment (Yoo et al., 2001, p. 15). The Cullen Bullen Subgroup formed in fluvial to delta and alluvial plain environments (McVicar et al., 2015). The Charbon Subgroup formed as a delta system with some marine influence (McVicar et al., 2015). The Wallerawang Subgroup is composed of alluvial and floodplain deposits (Yoo et al., 1991, p. 240). The coal measures vary in thickness across the Western Coalfield and are thinnest near the western boundary (50 m), and thickest near the eastern boundary (900 m) (Hutton, 2009, p. 51; Ward and Kelly, 2013). The Lithgow, Lidsdale, Ulan and

Katoomba coals are the dominant units of economic interest in the Western Coalfields, with the Irondale Coal and Middle River Coal Member of localised interest (Ward and Kelly, 2013). The deepest of these seams, the Lithgow Coal, is up to 600 m below the surface at its deepest, but occurs at the surface in some localised areas of lower elevation. The Katoomba Coal Member is the shallowest unit and outcrops at the surface or is close to the surface over much of its extent.



	Australian Stratigraphic Units Database (2015) Illawarra Coal Measures, as relevant to the Western Coalfield information within this chapter	Huleatt (1991, p. 39) Yoo et al. (1995, p. 243) Corkery and Co. (2008, p. 9) Corkery and Co. (2012, p. 8) Hutton (2009, p. 53) and Centennial Coal (2012, p. 7) Illawarra Coal Measures, as relevant to the Western Coalfield information within this chapter
Illawarra Coal Measures of the Western Coalfield	Wallerawang Subgroup	Wallerawang Subgroup
	Farmers Creek Formation	Farmers Creek Formation
	Katoomba Coal Member	Katoomba Coal Member
	Middle River Coal Member	Middle River Coal Member
	State Mine Creek Formation	State Mine Creek Formation*#
	Moolarben Coal Member	Moolarben Coal Member*#
	Charbon Subgroup	Charbon Subgroup
	Ulan Coal	Ulan Coal
	Lithgow Coal	Irondale Coal
	Irondale Coal	
	Cullen Bullen Subgroup	Cullen Bullen Subgroup
	Lidsdale Coal	Lidsdale Coal
	Nile Subgroup	Lithgow Coal
		Nile Subgroup
	*included in the Chabon Subgroup by Huleatt (1991, p. 39) #where no mention of the formation is made in Centennial Coal (2012)	

Figure 29 Stratigraphic hierarchy difference between the Australian Stratigraphic Units Database (Geoscience Australia and Australian Stratigraphy Commission, 2016) and various authors

1.1.3.2.2 Triassic sedimentary rocks

Narrabeen Group

In the Southern Coalfield the Narrabeen Group is divided into two subgroups: the Clifton and Gosford Subgroups (Hutton, 2009, p. 43). The Narrabeen Group is a Lower Triassic non-coal-bearing stratigraphic unit (Hutton, 2009, p. 43). The group is composed mainly of quartz-rich sandstone, shale and mudstone (Hutton, 2009, p. 43) which were formed within several different fluvial environments (Ward, 1972). Evidence of deposition in alluvial fan, braided and meandering stream and delta plain environments are all recognised within the Narrabeen Group (Ward, 1972). Formation of the Narrabeen Group was associated with a relatively slow period of marine transgression, characterised by sediment starvation through declining erosion at the sediment source (Ward, 1972). The dominant direction of deposition is thought to be towards the south and south-west, with some periodic influxes from the east (Ward, 1972).

The subdivision of the Narrabeen Group of the Western Coalfield is considered uncertain due to the lack of drilling to significant depths and so correlation of the group in the north and the south is approximate (Hutton, 2009, p. 51). The sequence has a maximum thickness of 656 m but is thinner near the west of the coalfield (Yoo et al., 2001, p. 52). However, in the north of the Western Coalfield the Narrabeen Group is reminiscent of the Digby Formation (part of the stratigraphy in the neighbouring Gunnedah Basin) and is composed of conglomerate, sandstone, quartz sandstone and siltstone (Yoo et al., 2001, p. 52).

Hawkesbury Sandstone

The Triassic aged quartz-rich Hawkesbury Sandstone has a maximum stratigraphic thickness of between 250 and 290 m (Conaghan and Jones, 1975; Australian Stratigraphic Database, 2015). Some mudstone is present within this formation, with Conaghan and Jones (1975) estimating a mudstone to sandstone ratio of 20:1 in favour of sandstone. Although some refer to the Hawkesbury Sandstone as a massive sandstone unit (Jones and Rust, 1983), Conaghan and Jones (1975) referred to known areas of cross-sets in a 'sheet facies' where cross-sets range in size from a few centimetres to a few metres. Deposition is thought to have been influenced by strong currents in shallow marine, littoral, estuarine, fluvial, lacustrine or aeolian environments (Conaghan and Jones, 1975). A braided stream environment with massive (up to 15 m) floodplain deposit formation is described for the massive sandstone, and was favoured among researchers (Jones and Rust, 1983). Miall and Jones (2003) found that fluvial modelling of the Hawkesbury Sandstone indicated channel belts in excess of 2.5 km wide. Deposition is thought to have occurred in a north-easterly direction (Ward, 1972). Towards the eastern boundary of the Western Coalfield the Hawkesbury Sandstone reaches a thickness of around 244 m, thinning to the west and becoming only 52 to 55 m thick within a minimum distance of 25 km (McVicar et al., 2015).

Mittagong Formation

The Mittagong Formation is a coal-barren unit, formally known as the Passage Beds, which represents the gradational change from the underlying Hawkesbury Sandstone to the overlying Wianamatta Group (Bamberry, 1991, p. 47). Interbedded shales and fine-grained sandstone layers have maximum thickness of 15 m (Bamberry, 1991, p. 47; Ward and Kelly, 2013).

Wianamatta Group

The Middle Triassic aged Wianamatta Group was deposited during a single marine regression (Herbert, 1979). The group is subdivided into three units, the Ashfield Shale, Bringelly Shale and Minchinbury Sandstone; both the Ashfield Shale and the Bringelly Shale are further subdivided into several constituent units (Herbert, 1979; Geoscience Australia and Australian Stratigraphy Commission, 2016). The lowermost Ashfield Shale consists of a gradational sequence of lacustrine through to marine or brackish facies (Herbert, 1979). The Minchinbury Sandstone is the continuing gradation of the move to shoreline facies, particularly beach and barrier bar environments (Herbert, 1979). The uppermost Bringelly Shale initially formed in lagoonal and marsh environments but slowly graded into alluvial or estuarine coastal plain facies (Herbert, 1979). Hutton (2009, p. 43) stated that the Wianamatta Group only occurs within the northern portion of the Southern Coalfield. Only a single subunit of the Wianamatta Group is recognised in the Western Coalfield, the Ashfield Shale (McVicar et al., 2015).

1.1.3.2.3 Permian to Triassic igneous rocks

Beginning at the Permo-Triassic boundary, basaltic igneous intrusions pierce the stratigraphic record of the Sydney Basin bioregion (Ward and Kelly, 2013). These basaltic intrusions continued sporadically into the Neogene (Ward and Kelly, 2013). A rhyolitic to dacitic pyroclastic igneous formation, the Rylstone Volcanics, are composed of tuffaceous sandstone, breccia, conglomerate, siltstone, thin airfall tuff beds and flow banded rhyolite lavas (Geoscience Australia and Australian Stratigraphy Commission, 2016). It underlies the Permian Shoalhaven Group (Geoscience Australia and Australian Stratigraphy Commission, 2016). A late Permian volcanic complex consisting of small dykes and sills, and large sheet intrusion, form the Coonemia Complex in the vicinity of Nowra (Carr, 1997).

1.1.3.2.4 Jurassic to Quaternary rocks

Sedimentary rocks

Jurassic and Cretaceous sedimentation took place in the north of the Western Coalfield, depositing the Purlawaugh Formation, Pilliga Sandstone and the Bungil Formation (Yoo et al., 1995, p. 234); these are discussed in Section 1.1.3 of companion product 1.1 for the Hunter subregion (McVicar et al., 2015). However, to the south of the Western Coalfield and within the Southern Coalfield, the deposition of Jurassic sedimentary rocks is speculative, as there is no existing stratigraphic record for that time period (Philp and Saxby, 1980). From the Cretaceous into the Quaternary, sedimentary processes continued across the Sydney Basin, depositing alluvium, colluvium, gravels, sands, silts, clays, peat, cemented conglomerates, and laterites (Herbert, 1983a; Stroud et al., 1985; Watkins et al., 1997; Thomas et al., 2013). The distribution of surface geology in the Sydney Basin bioregion (Figure 24) can be described as dominantly Triassic and Permian, with notable deposits of Quaternary alluvium.

Igneous rocks

The basaltic intrusions previously mentioned (see Section 1.1.3.2.3) continued through the Jurassic and Cretaceous into the Paleogene and Neogene (Ward and Kelly, 2013). Basaltic flows from the Paleogene occur in the Southern Coalfield’s Mittagong region (Ward and Kelly, 2013). The youngest of these basaltic intrusions are in places covered by unconsolidated fluvial and coastal sediment ranging in age from Paleogene to Quaternary (Ward and Kelly, 2013). Dyke and sill intrusion occurred commonly in the Paleogene and Neogene (Ward and Kelly, 2013). No igneous activity is known after the Neogene.

The Jurassic aged intrusive Mount Gibraltar Microsyenite is dominantly composed of syenite (Ward and Kelly, 2013). The Mount Gibraltar Microsyenite intrudes the Wianamatta Group (Bodorkos, 2010, p. 87). The Mount Gibraltar Microsyenite is found at Mount Gibraltar, Mount Jellore and Mount Flora in the Mittagong region of the Southern Coalfield (Ward and Kelly, 2013). The syenite intrusive is also found as a sill at Mount Alexander intruding the Wongawilli Coal (Ward and Kelly, 2013).

Diatremes occur across the basin and are filled with volcanic breccia (Crawford et al., 1980, p. 296; Ward and Kelly, 2013). Crawford et al. (1980, p. 296) stated that 95 diatremes are known within the Sydney Basin, and another 60 were inferred. Branagan and Packham (2000) later downgraded this estimate to just over 30 diatremes. The diatremes are believed to be Jurassic in age (Crawford et al., 1980, p. 298). The internal breccia is largely composed of volcanic (amygdaloidal and basaltic) fragments set in a tuffaceous matrix, though sandstone and shale fragments also occur (Crawford et al., 1980, p. 313).

1.1.3.3 Basin history

In the earliest Permian, the Sydney Basin (as currently defined) did not exist, although deposition of the basin's lowermost stratigraphic units had begun as early as the Late Carboniferous (Brakel, 1991, p. 12). This deposition took place in the north and south of the basin in fluvial and lacustrine environments (Brakel, 1991, p. 12). This is not to say that structural features of the basin did not exist in the early Permian; for example, the volcanic rift along the Lapstone Fault (a basement feature) was forming even then, but the main period of activity occurred in the late Permian (Harrington and Brakel, 1981; Harrington and Brakel, 1991, p. 206). A depositional hiatus (forming a widespread disconformity) across the Sydney Basin has been attributed to tectonic movement that later resulted in the marine transgression event of the early Permian (Brakel, 1991, p. 13). Depositional settings were largely controlled by the marine transgression and regression cycles that directly impacted the basin (Herbert, 1997; O'Neill and Danis, 2013). These continual large and small cycle sea-level changes resulted in the formation and distribution of the marine, fluvial and deltaic environments that were the dominant environmental settings for the basin (Herbert, 1997).

The SGBB overlies and is bounded by the series of older geological domains (fold belts) collectively known as the Tasman Fold Belt (O'Neill and Danis, 2013). The Tasman Fold Belt contains the Ordovician to early Cretaceous rocks of the Delamerian Orogen, Lachlan Fold Belt, New England Fold Belt, Thomson Fold Belt and Kanmantoo Fold Belt (O'Neill and Danis, 2013). The evolution of these fold belts began in the Mesoproterozoic during breakup of an older supercontinent, and were further influenced during middle Cambrian development of a passive and a convergent margin system, and subsequently by the Carboniferous formation of Pangaea and the earliest signs of the Pangaea breakup (Veevers, 2000; O'Neill and Danis, 2013). Sitting to either side of the Sydney Basin are two of the five tectonic realms of the Tasman Fold Belt, the New England Fold Belt to the north and north-east and the Lachlan Fold Belt to the west and south-west (Scheibner, 1978; Powell et al., 1990). The rocks of the Tasman Fold Belt have been directly linked to the SGBB as a sediment source (O'Neill and Danis, 2013). The dominant structural features of the Sydney Basin are aligned in the direction of the underlying rift deformation, north-east to south-west (Korsch et al., 2009; Haworth, 2003).

The earliest structural development of the SGBB took place in the Middle Devonian, with the formative beginning of two elements of the Tasman Fold Belt, the Lachlan Fold Belt and the Kanmantoo Fold Belt. This early phase of development of the Tasman Fold Belt ceased in the early Carboniferous (Scheibner, 1999, p. 26). Also occurring around this time was subsidence-related volcanic activity within the area of the proto New England Fold Belt (Scheibner, 1999, p. 26). Plate interactions generating orogenic events in the vicinity of the New England Fold Belt, and parts of the Lachlan Fold Belt, resulted in loading and flexure that led to the depressed structural feature that eventually evolved into the SGBB (Scheibner, 1999, p. 26).

During the middle to Late Carboniferous, uplift, faulting, crustal block rotation and extension related to the Hunter-Bowen Orogeny (super cycle 2) resulted in crustal extension to form the first major depression of the Sydney and Gunnedah basins (Tadros, 1995, p. 166; O’Neill and Danis, 2013). For more detail on super cycles see O’Neill and Danis, 2013, pages 7 to 10.

In the Late Carboniferous, in cycle 3 of the Hunter-Bowen Orogeny, the extension of the crust resulted in major rift events affecting the areas of the Bowen and Sydney basins (O’Neill and Danis, 2013). The bulk of the SGBB formation began at some stage between 300 and 268 million years ago in the Late Carboniferous to early Permian when rifting resulted in an elongated area of deposition for some glacially derived sedimentation, though earlier formation had occurred (Tadros, 1995, p. 166; O’Neill and Danis, 2013). Following this period of rifting, volcanic activity in the early Permian formed the base of the Sydney Basin as seafloor spreading and westward subduction took place (O’Neill and Danis, 2013). For the remaining middle Permian and into the late Permian, cycle 3 of the Hunter-Bowen Orogeny continued to form the SGBB as compression and large scale folding resulted in the north to south deformation of the basins (to resemble their modern structural assemblage) and the deposition of the Greta Coal Measures (O’Neill and Danis, 2013).

During the late Permian, as part of the fourth cycle of the Hunter-Bowen Orogeny the SGBB was subject to compression and crustal loading due to convergence. This resulted in development of foreland basins, rather than rift basins (O’Neill and Danis, 2013). At this time coal deposition was widespread throughout the SGBB, with the bulk of the source rock originating from the Tasman Fold Belt (Scheibner, 1999, p. 28; O’Neill and Danis, 2013). In the Lower Triassic, sedimentary deposition was dominated by fluvial transport during a period of continued plate convergence and tectonic uplift (O’Neill and Danis, 2013). Towards the final stage of the Hunter-Bowen Orogeny, continued collision and uplift completed sedimentation of the basins as major faulting activity brought about folding, and built the dominant anticline and syncline structures (O’Neill and Danis, 2013).

Rifting of Pangaea resulted in the reactivation of older features and volcanic eruptions within the Sydney Basin (O’Neill and Danis, 2013). The last major phase of tectonic activity which affected the Sydney Basin occurred over 150 million years ago (Wellman, 1987; Haworth, 2003). The Sydney Basin is now regarded as being tectonically stable (Haworth, 2003).

1.1.3.4 Coal and hydrocarbons

The following is a brief summary of the coal and hydrocarbon resources of the onshore Sydney Basin bioregion. For a more in-depth description of these resources, see Section 1.2.1 of companion product 1.2 for the Sydney Basin bioregion (Hodgkinson et al., 2018).

1.1.3.4.1 Coal

The SGBB is a globally significant sedimentary basin for coal (Ward and Kelly, 2013). Coal was first discovered in the Sydney Basin in 1797 (Ward et al., 2014) and the Sydney Basin is now classed as one of Australia’s main coal provinces (Philp and Saxby, 1980; Brakel, 1991, p. 10). The Coalfield Geology Council of NSW divides the basin into five constituent coalfields, namely the Newcastle, Hunter, Western, Central and Southern coalfields (Figure 23; Saghafi et al., 2007; Ward and

Kelly, 2013). The Southern Coalfield was previously known by several names, including the South-western Coalfield, the Southern Coalfield and the Clyde River Coalfield (Brakel, 1991, p. 11). The current Hunter and Newcastle coalfields were also previously termed the Northern Coalfield (Brakel, 1991, p. 10). The net volume of coal is greatest within the Hunter, Newcastle and Southern coalfields, specifically in the lower and upper Permian Greta, Tomago, Wittingham, Newcastle and Illawarra coal measures (Scott and Hamilton, 2006; Ward and Kelly, 2013). All economic coals within the Sydney Basin are Permian in age and are generally of medium to high volatile bituminous rank (Saghafi et al., 2007).

Across the entire Sydney Basin, most coals have reached the stage of thermal maturation suitable for gas formation (Scott and Hamilton, 2006; Ward and Kelly, 2013). The known gas content has been found to increase with increasing depth from surface (Ward and Kelly, 2013). Although a large proportion of gas contained within Sydney Basin coals is methane-rich, there are some areas that are rich in carbon dioxide or other gases (Faiz et al., 2007; Herbert 1983b; Pinetown 2013; Ward and Kelly, 2013). Previous investigations (Faiz et al., 2007; Scott and Hamilton, 2006; Pinetown, 2013) have concluded that the variance in gas content is due to the effect of different maturation influences (thermogenic, biogenic and/or magmatic heat; Ward and Kelly, 2013).

Coal in the Southern Coalfield is utilised as a resource through both underground mining activities (Saghafi et al., 2007; Ward and Kelly, 2013) and CSG operations, with gas from coal also being extracted from the underground mining operations (Ward and Kelly, 2013). The Southern Coalfield is considered to have a high potential for CSG resources with the main phase of thermal gas generation having been reached (Scott and Hamilton, 2006; Ward and Kelly, 2013). The coal in the Southern Coalfield is considered to differ in rank from the other coalfields; it is classed as low to high volatile bituminous coal (Saghafi et al., 2007). The coal is buried to great depths in some regions of the basin where burial exceeds 300 m (Saghafi et al., 2007). Hutton (2009, p. 44) considers the only economic coals to be those of the Sydney Subgroup within the Illawarra Coal Measures, predominantly from the Bulli Coal, the Balgownie Coal Member, the Wongawilli Coal and the Tongarra Coal.

The work of Scott and Hamilton (2006) identified prospective CSG regions bordering the Western Coalfield, or within the coalfield to the very north-west (Ward and Kelly, 2013). Underground mining is the most common method of coal extraction (Brakel, 1991, p. 12) but some open-cut coal mines are present (Saghafi et al., 2007).

1.1.3.4.2 Conventional hydrocarbon potential

Exploration and discoveries

In the late 1800s coal-based drilling projects discovered natural gas flows (Cadman et al., 1998, p. 144). In 1910 the first petroleum exploration was undertaken; within 28 years a total of 14 petroleum exploration wells had been drilled in the Sydney Basin (Swarbrick and Morton, 1993, p. 29; Cadman et al., 1998, p. 144). These initial exploration wells all resulted in gaseous shows and one contained indications of oil (Adler, 1993, p. 29; Cadman et al., 1998, p. 144, p. 145). A single well drilled at the site of the Balmain Colliery in 1937, produced approximately 4300 m^3/week of gas (Cadman et al., 1998, p. 145). However, no further deposits of economic significance were found (Adler, 1993, p. 29). All of the petroleum exploration in the early 1900s was undertaken based on interpretation of the surface geology (Cadman et al., 1998, p. 145).

In the 1950s a second round of petroleum exploration took place (Cadman et al., 1998, p. 145). Exploration efforts in the mid-1900s were aided by limited seismic reflection data (Cadman et al., 1998, p. 145). Seismic data acquisition across the basin has occurred since the 1960s but has been irregular and is not extensive (Cadman et al., 1998, p. 146). Between the 1950s and 1998, a total of 69 further exploration wells had been drilled in the search for conventional hydrocarbon resources (Cadman et al., 1998, p. 145). The majority of exploration wells resulted in gas shows and eight wells drilled into the Narrabeen Group resulted in measured flow rate for gas (Cadman et al., 1998, p. 145). Two wells discovered gas flow in the Illawarra Coal Measures and minor flow in the Shoalhaven Group (Cadman et al., 1998, p. 145). Following this, the Narrabeen Group was explored further in the Camden region, where flow rates were also recorded (Cadman et al., 1998, p. 145). Several oil shows have been noted from these early exploration efforts but no major discovery has been found (Cadman et al., 1998, p. 145) though oil is thought to be more prominent offshore. Most of these shows occurred in the north-eastern Sydney Basin (onshore; Cadman et al., 1998, p. 145). However many of these exploration wells did not penetrate to depths beyond the Triassic strata, leaving the older stratigraphy largely untested (Cadman et al., 1998, p. 145, 146).

Hydrocarbon systems

Source rocks and maturation

Total organic carbon (TOC) data point to the gas source rocks of the Sydney Basin being dominantly late Permian, principally the Tomago, Newcastle, Wittingham and Illawarra coal measures (Figure 30; Cadman et al., 1998, p. 147). These stratigraphic units have TOC values of around 20%, with a greater percentage of inertinite than other macerals (Cadman et al., 1998, p. 147). The Greta Coal Measures (Figure 30) also have significant exinite maceral counts, indicating oil potential (Cadman et al., 1998, p. 147). Cadman et al. (1998, p. 147) stated that in addition to the coal measures, the marine incursions of the late Permian may also hold potential for oil. The Lower Triassic shales of the Narrabeen Group are considered the likely source of gas within the Narrabeen Reservoir (Figure 30; Cadman et al., 1998, p. 148).

The absence of Jurassic strata (due to erosion) means that precise thermal modelling is not possible. However, it is likely that the lower Permian source rocks (Greta Coal Measures) of the Sydney Basin reached thermal maturity during the Triassic through to the Jurassic (Cadman et al., 1998, p. 148). The late Permian source rocks (Tomago, Newcastle, Wittingham and Illawarra Coal Measures) were in the thermal maturity window from the Upper Jurassic (Cadman et al., 1998, p. 148). The Lower Triassic source rocks (Narrabeen Group) within major depocentres reached thermal maturity during the middle Cretaceous (Cadman et al., 1998, p. 148). Geoscience Australia (2015a) state that the generation of hydrocarbons is still in progress.

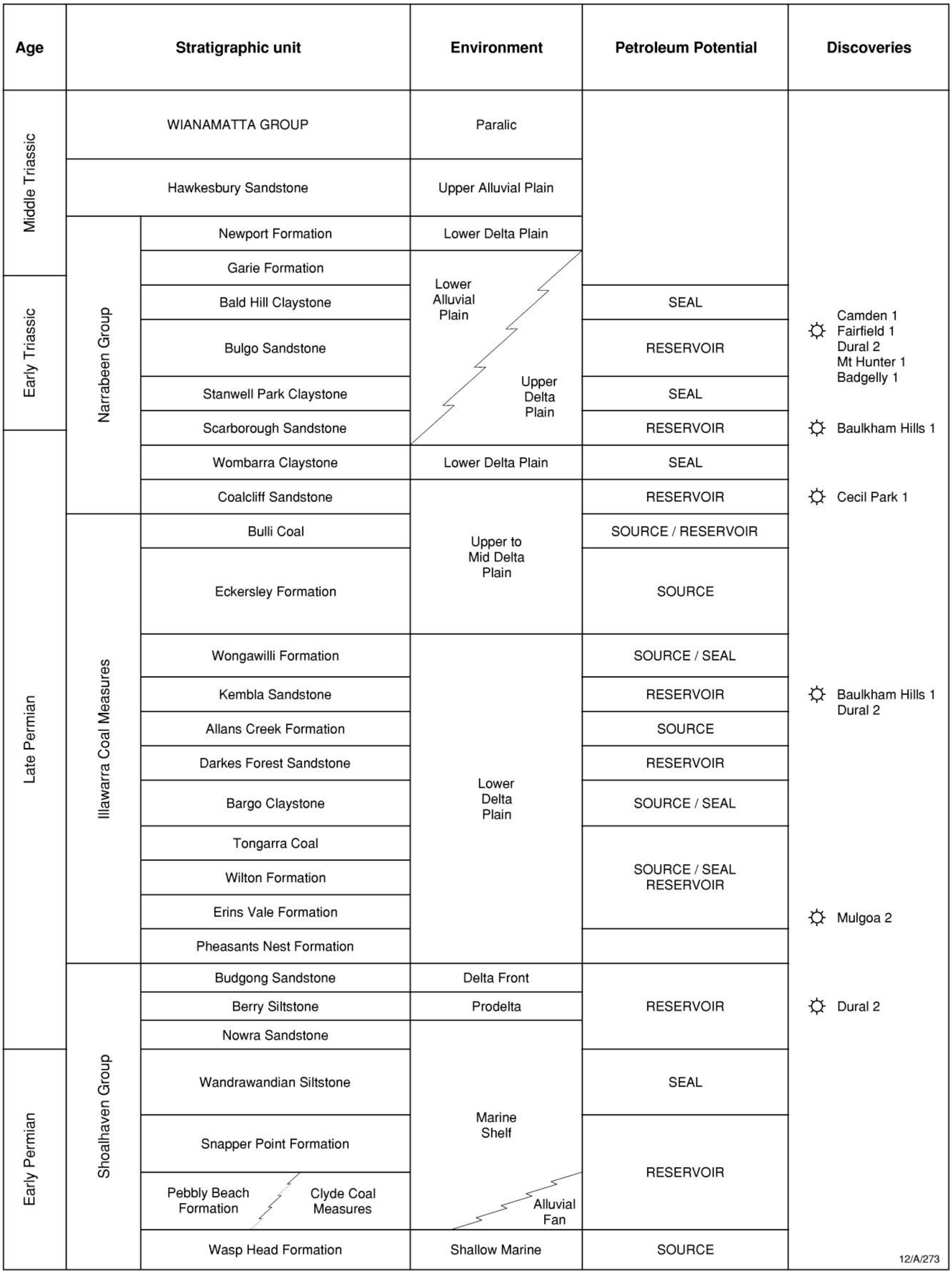
Reservoirs and seals

Potential reservoirs have been identified within the Permian and Triassic stratigraphy of the Sydney Basin (Cadman et al., 1998, p. 146). The Narrabeen Group holds several potential reservoirs within its fluvial sandstones (Bulgo Sandstone, Scarborough Sandstone and Coal Cliff Sandstone; Figure 30) which are sealed by the fine-grained claystone deposits of a floodplain or lower delta plain (Bald Hill Claystone, Stanwell Park Claystone and Wombarra Claystone; Figure 30; Cadman et al., 1998, p. 146). The porosities of these reservoirs are variable and though clay overgrowths limit the pore space, porosity values of up to 20% are recorded in sandstone units (Cadman et al., 1998, p. 146). Due to the clay overgrowths, permeability is generally low (<10 millidarcies) resulting in moderately good reservoirs (Cadman et al., 1998, p. 146).

The Illawarra Coal Measures and the Shoalhaven Group (Figure 30) have been found to contain gas in several wells (Cadman et al., 1998, p. 146). While the potential reservoirs of the Illawarra Coal Measures are composed of suitable reservoir material, the permeability is low (Cadman et al., 1998, p. 146). The most permeable unit is a fluvial unit that has been reworked as a result of marine incursion, the Darkes Forest Sandstone (Figure 30; Cadman et al., 1998, p. 146, 147). Of the Shoalhaven Group the Muree, Nowra and Cessnock sandstones display good reservoir quality, while the Mulbring and Berry siltstones, along with the siltstone in the Branxton Formation, form potential seal units (Cadman et al., 1998, p. 147).

Traps and seals

Anticlinal and fault dependent closures formed during the Permo-Triassic compressional phase have produced structural traps for the hydrocarbons generated during the Triassic, sourced from lower Permian rocks (Cadman et al., 1998, p. 148). However there is the potential for oil reservoirs near the depocentres to have been flushed by later gas flow (Cadman et al., 1998, p. 148). Extension during the Late Cretaceous rifting resulted in the formation of fault-dependent and four-way-dip closures (Cadman et al., 1998, p. 148). These Late Cretaceous traps may lock in Permian and Triassic hydrocarbons (Cadman et al., 1998, p. 148). During the Paleogene and Neogene compression of the basin resulted in folding and faulting, but also the reactivation of existing structure (Cadman et al., 1998, p. 148). It is likely that the late compressional phase could have breached existing traps resulting in secondary migration (loss) of the hydrocarbons (Cadman et al., 1998, p. 148).



Age	Stratigraphic unit		Environment	Petroleum Potential	Discoveries
Middle Triassic	WIANAMATTA GROUP		Paralic		
	Hawkesbury Sandstone		Upper Alluvial Plain		
	Narrabeen Group	Newport Formation	Lower Delta Plain		
		Garie Formation	Lower Alluvial Plain Upper Delta Plain		
Early Triassic		Bald Hill Claystone		SEAL	
		Bulgo Sandstone		RESERVOIR	☼ Camden 1 Fairfield 1 Dural 2 Mt Hunter 1 Badgelly 1
		Stanwell Park Claystone		SEAL	
		Scarborough Sandstone		RESERVOIR	☼ Baulkham Hills 1
Late Permian		Wombarra Claystone	Lower Delta Plain	SEAL	
		Coalcliff Sandstone	Upper to Mid Delta Plain	RESERVOIR	☼ Cecil Park 1
	Illawarra Coal Measures	Bulli Coal		SOURCE / RESERVOIR	
		Eckersley Formation		SOURCE	
		Wongawilli Formation	Lower Delta Plain	SOURCE / SEAL	
		Kembla Sandstone		RESERVOIR	☼ Baulkham Hills 1 Dural 2
		Allans Creek Formation		SOURCE	
		Darkes Forest Sandstone		RESERVOIR	
		Bargo Claystone		SOURCE / SEAL	
		Tongarra Coal		SOURCE / SEAL RESERVOIR	
		Wilton Formation			
		Erins Vale Formation			☼ Mulgoa 2
		Pheasants Nest Formation			
	Shoalhaven Group	Budgong Sandstone	Delta Front	RESERVOIR	
		Berry Siltstone	Prodelta		☼ Dural 2
		Nowra Sandstone	Marine Shelf		
Early Permian		Wandrawandian Siltstone		SEAL	
		Snapper Point Formation		RESERVOIR	
		Pebbly Beach Formation Clyde Coal Measures	Alluvial Fan		
		Wasp Head Formation	Shallow Marine	SOURCE	

Figure 30 Potential petroleum systems of the southern Sydney Basin

Source: Cadman et al. (1998, p. 143)

1.1.3.5 Potential basin connectivity

The Sydney Basin bioregion is connected to the Hunter subregion of the Northern Sydney Basin bioregion in the north, where no geological constraint separates these two bioregions. Individual coalfields in the Hunter subregion are also in the Sydney Basin bioregion. The shallow basement high of the Mount Coricudgy Anticline represents the structural divide between the Sydney and Gunnedah basins, although there is similarity in stratigraphy (Danis et al., 2011). This similarity is reason to assume that there is a direct connection remaining between the two basins, although structurally disrupted to varying degrees. The Sydney Basin sits unconformably on the older Ordovician, Silurian and Devonian basement rocks towards the south (Packham and Day, 1969). The eastern portion of the Sydney Basin sits on the older rocks of the offshore extension of the New England Fold Belt (O'Neill and Danis, 2013). The Blue Mountain and Illawarra Shelves (western Sydney Basin) are atop the underlying Lachlan Fold Belt which is predominantly metamorphic, volcanic and intrusive rocks of low hydraulic conductivity (Brakel, 1991, p. 11). The central portions of the basin are also thought to sit on top of the Lachlan Fold Belt (Brakel, 1991, p. 11). The Upper Carbonifeous to Middle Triassic rocks of the Hunter subregion (northern Sydney Basin bioregion) overlie rocks of the New England Fold Belt (Brakel, 1991, p. 11). The basin is further constrained offshore by the edge of the continental shelf to the east.

See Section 1.1.4 for details about the hydraulic connectivity of the basin in greater detail, with reference to groundwater-geological interaction.

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1.1.4 Hydrogeology and groundwater quality

Summary

The southern part of the geological Sydney Basin is primarily a Permian-Triassic sedimentary rock sequence underlain by undifferentiated sedimentary rocks of Carboniferous and Devonian age. Locally there are important aquifers within the Hawkesbury Sandstone and Narrabeen Group and unconsolidated alluvial aquifers associated with present-day drainage networks and coastal deposits.

Alluvial deposits occur along the valleys, creeks and floodplains of the Nepean, Hawkesbury, Georges and Shoalhaven rivers in the bioregion. These deposits are generally shallow, forming unconfined aquifers that are responsive to rainfall and streamflow. Water movement in these deposits occurs as intergranular flow through the preferential pathways provided by interconnected, higher permeability sand and gravel lenses. Groundwater recharge to the alluvial aquifers is primarily from rainfall, with minor contributions from irrigation, leaky service mains and flow from the underlying bedrock units.

Late Triassic Wianamatta Group occurs as scattered remnant areas in the Southern Highlands, with major outcrops predominantly over the Cumberland Plain west of Sydney. The aquifer system comprises residual soils, colluvium and fine-grained rocks derived from shales, floodplain alluvium and weathered saprolite. Aquifers in the Wianamatta Group generally contain highly saline groundwater and have very low yields.

The Hawkesbury Sandstone occurs across the entire geological Sydney Basin, extending from the Southern Highlands to the Putty area in the north, and to the lower Blue Mountains. The Hawkesbury Sandstone comprises friable, fine- to coarse-grained, mature and well-sorted quartzose sandstone with some shale lenses of limited areal extent, resulting in localised aquitards. Water quality within the upper sections of the Hawkesbury Sandstone is commonly poorer than the lower sections due to leakage from overlying shale formations. Possible upward flow or migration of brackish to saline groundwater along fractures from underlying Narrabeen Group aquifers or Permian coal measures may be contributing to brackish conditions in the deeper Hawkesbury Sandstone on the eastern side of the Lapstone Structural Complex.

The aquifers of the Narrabeen Group, Bulgo and Scarborough sandstones, as well as the Bald Hill Claystone, outcrop in the valleys of the Cordeaux and Avon reservoirs, around the Southern Coalfields. Water quality in the Narrabeen Group is poorer than in the Hawkesbury Sandstone, with levels of total dissolved solids (TDS) (salinities) ranging from around 1500 to 5000 mg/L TDS.

The horizontally layered sandstone strata in the southern part of the geological Sydney Basin, which host the main aquifer systems, show particular features (e.g. dual/secondary porosity, fracturing and bedding plane shearing) related to local stress relief effects and large-scale deformation. The main role of groundwater in the Southern Coalfield is to support streams through baseflow and groundwater-dependent ecosystems, with both the Hawkesbury and Bulgo sandstone aquifers providing most of the baseflow.

The NSW Government undertakes groundwater planning and management via water sharing plans, allowing the management of individual groundwater systems. Water source areas of two existing and three proposed water sharing plans intersect the Sydney Basin bioregion. Groundwater extractions from these water sources areas are used for a range of purposes including domestic, stock, irrigation, town water supply and industrial purposes, with a proportion of water protected for the environment.

1.1.4.1 Groundwater systems

1.1.4.1.1 Hydrogeological characteristics of the Sydney Basin bioregion

The southern part of the geological Sydney Basin is primarily a Permian-Triassic sedimentary rock sequence underlain by undifferentiated sedimentary rocks of Carboniferous and Devonian age (see Figure 24 and Figure 28 in Section 1.1.3). Regional aquifers containing groundwater of a quality and yield suitable for large-scale development are not present in the geological Sydney Basin, however, locally there are important aquifers within the Hawkesbury Sandstone and Narrabeen Group (Ross, 2014) and unconsolidated alluvial aquifers associated with present-day drainage networks and coastal deposits.

Across the bioregion, sandstone units behave as porous and fractured rock aquifers whereas claystones and shales behave as aquitards, with generally variable water quality (AGL, 2013).

The main groundwater systems are associated with the following geological features:

1. Unconsolidated Cenozoic alluvial (along river floodplains) and dune/beach deposits (for example, the Botany Sand Beds (BSB))
2. Upper Triassic Wianamatta Group rocks where minor aquifers and aquitards occur (Bringelly Shale, Minchinbury Sandstone, and Ashfield Shale)
3. Middle Triassic Hawkesbury Sandstone aquifers (including Newport and Garie formations of the Narrabeen Group)
4. Lower Triassic Narrabeen Group sandstone aquifers (Bulgo and Scarborough sandstones)
5. Permian water-bearing units (Illawarra Coal Measures).

Figure 31 shows the surface extent of these geological features across the bioregion.

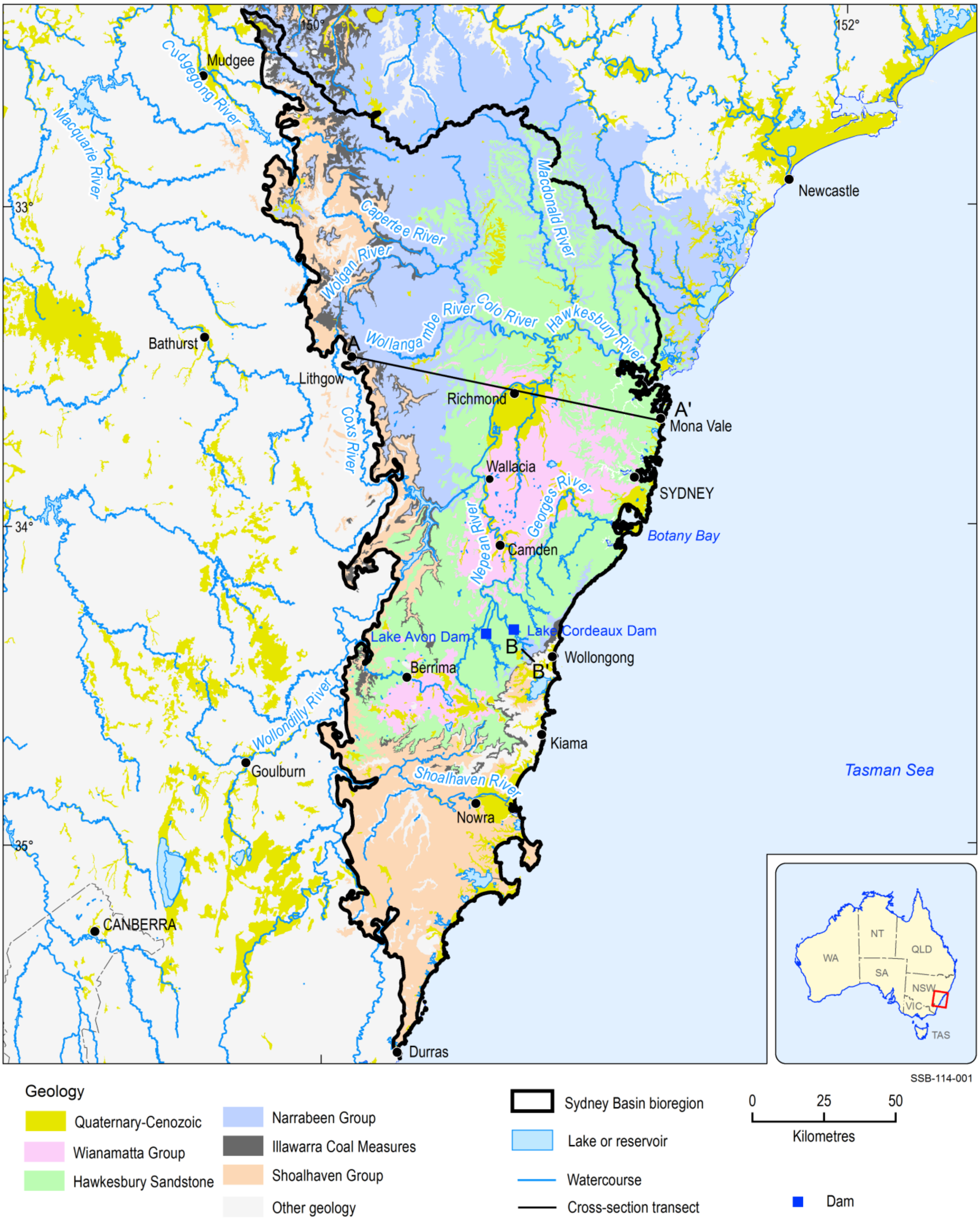

Figure 31 Surficial extent of main hydrogeological units in the Sydney Basin bioregion

Transects A-A' and B-B' are approximate locations of geological cross-sections presented in Figure 32 and Figure 33
Data: Geoscience Australia (Dataset 1)

Figure 32 is a schematic geological cross-section in a west to east direction across the Sydney Basin bioregion (transect A-A' in Figure 31 from Lithgow to Mona Vale), which illustrates the layering of the main geological formations.

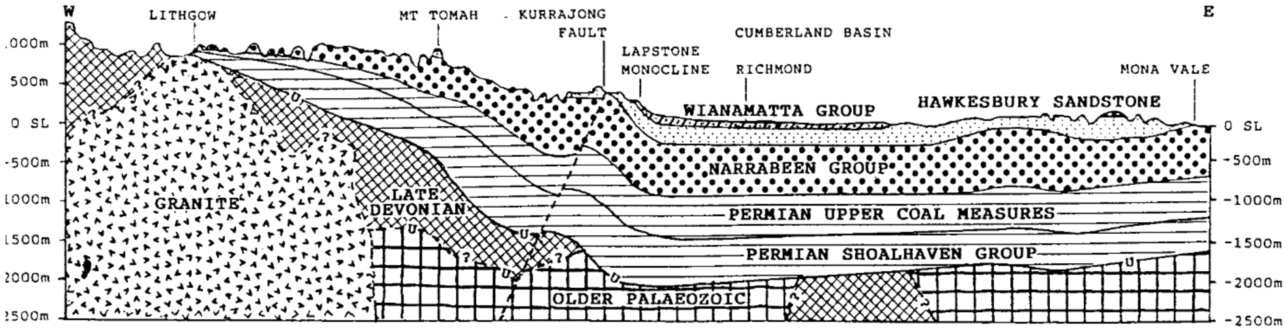

Figure 32 Schematic west to east geological cross-section of the Sydney Basin bioregion

The transect extends from Lithgow in the west and traverses through Mount Tomah and Richmond to Mona Vale in the east
Source: Australian Plants Society, North Shore Group (2011)

Unconfined Cenozoic alluvial/sediment aquifers

Alluvial deposits occur along the valleys, creeks and floodplains of the main rivers in the region: Nepean, Hawkesbury, Georges and Shoalhaven (shown in Figure 10 in Section 1.1.2). These deposits are generally shallow, forming unconfined aquifers that are responsive to rainfall and streamflow. Together with shallow underlying sandstone units they provide low to medium bore yields and have hydraulic transmissivities greater than 20 m^2/day (Parsons Brinckerhoff, 2013). In the geological Botany Basin in southern Sydney significant unconsolidated coastal sand and dune deposits form the BSB.

Nepean River

Around the Camden area, the alluvial deposits of the Nepean and paleo-Nepean River have watertable levels close to 6 m below the surface, low to medium bore yields (mean of 0.2 ML/day extracted from 33 bores) and levels of total dissolved solids (TDS) (salinities) around 2150 mg/L TDS (AGL, 2013).

Hawkesbury River

The alluvial deposits of the Hawkesbury River, extending downstream of Warragamba Dam to the township of Spencer, are referred to as the Hawkesbury Alluvium Groundwater Source. Alluvial deposits are broadest in the Windsor to Wilberforce area with most bores drilled in thinner alluvia of minor tributaries. High salinity values may limit the potential use of groundwater in several areas of these alluvial deposits (NSW Government, 2011). The Hawkesbury alluvium is a significant alluvial groundwater system with reasonable levels of storage (NSW Government, 2015).

Around the Penrith-Richmond area in the eastern ridge of the Blue Mountains, Quaternary alluvial deposits associated with the Hawkesbury River are mostly a mixture of clean quartz sand and cobbles with interbeds up to 20 m thick of yellow clay. They are distinctly different from the Paleogene–Neogene alluvial deposits, which are richer in clay content (Green et al., 2010).

Georges River

Quaternary and Paleogene-Neogene alluvium along the Georges River contains a shallow, unconfined aquifer which is likely hydraulically connected to the Georges River (Parsons Brinckerhoff, 2014). Hydraulic testing indicates that hydraulic conductivities in the alluvium range from 0.003 to 0.1 m/day. On a regional scale, groundwater flow in the alluvium is towards the north-north-east, following the flow direction of the Georges River. Groundwater levels in the alluvial aquifer are relatively shallow (<5 m below ground level) (Parsons Brinckerhoff, 2014). Around Liverpool South, Parsons Brinckerhoff (2011) reported a water level of 8.5 m below the surface and a low bore yield of 0.01 ML/day at one bore within the alluvial aquifer.

The Ashfield Shale, which is part of the Wianamatta Group (see Figure 28 in Section 1.1.3), can be found around the alluvial deposits of the Georges River. This unit varies between 3 and 10 m in thickness, has hydraulic conductivities between 0.01 and 0.08 m/day and behaves as an aquitard. The underlying Hawkesbury Sandstone aquifer is unlikely to influence shallow groundwater flows given the presence of this aquitard (Parsons Brinckerhoff, 2014).

Shoalhaven River South Coast Alluvium

Around Nowra, alluvial aquifers associated with creeks and tributaries to the main Shoalhaven River occur as sand, silt, clay and gravel flanking the creek systems and as more widespread floodplain deposits. Water movement in these deposits occurs as intergranular flow through the preferential pathways provided by interconnected, higher permeability sand and gravel lenses. Within the Broughton Creek floodplain sediments, localised perched groundwater aquifers occur above interbedded clay horizons. Groundwater is typically shallow, between 0.5 and 4 m below the surface. Groundwater movement within the alluvial aquifer and floodplain sediments is towards low-lying topographic features, discharging into local creek systems or as springs (NSW Government, 2013).

South of Nowra in the Jervis Bay area, unconsolidated sand aquifers overlying Triassic sandstones show a rapid response to rainfall pulses. Historical water levels in selected bores around Lake Windermere range between 2 and 11 m below the surface with transmissivity values of 2700 m^2/day (Jacobson and Schuett, 1984).

Botany Basin (Botany Sand Beds)

The geological Botany Basin in southern Sydney (enclosing Botany Bay in Figure 31), originated from preferential erosion of the Paleogene-Neogene coastline and major paleodrainages of the older Triassic bedrock formations, which comprise interbedded shales and sandstones of the Ashfield Shale overlying the medium- to coarse-grained quartz sandstones of the Hawkesbury Sandstone. Numerous erosional episodes interrupted the sedimentary depositional environment, with the sedimentary column reflecting this transition. The Botany Sand Beds (BSB) dominate the sedimentary column of the geological Botany Basin and comprise up to 30 m of uniformly graded, well-sorted, clean and poorly cemented fine- to medium-grained quartz sands, with an average of 15 m saturated sand (Hatley, 2004; EA, 2007). These sand beds are underlain by clay and clay-rich quartz sand lenses and a basal unit consisting of fluvial and aeolian medium-grained sands with gravel lenses, together having a maximum thickness of around 45 m (Hatley, 2004). This sequence of unconsolidated sands of the geological Botany Basin generally makes for a productive aquifer.

At a larger scale, there exist two groundwater systems: one within the bedrock sequences of the Hawkesbury Sandstone; the other in the overlying unconsolidated sedimentary material, termed the BSB. Interactions between these two groundwater systems is acknowledged although not well understood (Hatley, 2004).

Groundwater recharge to the BSB is primarily from rainfall, with minor contributions from irrigation, leaky service mains and flow from the underlying bedrock units. For the BSB, infiltration from rainfall averages 22 and 44 ML/day for dry and wet periods, respectively (Badenhop and Timms, 2009).

Groundwater flow in the BSB follows the topographic gradient and is mainly inward towards Botany Bay. Water levels vary between 0 and 25 m depth below the surface, with the majority of the geological Botany Basin showing a mean depth of around 9 m. The BSB is mostly unconfined with the exception of semi-confined areas underlying discontinuous bands, beds and lenses of clay, silt, peat or an erosional discontinuity of intermittently cemented and hard sandy material termed the ‘Waterloo Rock’. The groundwater flow direction is from the recharge areas in the north-east towards Botany Bay at a rate of about 150 m/year (Badenhop and Timms, 2009).

The BSB has a mean thickness of about 20 m, with up to 53 m depth in paleochannels incised in the basement rocks. Hydraulic gradients range from 0.003 to 0.01; hydraulic conductivities range between 1.4 and 85 m/day; porosities range between 0.33 and 0.40; transmissivities vary between 230 and 630 m^2/day; and the storage coefficient varies between 0.17 and 0.26 (Hatley, 2004).

Wianamatta Group – minor aquifers and aquitards

The Wianamatta Group consists of three units: the Ashfield Shale, the Minchinbury Sandstone and the Bringelly Shale, with the Minchinbury Sandstone of negligible thickness (McNally, 2004). This group has a maximum thickness in western Sydney of up to 300 m, but with more typical thicknesses in the range of 100 to 150 m. The Wianamatta Group occurs as scattered remnant areas in the Southern Highlands, with major outcrops predominantly over the Cumberland Plain south-west of Richmond (Figure 31).

In western Sydney, two aquifer systems are associated with the shale formations of the Wianamatta Group. The upper aquifer system comprises residual soils and colluvium derived from the shales, floodplain alluvium and the weathered saprolite, and typically has a depth of 3 to 10 m. Hydraulic conductivities show a large variability and range between 0.01 and 10^{-5} m/day, with the higher end suggesting the presence of open fractures in weathered shales or ferricrete bands. The lower aquifer system occurs below the base of the weathering and comprises fine-grained mudrocks. This aquifer shows some degree of fracturing thus allowing some groundwater flows. Despite its low transmissivities, McNally (2004) refers to this system as an aquifer because it discharges small volumes of saline water to the surface. Hydraulic conductivities range between 0.001 and 10^{-8} m/day, with the lower end reflecting the intrinsic impermeability of the unfractured shale.

Both aquifers show limited storage and low bore yields, typically less than 0.1 ML/day (McNally, 2004; Parsons Brinckerhoff, 2013). Water-bearing fractures are widely spaced and sometimes poorly interconnected. This results in boreholes being dry when first drilled, then slowly filling with water over several weeks, causing substantial head and salinity variations in piezometers. Water within fractures is generally brackish to saline, especially in low relief areas, with typical values in the range of 5,000 to 50,000 mg/L TDS (McNally, 2004).

Green et al. (2009) and McLean and Ross (2009) argue that high salinity groundwater in this unit is due to the high proportion of soluble salts of marine origin available for dissolution, leaching and mobilisation. McNally (2004, 2009) argue that these rocks are not of marine origin, and that there is little pore space and the present rate of weathering is too small to produce such salinity values. As opposed to the marine origin model, McNally (2004, 2009) propose a depositional sea salt model in the form of saline rain as an alternative. He also explains the large temporal and spatial fluctuations in the salinity values as localised upward movements of salt water, cycles of dry/wet years, pressure fluctuations between shallow fresh water and deeper salt water in the shale terrain, and potential evaporation from the PVC tubing in piezometers or downward leakage of salty runoff around the piezometer seal.

Around Camden, 12 bores tapping the Wianamatta Group have a mean bore yield of 0.1 ML/day, a mean water level of 3.5 m below the surface and salinity around 2500 mg/L TDS (AGL, 2013).

Aquifers in the Wianamatta Group of the geological Sydney Basin are not typically targets for water supply due to lack of water-bearing zones, generally very low yields and in places highly saline groundwater (5,000 to >15,000 mg/L in Western Sydney area) (Russell et al., 2009).

Hawkesbury Sandstone aquifer

The Hawkesbury Sandstone is commonly grouped with the Newport and Garie formations of the Narrabeen Group and defined as the Hawkesbury Sandstone aquifer system (AGL, 2013). It occurs across the whole geological Sydney Basin and crops out over an area of about 20,000 km^2, extending from the Southern Highlands to the Putty area in the north, and to the lower Blue Mountains (Lee, 2009) (Figure 31). Typically, it has a dual porosity with preferential flow dominated by secondary porosity and fracture flow along joints and/or shear zones.

The Hawkesbury Sandstone comprises friable, fine- to coarse-grained, mature and well-sorted quartzose sandstone with some shale lenses of limited areal extent, resulting in localised aquitards (Zaid and Al Gahtani, 2015). Mean estimates of the clay matrix content range from 20 to 40%. Individual sandstone beds usually occur as elongated lenses up to 10 m thick and 1 km long (Cendón et al., 2014). Beds in the Hawkesbury Sandstone have been classified into three facies types, which are summarised in Table 11 (Cendón et al., 2014).

Table 11 Summary of Hawkesbury Sandstone facies and hydrological characteristics (after Cendón et al., 2014)

Facies	Sedimentary structure	Lithology	Hydraulic characteristics
Massive	Little or no structure; with erosional base	Poorly sorted, fine to medium size sands, dispersed gravels and claystone fragments	Reduced permeability. Lower primary macro-porosity compared with Sheet Facies
Sheet or Stratified	Large-scale foreset cross-beds occurring in sets and inclined at about 20 ° to the north-east; with a conforming base	Medium to coarse sand grains bound by silica cement with minor siderite	The most permeable of the three facies due to coarser grainsize, better sorting, cross-bedding structures and sets
Mudstone	Laminated. Commonly terminated laterally by erosion surfaces and overlain by massive facies; typically 0.3 to 5 m thick	Laterally uniform planar black laminated mudstone with thin interbedded grey siltstone. Mudstone facies form shales lenses accounting for about 5% of beds	Low permeabilities and formation of local aquitards

The hydraulic conductivity of the Hawkesbury Sandstone is related to the rock defect characteristics, which are influenced by the depth and in situ stress conditions as well as the presence of regional structural features. Based on 370 packer tests around the Sydney metropolitan area, scaled geometric mean hydraulic conductivities have been found to range from 0.5 m/day at the surface to 0.01 m/day at 50 m depth. Tammetta and Hewitt (2004) reported a mean hydraulic conductivity for the Hawkesbury Sandstone matrix of about 0.0019 m/day, based on six cores at depths of 8 to 37 m. Viable groundwater resources have been identified at Kangaloon (Southern Highlands), Leonay-Emu (western Sydney) and Wallacia (south-western Sydney, Figure 31), with bore yields of up 3.5 ML/day from sites located on major faults or close to volcanic intrusive bodies (Hawkes et al., 2009; Ross, 2014).

At the south-western margins of the geological Sydney Basin, localised perched aquifers within the Hawkesbury Sandstone have been observed, where the underlying shales of the Berry Formation of the Shoalhaven Group create a basal aquitard (Aquaterra, 2011). Slightly higher hydraulic conductivities of 0.1 to 0.5 m/day have been reported, reflecting the locally weathered and friable nature of the sandstone. Groundwater salinity in the Hawkesbury Sandstone is generally low (<100 mg/L TDS), whereas the deeper Berry Formation has more saline groundwater (1000 mg/L TDS) (Aquaterra, 2011).

At the western fringe of the geological Sydney Basin, on the lower sections of the Blue Mountains, the Hawkesbury Sandstone hosts a series of multi-layered aquifers. Three main groundwater systems have been identified:

1. A shallow unconfined aquifer in the upper sandstone aquifer, with topographically-driven groundwater flow and local discharge into hill-slope springs.
2. Intermediate (possibly) perched aquifers likely to discharge to mid-level valleys.
3. Deeper intermediate-scale dual porosity aquifers in the interlayered and fractured horizons of the sandstone discharging at lower levels in the landscape. This aquifer system is semi-confined to confined with the presence of artesian heads east of the Lapstone Monocline (see Figure 24 in Section 1.1.3) (Green et al., 2010).

In the Camden area, salinities tend to be fresher south of the Nepean River because of the proximity to recharge areas (738 mg/L TDS mean from 45 bores). Further north, the Hawkesbury Sandstone is overlain by up to 60 m of Wianamatta Group shales and salinities increase to moderately saline, with values of 3760 mg/L for the basal sandstone and 6190 mg/L in shallower parts of the aquifer (AGL, 2013; Parsons Brinckerhoff, 2013).

The peat swamps on the sandstone rocks of the Blue Mountains (western area of the basin) form in gently sloping headwater valleys, broad valley floors and alluvial flats, gully heads and open depressions on ridgetops (Commonwealth of Australia, 2014). Water flows through the swamps as sheet flow through the peat sediments, whereas groundwater can discharge to these swamps along fractures, joints or bedding planes intersecting the peat swamp. Usually, these swamps are associated with local groundwater flow systems of short path and residence time. The connection between these swamps and groundwater relies on perched aquifer conditions and thus is likely to be ephemeral (Commonwealth of Australia, 2014).

The aquifer in the Hawkesbury Sandstone within the Southern Coalfields is considered a low-yield system of good quality. It is well-developed for commercial production in the Mangrove Mountain area north of Sydney and partially developed in the Blue Mountains west of Sydney and in the Southern Highlands at Kangaloon and at Leonay-Wallacia (Merrick, 2008).

The swamps on the sandstone rocks of the Woronora and Illawarra plateaux south of Sydney are important ecosystems containing a diversity of endemic flora and fauna species (Section 1.1.7). These ecosystems contain threatened species and are classified as endangered ecological communities under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Upland swamps on the Hawkesbury Sandstone terrain of the Woronora and Illawarra Plateaux are either headwater and/or drainage divide or valley fill swamps (Ross, 2009; Fryirs et al., 2014). The groundwater systems beneath the swamps are conceptualised as perched water-bearing zones occurring in colluvial sediments with regional (fractured and porous rock) aquifers occurring in the deeper Hawkesbury Sandstone. They can be important sources of baseflow to Sydney water supply during dry periods. Perched water-bearing zones associated with the upland swamps (particularly Stockyard Swamp and Butlers Swamp) have been shown during long pumping trials to be unaffected by drawdown in the deeper sandstone aquifers (Ross and Carosone, 2009). This suggests these perched water-bearing zones behave as independent hydraulic systems from the underlying regional sandstone aquifer and therefore some level of protection against deep mine dewatering could be expected.

Narrabeen Group – deeper minor aquifers

At the north-east margin of the geological Sydney Basin, the Hawkesbury Sandstone is underlain by the Lower Triassic Terrigal Formation, the uppermost unit of the Narrabeen Group (see Figure 28 in Section 1.1.3 for a generalised stratigraphic column). Its geologic time equivalent south of the Hawkesbury River is the Newport Formation. The Terrigal Formation comprises an interbedded sequence of sandstone, siltstone and claystone some 200 m thick (Cendón et al., 2014). The Terrigal Formation has a lower primary porosity than the overlying Hawkesbury Sandstone, reflecting its clay-silt matrix and smaller mean grainsize.

Further south, around Camden, the Lower Triassic Scarborough Sandstone, a coarse-grained lithic sandstone grading into conglomerate (Mayne et al., 1974), and the Lower Triassic Bulgo Sandstone (see Table 12) are considered to be minor aquifers with bore yields of up to 0.1 ML/day (AGL, 2013) (Figure 33). The layered aquifers in the Bulgo Sandstone have low transmissivities in the range 0.1 to 0.5 m^2/day, whereas Madden (2010) suggests the Scarborough Sandstone is a dual porosity aquifer with dominant flow occurring in secondary rock features. The Bald Hill Claystone and Stanwell Park Claystone (Early Triassic) act as aquitards and limit the vertical flow of water between the Hawkesbury Sandstone and the Bulgo and Scarborough sandstones of the Narrabeen Group (Stammers, 2012; Bradd et al., 2012; McKibben and Smith, 2000; NSW Government, 2008).

Around the Southern Coalfields, the aquifers of the Narrabeen Group, Bulgo and Scarborough sandstones as well as the Bald Hill Claystone, outcrop in the valleys of the Cordeaux and Avon reservoirs (SCA, 2012). Figure 33 shows a schematic geological cross-section from the Kembla Creek arm of the Cordeaux Reservoir (transect B-B’ in Figure 31) to the eastern divide, indicating the interaction between the main aquifers of the Narrabeen Group and surface waters.

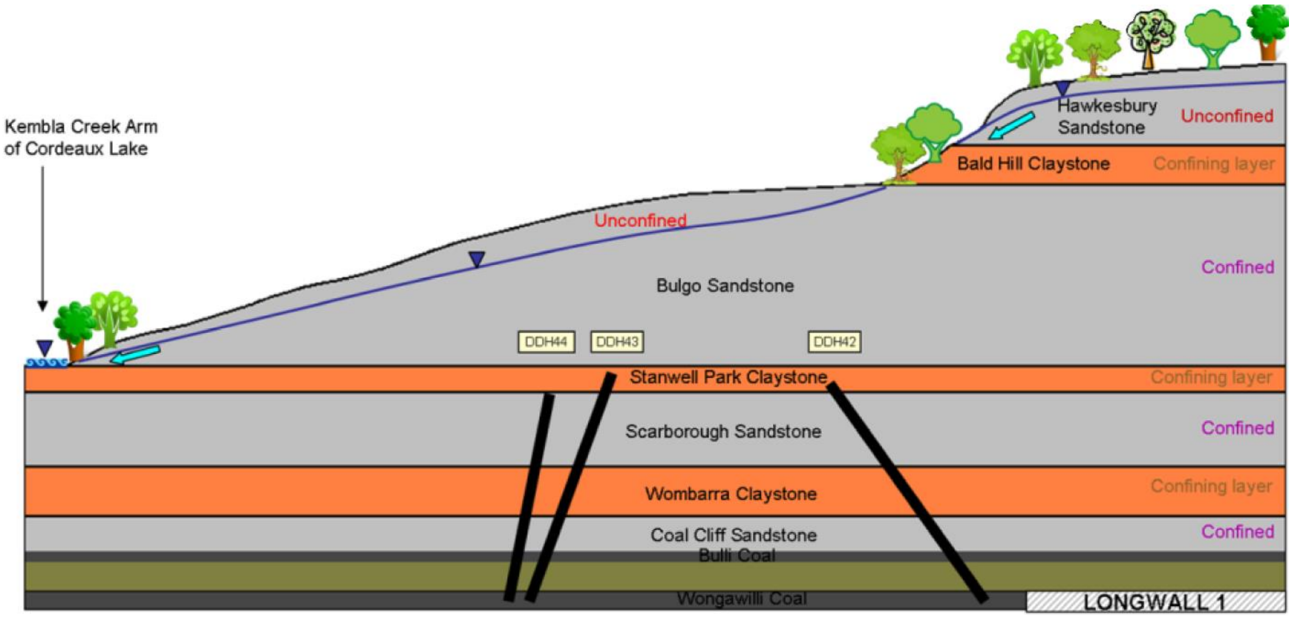

Figure 33 Schematic geological cross-section showing the positioning of the main Narrabeen aquifers along valleys of the Cordeaux Lake

Source: Madden and Ross (2009)

Water quality in the Narrabeen Group is poorer than in the Hawkesbury Sandstone (Madden and Merrick, 2009), with salinities ranging from around 1500 to 5000 mg/L TDS (AGL, 2013).

1.1.4.1.2 Aquifers and confining layers

Bradd et al. (2012) proposed a hydrogeological conceptual model for the interaction between aquifers and confining layers present in the geological Sydney Basin (Sydney Metro, Southern Rivers and the Hawkesbury-Nepean Catchment) based on Reynolds (1976). An equivalent conceptualisation has been proposed by Stammers (2012) for the Southern Coalfields (Figure 23 in Section 1.1.3). This model suggests an anisotropic system where horizontal groundwater flow through more permeable bedding planes is significantly greater than vertical flow. Although vertical flow is typically minimal in the region (Stammers, 2012), a degree of vertical flow is expected through joints and vertical fractures. The model assumes a system of perched aquifers as well as deeper saturated layers underlain by less permeable strata. The result is that groundwater does flow downwards, but in a step-wise fashion through a network of semi-connected aquifers linked by zones of increased vertical and horizontal conductivity (Reynolds, 1976; Stammers, 2012 and references therein; Bradd et al., 2012). Figure 34 shows a conceptual model for the occurrence of perched aquifers and the impact on aquifer connectivity and groundwater flow paths of vertical jointing.

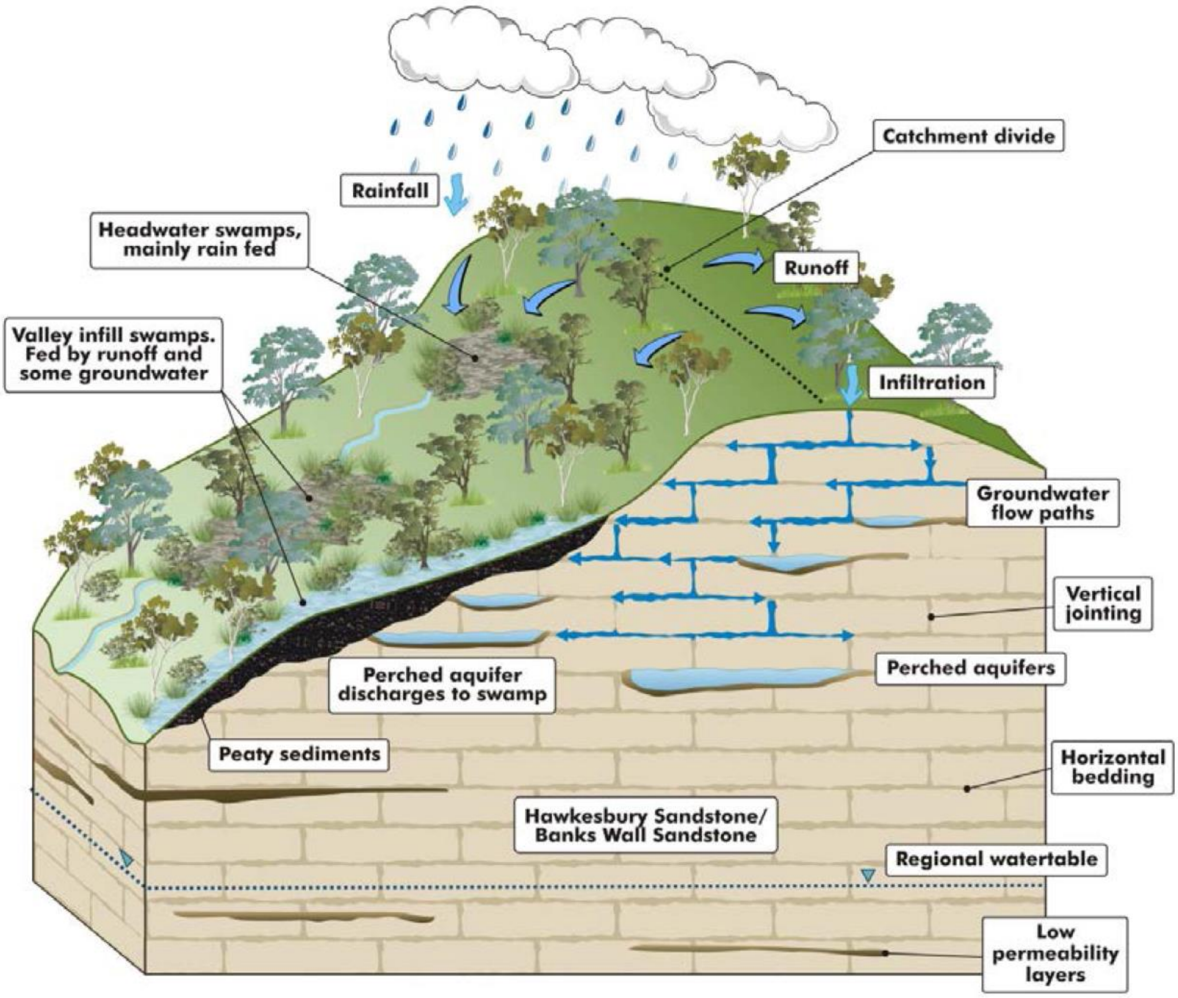

Figure 34 Conceptual model for the occurrence of perched aquifers and vertical connectivity enhanced by vertical jointing in the Hawkesbury Sandstone

Source: Commonwealth of Australia (2014)

Table 12 shows a summary of properties for the aquifers identified in the southern part of the geological Sydney Basin as well as the confining layers defining aquitards. The information is predominantly from the Southern Coalfields of the geological Sydney Basin, with only limited information from the Western Coalfields. AGL (2013) describes the following as the main confining layers in the Southern Coalfields:

- *Ashfield Shale and Mittagong Formation* (Middle Triassic), located above the Hawkesbury Sandstone and below the Minchinbury Sandstone, both limiting vertical leakage between alluvial aquifers and deeper sandstone aquifers.
- *Bald Hill Claystone*, located below the Hawkesbury Sandstone (and Newport and Garie formations) and above the Bulgo Sandstone.
- *Stanwell Park Claystone*, located below the Bulgo Sandstone and above the Scarborough Sandstone.
- *Wombarra Claystone* (Lower Triassic to upper Permian), separating the Illawarra Coal Measures (upper Permian) and the Scarborough Sandstone.

It has been suggested that the presence of these confining layers limits the interaction between sequences of shallow alluvial aquifers and deep sedimentary aquifers within the Permian coal measures (see e.g. AGL, 2013 and references therein; Parsons Brinckerhoff, 2013; Bartrop, 2014), thus suggesting some degree of disconnection with shallow aquifers. Other studies (e.g. Jankowski, 2009; Madden and Merrick, 2009; Madden, 2010; SCA, 2012), however, suggest an enhanced degree of vertical connectivity between confining layers and deep stratified sedimentary aquifers due to longwall mining, which is thought could have an impact on surface waters (McNally and Evans, 2007; NSW Government, 2007). Some of the potential impacts are the temporary or permanent loss of surface flow, depletion of overlying aquifers as a result of groundwater drawdown and the migration of gas or tracer elements to other aquifers or surface waters. The degree of connectivity between confining layers (claystones) and the aquifers within porous sandstones is a topic of considerable debate, where the presence of local permeable zones might enhance vertical connectivity (Ward and Kelly, 2013).

The Bald Hill Claystone is a particularly relevant aquitard as it occurs below the main aquifer of the Southern Coalfields, the Hawkesbury Sandstone (see Figure 35). Stammers (2012) and Bradd et al. (2012) suggest that it is generally accepted that the presence of the Bald Hill Claystone limits the exchange of groundwater between the Hawkesbury Sandstone and the underlying Bulgo Sandstone (McKibben and Smith, 2000; NSW Government, 2008), thus possibly providing some protection of potential impacts by coal mining activities.

The main role of these previous aquifers is to support streams through baseflow and groundwater-dependent ecosystems, with both the Hawkesbury and Bulgo sandstone aquifers providing most of the baseflow to surface water courses in the Southern Coalfield (Madden and Merrick, 2009).

Table 12 Hydrogeological properties for main stratigraphic units found in the Southern Coalfields of the geological Sydney Basin

Age	Stratigraphic unit	Hydrogeological unit	K_h (m/day)	K_v (m/day)	T (m^2/day)	Groundwater TDS (mg/L)
Quaternary/ Neogene	Alluvial deposits	Unconfined aquifer	1–10	1–10	>20	
Triassic	Bringelly Shale, Minchinbury Sandstone, Ashfield Shale (Wianamatta Group)	Aquitard Perched aquifer Aquitard	0.01	0.05	<1[a]	>3,000
	Hawkesbury Sandstone	Unconfined/semi-confined aquifer	0.1	0.05–6.0×10^{-4}	1–5	500–10,000
	Bald Hill Claystone	Aquitard	1.0×10^{-5}	5–10		
	Bulgo Sandstone	Minor confined aquifer	5.5×10^{-4}	1.1×10^{-4}	0.1–0.5	1,500–5,000
	Stanwell Park Claystone	Aquitard	3.0×10^{-5}	6.0×10^{-6}		
	Scarborough Sandstone	Minor confined aquifer	0.01	0.005	0.1–0.5	
	Wombarra Claystone	Aquitard	3.0×10^{-5}	6.0×10^{-6}		
Permian	Illawarra Coal Measures	Confined water-bearing zones	0.05[b]	0.025[b]	0.005–0.1	>2,000

[a] Ashfield Shale

[b] Bulli Coal

K_h = hydraulic conductivity (horizontal); K_v = hydraulic conductivity (vertical); T = transmissivity; TDS = total dissolved solids

Data: AGL (2013); Parsons Brinckerhoff (2013)

In the north-east area of the geological Sydney Basin, the main aquifers are contained in the Quaternary alluvium covering low-lying areas and valleys of surface water courses, and fractured sandstone of the Narrabeen Group. Coal seams act as water-bearing units, typically with poor groundwater quality (reported salinity range 3,330 and 14,300 mg/L TDS, AGL (2013)), and are separated by interburden sediments functioning as aquitards (GHD, 2014). In general, Quaternary alluvium hosts unconfined and laterally discontinuous shallow aquifers. Along the Central Coast, in the north-east area of the geological Sydney Basin but outside the Sydney Basin bioregion, similar aquifers are identified by Molloy et al. (2009): fractured sandstone aquifers, barrier beach sand aquifers and alluvial aquifers. These aquifers are generally of limited extent and consist of clayey and silty materials yielding poor quality groundwater (up to 7000 mg/L TDS) (Molloy et al., 2009).

Fractured Triassic sandstone hosts unconfined perched aquifers as well as semi-confined aquifers separated by relatively impermeable claystone layers, where groundwater flow is dominated by fractures, fissures and bedding in the strata (GHD, 2014). Within the Narrabeen Group, aquifers are hosted by the Terrigal Formation and are unconfined over much of the area north-east of Gosford (Molloy et al., 2009). Bore yields from the Terrigal Formation are reported between 0.5 to 29 L/s with hydraulic conductivities ranging from 0.3 to 50.2 m/d, and salinities in the range of 210 to 6870 mg/L TDS (Molloy et al., 2009). The Patonga Claystone (youngest unit of the Clifton Subgroup) underlies the Terrigal Formation and is considered low yielding with moderate to high salinity. West of Wyong, in the Kulnura-Mangrove Mountain aquifer system, modelling results have reported for the Hawkesbury Sandstone horizontal hydraulic conductivities of 0.01 to 0.5 m/d with transmissivities ranging between 5 and 50 m^2/d (Molloy et al., 2009).

In the Blue Mountains, on the Newnes Plateau and in the Southern Highlands, aquifers associated with sensitive ecological areas have a similar conceptual model as the one proposed by Bradd et al. (2012). Shallow aquifers form in higher permeability areas of the Banks Wall and Hawkesbury sandstones and groundwater flow is predominantly horizontal with vertical flow occurring via fissures/fractures that cross-cut bedding (Figure 34). These groundwater systems are associated with highland peat swamps (permanently or sporadically connected to the groundwater system) and are considered to be local groundwater flow systems of typically fresh groundwater, and relatively short flowpaths and residence times (Commonwealth of Australia, 2014).

Danis (2014) summarises the main aquifers in the geological Sydney Basin as: shallow unconfined alluvial aquifers (e.g. Botany Sand Beds), semi-confined fractured Triassic formations (e.g. Hawkesbury Sandstone Aquifer), confined water-bearing units (e.g. Permian coal measures), and fractured basal rocks (e.g. granites and basement rocks).

1.1.4.1.3 Structural features and impact on hydrogeological characteristics

The horizontally layered sandstone strata in the southern part of the geological Sydney Basin, which host the main aquifer systems, show particular features (e.g. dual porosity, fracturing and bedding plane shearing) related to local stress relief effects and large-scale deformation (Russell et al., 2009). Regional scale deformation in the southern part of the geological Sydney Basin created a topographic low known as the Cumberland Basin and surrounding elevated plateaux: Blue Mountains, Hornsby (Lochinvar-Kulnura Ridge), Woronora and Illawarra (Figure 24 and Figure 27 in Section 1.1.3).

A major structural group of north-south trending monoclines and faults in the geological Sydney Basin corresponds to the *Lapstone Structural Complex* (Figure 27 in Section 1.1.3), which overlies a deep-seated basement structure (Webb et al., 2009). It forms the frontal ridge of the Blue Mountains Plateau on the western margin of the basin and is indicated by structural lines that extend over 160 km (McLean and Ross, 2009; Webb et al., 2009). The impact of these large-scale features is reflected in improved connectivity and enhanced permeability of overlying aquifers. For example, Russell et al. (2009) suggest that fractures and joints enhance the secondary porosity of sandstone aquifers, improving bore yields in specific areas (e.g. in the Kangaloon Structural Corridor in the Southern Highlands). McLean and Ross (2009) suggest that intense flexural fracturing over the width of the monocline at Leonay has enhanced bore yields compared to the Wallacia drilling site, where the development of the complex is more brittle and is expressed as the Nepean Fault (Webb et al., 2009).

McLean and Ross (2009) suggest the Mittagong horst-graben complex in the upper catchment of the Nepean River has increased the permeability and bore yields in the highly fractured and faulted blocks of the Hawkesbury Sandstone aquifer. Nolan (2009), however, suggests that the increased yields are not due to the presence of fractures associated with the horst-graben structure but to the accessibility (at surface) of a more productive sandstone unit.

In the Kangaloon Structural Corridor (Southern Highlands), fractures and jointing have enhanced recharge and improved bore yields from less than 0.4 ML/day to up to 3.5 ML/day (Russell et al., 2009). Permeabilities for massive sandstone units in the upper catchment of the Nepean River are reported to be two orders of magnitude less than the same fractured strata (Russell et al., 2009).

1.1.4.2 Groundwater quality

Groundwater quality within the Hawkesbury Sandstone varies from fresh to slightly saline and from slightly acidic to slightly alkaline, and is high in iron (SCA, 2005). Water quality within the upper sections of the Hawkesbury Sandstone is often poorer than the lower sections due to leakage from the overlying shale formations. Possible upward flow or migration of brackish to saline groundwater along fractures from underlying Narrabeen Group aquifers or Permian coal measures may be contributing to brackish conditions in the deeper Hawkesbury Sandstone on the eastern side of the Lapstone Structural Complex (Russell et al., 2009). In areas around Camden, the sandstone groundwater is commonly acidic with some pH values recorded below 5 (AGL, 2013).

A centrally-located accumulation of saline water (exceeding 3000 mg/L TDS) exists beneath the Cumberland Basin (Figure 27 of Section 1.1.3), corresponding to a pattern where groundwater flows radially from elevated recharge areas around the fringes of the downwarped region and is constrained by limited discharge locations (Russell et al., 2009).

Analyses of water quality in an oil and gas exploration bore located to the north of the Wallacia investigation area (south-western Sydney, Figure 31) show that salinity increases with depth in the Narrabeen Group and Illawarra Coal Measures (Parsons Brinckerhoff, 2009).

Groundwater salinity of Triassic age shale units (Wianamatta Group) in the Southern Highlands is generally considerably less (typically <3000 mg/L) than that in the Sydney area (mainly >5000 mg/L). This is attributed to the higher elevation of the former, caused by regional and intermediate deformation and uplift, which contributes to greater flushing of accumulated salts from the rock matrix (Russell et al., 2009).

The Ashfield and Bringelly shales (Late Triassic Wianamatta Group), though primarily aquitards, do include scattered zones of fracture porosity within the weathered bedrock and groundwater is generally saline, typically in the range of 5,000 to 50,000 mg/L (McNally, 2009). The Ashfield and Bringelly Shales are associated with surface salting in parts of western Sydney. At some locations, where the Ashfield Shale overlies or is immediately up gradient of the Hawkesbury Sandstone, saline groundwater from this aquitard contributes to the higher salinities observed in the upper part of the sandstone (Webb et al., 2009). At the same time, upward flow and migration of brackish/saline groundwater from the underlying Narrabeen Group may be contributing to brackish conditions of the deeper Hawkesbury Sandstone on the eastern side of the Lapstone Structural Complex (Webb et al., 2009). This mechanism supports the conceptual model explaining the origin and migration of saline groundwater proposed by Green et al. (2009) and McLean and Ross (2009), and disputes that proposed by McNally (2004, 2009).

The regolith aquifers in the western Sydney area have groundwater with generally low salinities (<1000 mg/L), particularly following heavy rainfall when the salinity can be similar to that in the nearby semi-perennial streams (McNally, 2009).

Groundwater quality of the coal seams in the Illawarra Coal Measures is generally poor, with moderately saline groundwater, mostly between 5,000 and 10,000 mg/L (AGL, 2013).

1.1.4.3 Groundwater flow

The dominant recharge mechanism in the geological Sydney Basin is likely to be infiltration of rainfall and runoff through alluvial deposits in valleys, particularly where they are incised into weathered Hawkesbury Sandstone (Parsons Brinckerhoff, 2011). Similarly, recharge through infiltration takes place where the underlying units of the Narrabeen Group outcrop. Towards the west, groundwater recharge to the Hawkesbury Sandstone occurs on the Blue Mountains plateau (west of the Lapstone Structural Complex) (Webb et al., 2009). Recharge for deeper sandstone aquifers comes mainly from infiltration of rainfall over outcropping areas and through inter-aquifer leakage (SCA, 2012). In the Southern Coalfields, the deeper aquifers occurring in the Bulgo and Scarborough sandstones (Narrabeen Group) outcrop in the valleys of the Cordeaux and Avon reservoirs and thus recharge is expected at times of higher water level (SCA, 2012).

In general, the hydraulic conductivity of shallow unconsolidated materials associated with alluvial deposits and soils is comparatively higher than the hydraulic conductivity of deeper consolidated rocks present in the Wianamatta Group, Hawkesbury Sandstone and Narrabeen Group (Table 12). Shallow groundwater through unconsolidated and surface material flows much faster than through consolidated rocks in the Wianamatta Group (Stammers, 2012; Bradd et al., 2012). Main discharges from the aquifer systems occur naturally at the surface to creeks and to the reservoirs as baseflow and seeps, and by evapotranspiration through vegetation.

On a local scale, topography controls the groundwater flow near the ground surface in alluvial and shallow aquifers. In these systems, groundwater flow is likely to be localised and limited in extent, with occurrence of perched aquifers controlled by the presence of fine-grained materials. In general, these systems are responsive to rainfall and streamflow (SCA, 2012). On a regional scale, SCA (2012) describes the groundwater flows for the geological Sydney Basin as being controlled by the basin geometry, topography and major hydraulic boundaries (Figure 35). In the south-central area of the basin regional groundwater flow is predominantly towards the north or north-east, eventually discharging via the Georges, Parramatta or Hawkesbury river systems, and ultimately offshore to the east (SCA, 2012; Parsons Brinckerhoff, 2013).

Across the geological Sydney Basin, it is generally accepted that groundwater flow is predominantly in the horizontal direction given the enhanced flow along bedding plane joints in sandstone formations (Ward and Kelly, 2013). Generally, the low permeability claystones overlying the coal measures throughout the basin behave as a hydraulic barrier limiting vertical flux exchange between deep coal measures and porous sandstones (SCA, 2012; Ward and Kelly, 2013). Ward and Kelly (2013) recognise that the presence of permeable fault zones might enhance the fluid connectivity between rocks above and below the claystones.

Towards the west of the geological Sydney Basin, groundwater flows eastwards across the Lapstone Structural Complex towards the Nepean River and Cumberland Plain (Webb et al., 2009).

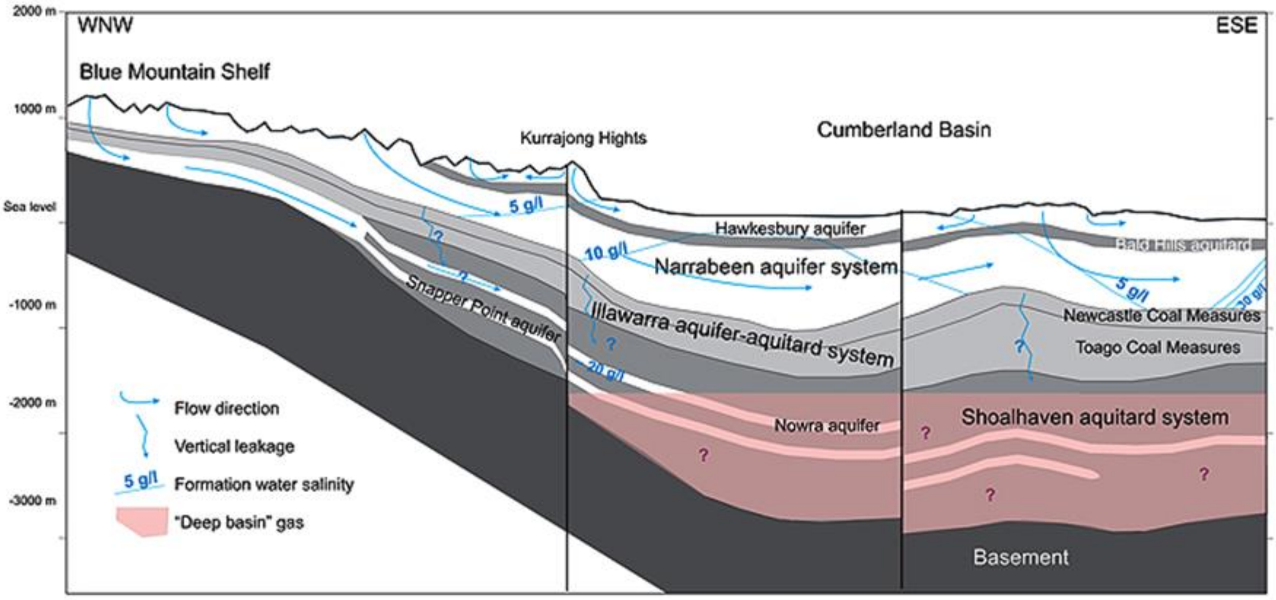

Figure 35 Conceptualised basin-scale hydrology along a west-north-west to east-south-east cross-section in the Sydney Basin

Source: Michael et al. (2009) (the stratigraphic framework modified by Michael et al. (2009) from Harrington et al. (1989)). This figure has been reproduced with the permission of CO2CRC.

1.1.4.4 Groundwater use

To maintain and protect the health of rivers and groundwater systems, the NSW government established water sharing plans (WSPs) for the state's aquifers under NSW's *Water Management Act 2000*. The Act requires that water be allocated for the fundamental health of a groundwater source and its dependent ecosystems as a first priority. The water sharing plans are reviewed every ten years.

Most of the groundwater in the Sydney Basin bioregion is managed under NSW's *Water Sharing Plan for the Greater Metropolitan Region Groundwater Sources 2011*. Other groundwater WSPs that cover parts of the bioregion are NSW's *Water Sharing Plan for the Murray-Darling Basin Porous Rock Groundwater Sources 2011* and *Water Sharing Plan for the Murray-Darling Basin Fractured Rock Groundwater Sources 2011*. The draft WSPs for the North Coast Groundwater Sources, Clyde River Unregulated and Alluvial Water Sources and South Coast Groundwater Sources, which are currently under development with a view to commencement in 2016, will manage extractions from the remaining groundwater sources within the Sydney Basin bioregion. Table 13 outlines the groundwater sources covered by the existing coastal water sharing plans. The locations of the groundwater source areas are shown in Figure 36.

Table 13 Commenced coastal water sharing plans and groundwater share components for groundwater sources in the Sydney Basin bioregion

Water sharing plan	Status	Groundwater source	Estimated groundwater share component (ML/y)
Greater Metropolitan Groundwater Sources	Published 2 March 2011. Commenced 1 July 2011	Botany Sands Groundwater Source	11,156
		Coxs River Fractured Rock Groundwater Source	114
		Goulburn Fractured Rock Groundwater Source	3,051
		Hawkesbury Alluvium Groundwater Source	1,019
		Maroota Tertiary Sands Groundwater Source	189
		Metropolitan Coastal Sands Groundwater Source	1,409
		Sydney Basin Blue Mountains Groundwater Source	138
		Sydney Basin Central Groundwater Source	2,592
		Sydney Basin Coxs River Groundwater Source	6,926
		Sydney Basin Nepean Groundwater Source	16,283
		Sydney Basin North Groundwater Source	557
		Sydney Basin Richmond Groundwater Source	15,894
		Sydney Basin South Groundwater Source	2,880
Kulnura Mangrove Mountain Groundwater Sources	Commenced 1 July 2003. Extension to 1 July 2016. To be merged with Water Sharing Plan for the North Coast Groundwater Sources	National Park, State Forest and Drinking Water Catchment Groundwater Source	0
		Wollombi Brook Groundwater Source	36
		Brisbane Water Groundwater Source	41
		Ourimbah Creek Groundwater Source[a]	724
		Wyong River Groundwater Source[a]	452
		Upper Mangrove Groundwater Source[b]	346
		Lower Mangrove and Popran Creeks Groundwater Source	1,084
		Mooney Mooney and Mullet Creeks Groundwater Source	783
Total			**65,674**

[a]denotes that the water source area falls outside the Sydney Basin bioregion
[b]denotes that only a portion of the water source area falls within the Sydney Basin bioregion
Data: NSW Office of Water (Dataset 19)

Table 13 provides a summary of the share components of the groundwater sources in the two commenced coastal WSPs for the Greater Metropolitan Region and Kulnura Mangrove Mountain. The groundwater share components in the draft WSP areas have not yet been finalised.

Generally, one share component is equivalent to 1 ML/year unless an available water determination (AWD; the volume of water available to licence holders for any particular water year) of anything other than 1 ML/share is issued. AWDs of less than 1 ML/share may be issued for aquifer access licences under WSPs to ensure compliance with the long term average annual extraction limits (LTAAEL) identified by the relevant WSP.

Alluvial and non-alluvial aquifers are present in the Sydney Basin bioregion and groundwater extraction from these aquifers is used for a range of purposes including domestic, stock, irrigation, town water supply and industrial purposes, with a proportion of water protected for the environment in all water sources. Groundwater entitlement (65,674 ML/y, Table 13) within the bioregion is relatively minor (approximately 5%) compared to surface water entitlement (1,206,835 ML/y, Table 19 in Section 1.1.5). However, some parts of the identified water sources are located outside the Sydney Basin bioregion, so the actual allocations may vary slightly from the percentage reported in this product. Groundwater and surface water usage and entitlements are discussed in companion product 1.3 for the Sydney Basin bioregion (Herron et al., 2018).

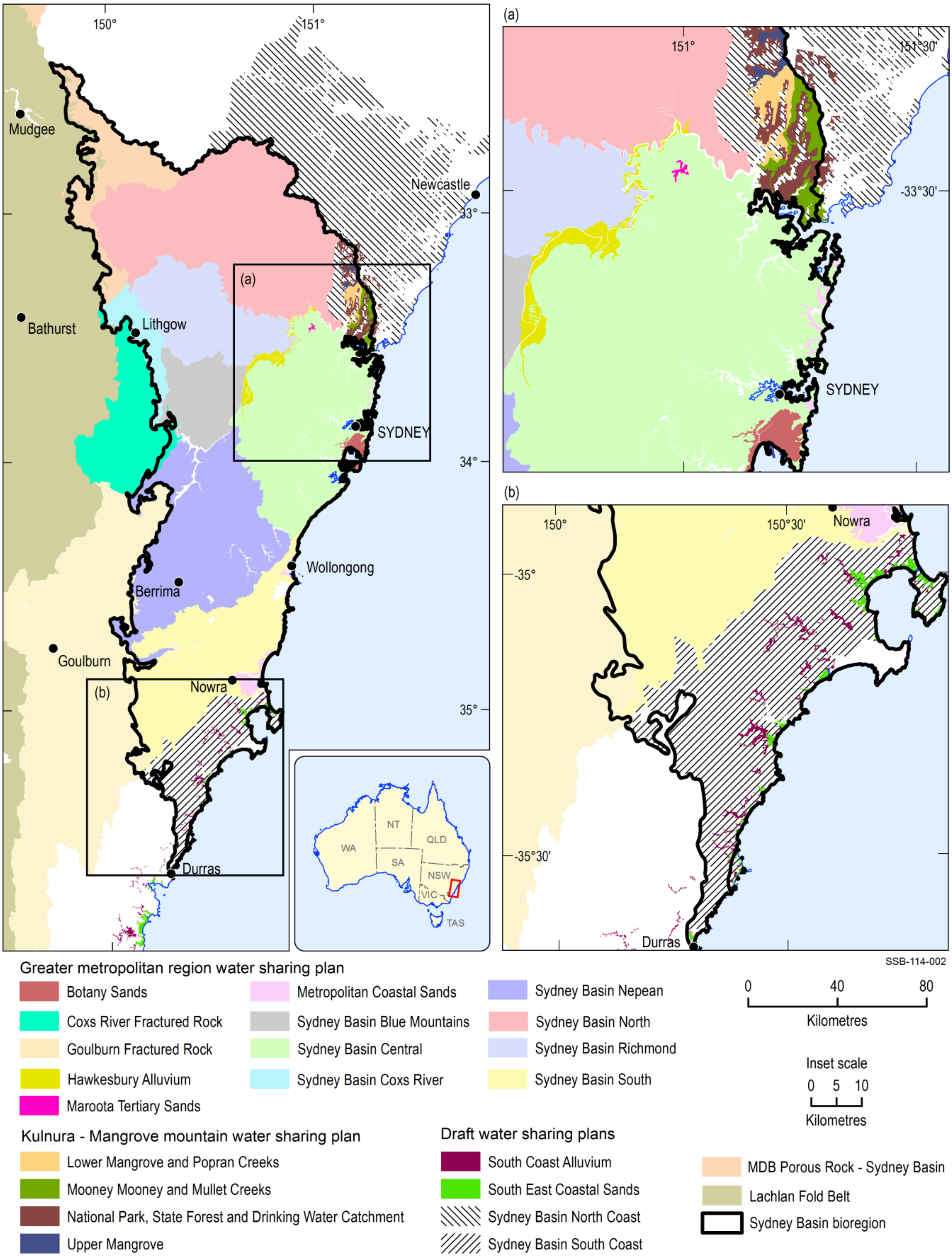

Figure 36 Groundwater source areas in the Sydney Basin bioregion

Data: Bureau of Meteorology (Dataset 3)

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1.1.5 Surface water hydrology and water quality

Summary

The Sydney Basin bioregion includes all or parts of the Hawkesbury River, Shoalhaven River, Sydney Coast-Georges River, Clyde River-Jervis Bay, Wollongong Coast and Macquarie-Bogan river systems. The Hawkesbury river basin, which includes the Hawkesbury, Nepean, Wollondilly and Coxs rivers, dominates the bioregion.

The Hawkesbury and Shoalhaven river basins are important water supply catchments to the densely populated Greater Sydney metropolitan area. There are 18 major dams (storage capacity >1 GL) in the bioregion, ten of which contribute to Greater Sydney's water supply, while others meet the needs of Blue Mountains, Nowra and Southern Highlands communities. With a capacity of 2031 GL, Warragamba Dam (Lake Burragorang) is by far the largest water storage and supplies about 80% of Sydney's water.

Water quality is of paramount importance for drinking water supply and is closely monitored by WaterNSW. Protected and special areas have been designated around Nepean river basin water storages and Lake Burragorang, which restrict access to and use of these areas. Salinity is relatively low in the water supply catchments, but increases in the Hawkesbury River when it reaches the tidal zone between the Colo and Macdonald rivers.

Streamflow volumes for the Sydney Basin bioregion tend to be highest in February and August. Streamflow is typically lower and less variable between September and January than between February and August.

1.1.5.1 Surface water systems

The Sydney Basin bioregion includes all or parts of six major river basins or river regions. These are the Hawkesbury River, Shoalhaven River, Sydney Coast-Georges River, Clyde River-Jervis Bay, Wollongong Coast and Macquarie-Bogan river systems. Except for the Macquarie-Bogan river basin, these rivers drain from the Great Dividing Range to the NSW coastline (Figure 10 in Section 1.1.2).

1.1.5.1.1 Surface drainage networks

The Hawkesbury river basin dominates the subregion with 16,050 km^2 of its 22,000 km^2 basin within the bioregion (65% of the bioregion area) (Table 14). The main southern tributaries of the Hawkesbury River are the Nepean, Wollondilly and Coxs rivers, which are important water supply catchments to Sydney. The Wollondilly River joins with the Coxs River at Lake Burragorang and then continues as the Warragamba River until it meets the Nepean River. Much of the headwaters of the Wollondilly River are outside the bioregion. The Nepean River rises in the Southern Highlands, near Robertson, and flows northwards through the Nepean Dam until it meets the Grose River and becomes the Hawkesbury River. The Nepean River is fed from a number of westerly flowing tributaries, including the Avon, Cordeaux and Cataract rivers. The Hawkesbury River's main northern tributaries, the Colo and the Macdonald rivers, rise in the Great Dividing Range to the west and the Hunter Range to the north and flow towards the east and south to meet the Hawkesbury River. Most of their catchments are within national parks and the rivers are unregulated and valued for their wilderness values. The Hawkesbury River becomes tidal near the confluence of the Nepean River and Grose River, about 4 km upstream of Richmond (NSW Public Works, 1987). Table 15 summarises the basin areas and areas within the bioregion for the Hawkesbury's main sub-basins. While the natural flow of many of the rivers and streams in the Hawkesbury-Nepean river basin has been altered by water storages, the system is considered unregulated because water is not captured and released into the river for extraction by downstream users (NSW Primary Industries Water, 2016).

The Shoalhaven river basin rises in the Gourock and Minuma ranges, outside and to the south of the bioregion. It flows in a northerly direction, receiving inflows from Sallee Creek, Budlong Creek and Kangaroo River. Total catchment area is about 7200 km^2, of which just over 2900 km^2 is in the bioregion (Table 14). It is an important source of drinking water to Greater Sydney and the Southern Highlands

The Sydney Coast-Georges River and Wollongong Coast basins are relatively small. The Georges, Woronora and Hacking rivers are the main Sydney catchments; the Minnamurra River and Macquarie Rivulet dominate the Wollongong Coast. These coastal basins are located entirely within the bioregion and cover an area of 2536 km^2. The Clyde River-Jervis Bay coastal basins lie in the south of the bioregion and are bounded to the west by the Shoalhaven river basin.

The Sydney Basin bioregion includes a small area of the Cudgegong and Turon river basins, which are tributaries of the Macquarie-Bogan river basin within the Murray-Darling Basin. These rivers rise in the north-west, behind the Capertee and Wolgan rivers (in the Colo river basin) and flow westward, away from the Sydney Basin bioregion. This westward draining part of the bioregion represents 6% of the bioregion's total area (Table 14).

Table 14 Major river basins in the Sydney Basin bioregion

River basin	River basin area (km^2)	River basin area within the Sydney Basin bioregion (km^2)	Percent of the Sydney Basin bioregion (%)
Hawkesbury	21,922	16,049	65%
Shoalhaven	7,178	2,905	12%
Sydney Coast-Georges River	1,753	1,747[a]	7%
Clyde River-Jervis Bay	3,291	1,566	6%
Macquarie-Bogan	73,044	1,530	6%
Wollongong Coast	793	789[a]	3%

[a]Area within the Sydney Basin bioregion is slightly smaller than basin area due to differences in the mapped coastlines for river basins and the Sydney basin bioregion.
Data: Bureau of Meteorology (Dataset 1)

Table 15 Sub-basins of the Hawkesbury river basin

Hawkesbury sub-basins	Basin area (km^2)	Basin area within bioregion (km^2)	Percent in bioregion (%)
Colo	4627	4625	100%
Nepean	2621	2621	100%
Macdonald	1912	1904	100%
Wollondilly	5198	1397	27%
Coxs	2725	1024	38%
Wingecarribee	744	710	95%

Data: Bureau of Meteorology (Dataset 1)

1.1.5.1.2 Surface water infrastructure

There are 18 major dams (storage capacity >1 GL) within the Sydney Basin bioregion, many of them constructed to ensure a secure supply of water to the Sydney and Wollongong urban centres. Table 16 lists these storages, their storage capacities and managing authorities. The Blue Mountains entry comprises five storages, only one of which (Upper Cascade) has a capacity greater than 1 GL; the capacity in Table 16 is the total for all five storages. The locations of the storages are shown in Figure 37.

Through an interconnected system of dams, river channels, pipelines, canals, weirs and pumping stations, water from the Coxs, Wollondilly, Nepean, Wingecarribee, Kangaroo and Shoalhaven rivers is made available to Greater Sydney’s water supply system. This water supply system, managed by WaterNSW (formerly Sydney Catchment Authority and State Water Corporation), services more than 4.5 million people in Sydney, Wollongong, Blue Mountains, Shoalhaven, Goulburn and Southern Highlands regions. It comprises five subsystems: Warragamba; Upper Nepean; Shoalhaven; Woronora and Blue Mountains. Despite the level of water resource development, this is not considered a regulated system.

Lake Burragorang, which was formed by the construction of Warragamba Dam and extends back into the Coxs and Wollondilly river valleys, is Sydney’s largest water supply. At 2031 GL, it accounts for over 70% of the bioregion’s storage capacity and stores about 80% of Sydney’s water. Water flows under gravity through two pipelines to Prospect Filtration Plant from where it is distributed to Sydney, Penrith and the lower Blue Mountains.

Table 16 Major storages, managing authorities and storage capacities (ML) in the Sydney Basin bioregion

Major storage	Managing authority	Capacity[a] (ML)
Lake Burragorang (Warragamba)	WaterNSW	2,031,000
Avon	WaterNSW	214,360
Cataract	WaterNSW	97,370
Cordeaux	WaterNSW	93,640
Lake Yarrunga (Tallowa)	WaterNSW	90,000
Woronora	WaterNSW	71,790
Nepean	WaterNSW	68,100
Prospect	WaterNSW	48,200
Lake Lyell	Delta Electricity	34,192
Thomsons Creek	Delta Electricity	27,500
Wingecarribee	WaterNSW	25,880
Fitzroy Falls	WaterNSW	22,920
Danjera	Shoalhaven City Council	7,660
Wallerawang	Delta Electricity	4,004
Bamarang	Shoalhaven City Council	3,800
Blue Mountains (includes Upper Cascade, Middle Cascade, Lower Cascade, Greaves Creek, Lake Medlow)	WaterNSW	2,890
Medway	Wingecarribee Shire Council	2,046
Bundanoon	Wingecarribee Shire Council	1,170
Total capacity		**2,846,522**

[a] Capacity includes dead storage, which is the volume of water below the lowest offtake point.
Data: Bureau of Meteorology (2015)

The ten other major storages operated by WaterNSW account for a further 26% of the bioregion's water storage capacity. Lakes Avon, Cataract and Cordeaux on tributaries of the Nepean River are the largest of these and together with Lake Nepean are the storages making up the Upper Nepean water supply system. The Avon storage supplies the Wollongong area via the Illawarra Filtration Plant. The Upper Nepean System also supplies Camden, Campbelltown and Wollondilly areas. A tunnel between the Avon and Nepean dams allows water to be moved from the Shoalhaven system to the Illawarra region. The Shoalhaven system supplies the Southern Highlands and Goulburn from Wingecarribee Reservoir and can top up Sydney and Illawarra water supplies via the Wingecarribee River which flows into Lake Burragorang or via the Glenquarry Cut canals and pipelines into the Nepean Dam.

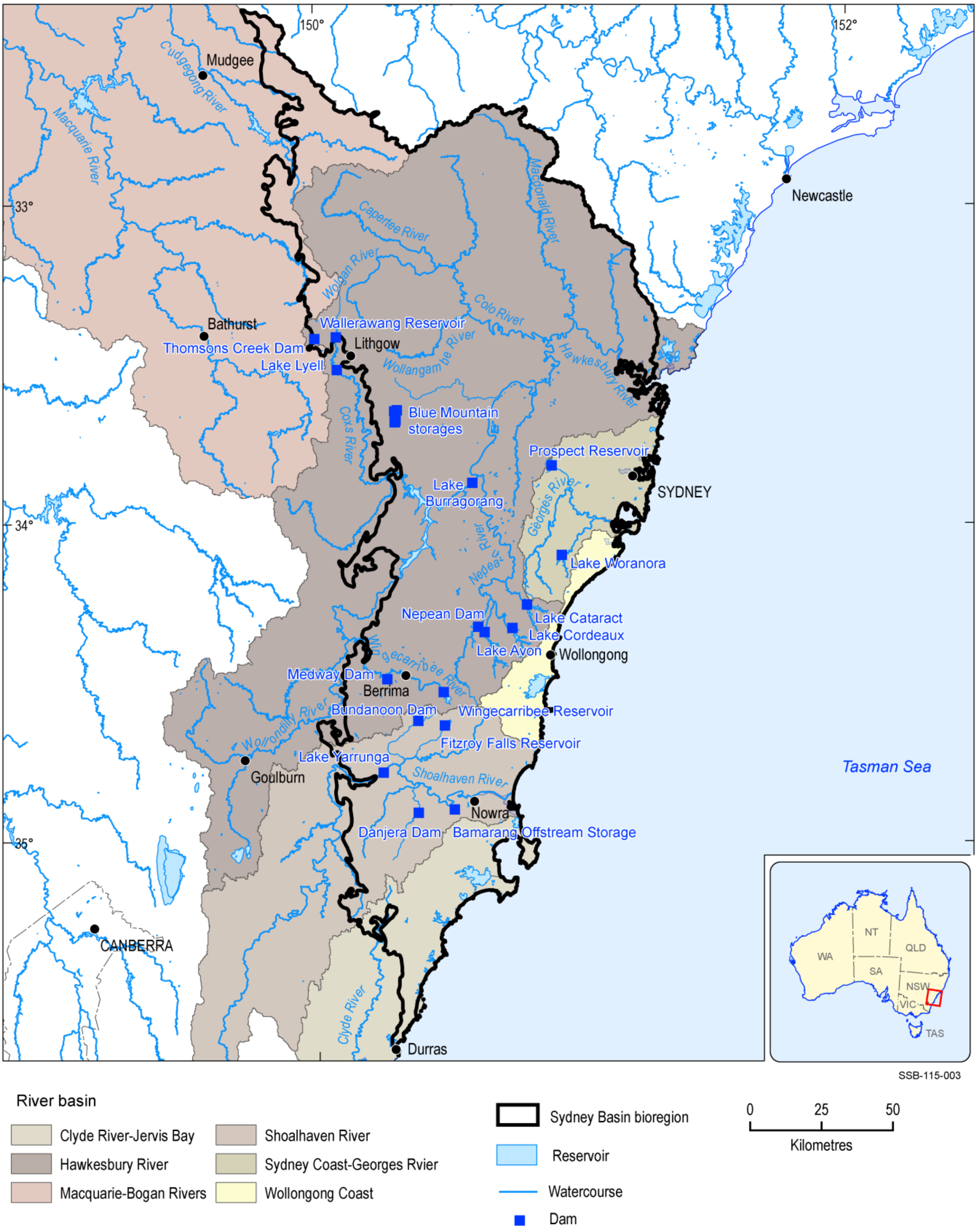

Figure 37 Major water storages (>1 GL capacity) in the Sydney Basin bioregion

Data: Bioregional Assessment Programme (Dataset 2)

The Woronora water supply is not integrated with the other parts of the Greater Sydney water supply system. The dam holds water from the Woronora River and supplies residents of southern Sydney and northern Wollongong. Similarly, the Blue Mountains water supply system is a discrete system that captures water from Blue Mountains catchments to supply the upper and middle Blue Mountains. It can be supplemented with water from Oberon Dam, outside the region, via a pipeline from the Fish River scheme.

The Fish River water supply scheme transfers western flowing water east of the Great Dividing Range to supply water to Lithgow for domestic and industrial uses and also supplements town water supplies in the Blue Mountains.

A number of smaller storages – Danjera, Bamerang, Medway and Bundanoon – supplement water supplies to Nowra and Southern Highland towns.

1.1.5.1.3 Flooding history

The Hawkesbury-Nepean floodplain extends from just downstream of Warragamba Dam, near Wallacia to Sackville and includes the urban areas of Penrith, Windsor and Richmond in western Sydney. The floodplain is downstream of a vast catchment, with many major rivers delivering water into the Hawkesbury River. The area is vulnerable to floods because the Hawkesbury River channel is forced to narrow as it enters Sackville Gorge between Windsor and Wisemans Ferry. During high flows, water cannot funnel into the gorge quickly enough and instead backs up and spills onto the floodplain. There have been numerous serious floods on the Hawkesbury-Nepean floodplain since European settlement. The highest recorded flood occurred in 1867 when the river height at Windsor reached 19.2 mAHD. It was also the worst flood in terms of loss of life and destruction of property and livestock. The next most major floods occurred in 1961 and 1964 when peak heights of 15.09 and 14.4 mAHD, respectively, were recorded at Windsor. Since then there were floods in 1978, 1988 and 1990 (NSW State Emergency Service, 2015a).

Flood frequency analysis reported in the *Hawkesbury Nepean Flood Emergency Sub Plan* (NSW State Emergency Service, 2015a) estimates that the 1867 flood was a one in 250-year event, while the 1961 flood was a one in 40-year event. The more recent floods of 1988 and 1990 were between one in 10 and one in 20-year events. The probable maximum flood (PMF) for the Hawkesbury-Nepean, assuming full storage at Warragamba Dam (Lake Burragorang), a fully saturated catchment and around 790 mm of rainfall across the Lake Burragorang catchment over a 72-hour period, has been estimated to be a one in 100,000-year event. The 1867 was equivalent to 40% of the volume of water in a PMF and the 1967 had about 24% of the volume of water in a PMF.

Record floods were recorded in the Nepean River in 1873 (16.54 m at Camden; 20.62 m at Wallacia) and in 1964 (17.88 m at Menangle). On the Georges River at Liverpool, the highest recorded flood was 7.53 m in 1897. In 1988, the Georges River at Milperra recorded its highest flood (NSW State Emergency Service, 2015b).

1.1.5.1.4 Periods of dry

Significant dry spells and periods of drought have affected streamflows in the bioregion. In Figure 38, streamflow variability is summarised for three gauging stations across the bioregion using a difference from mean analysis (Bureau of Meteorology, 2016). Below-average flows were recorded at each site for at least a five-year period around the early 1980s and for a longer period (at least 15 years) from about 1994.

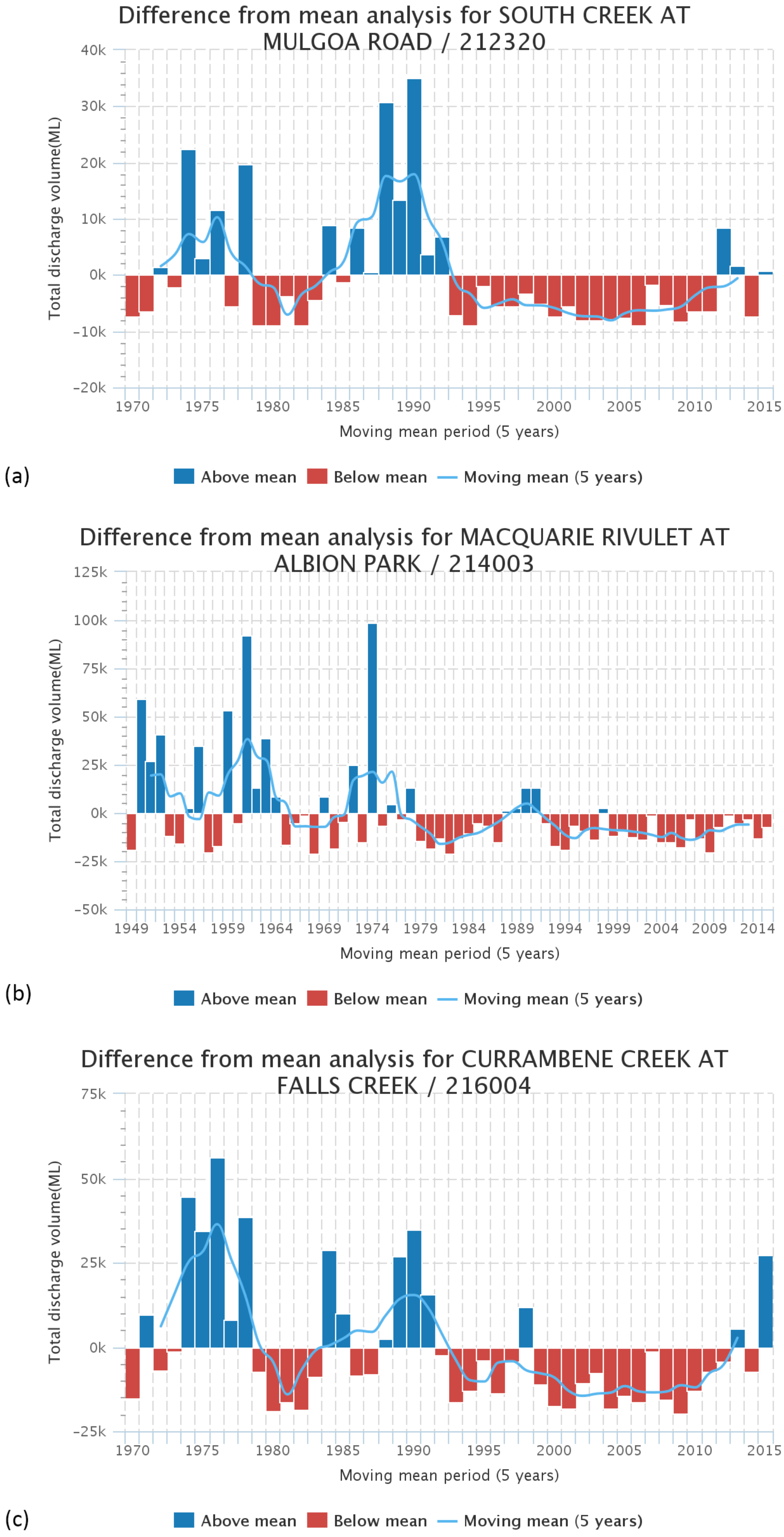

Figure 38 Difference from mean analysis for (a) South Creek at 212320, (b) Macquarie Rivulet at 214003 and (c) Currambene Creek at 216004

Source: Bureau of Meteorology (2016)

In intermittent streams, where streamflow is characterised by a variable connection between groundwater and streamflow in response to fluctuating watertable depth, prolonged periods of low rainfall can cause a shift to longer periods and/or more extensive areas of no flow along a stream channel, as the watertable drops below the depth of the channel bed. The flow duration curves in Figure 39 illustrate this variability for an intermittent stream in the bioregion, South Creek at Mulgoa Road (212320). Over the 45 years of record, flow has been recorded about 70% of the time. On average, the stream flowed more continuously between 1970 and 2000 (>80% of the time) than it has in the 15 years since then. Between 2000 and 2009 when much of south-eastern Australia was experiencing a prolonged drought, the gauge recorded no flow for around 45% of that time.

If dry conditions become increasingly severe, even predominantly perennial streams may experience disconnections, varying from localised, relatively short duration disconnections to longer, more extensive occurrences of no flow. Figure 40 shows flow duration curves for a perennial stream. The long flat tail indicates that a continuous low flow is sustained throughout the year and that the connection to groundwater persists even during extended dry periods. In the period since 2010, flows have been on average lower across the entire flow regime than the long-term average for this gauging station (about 65 years of record).

Changes in low flows due to mining-induced groundwater drawdown could lead to longer periods of no flow days and/or longer stretches of river that cease to flow than occur under pre-disturbance conditions.

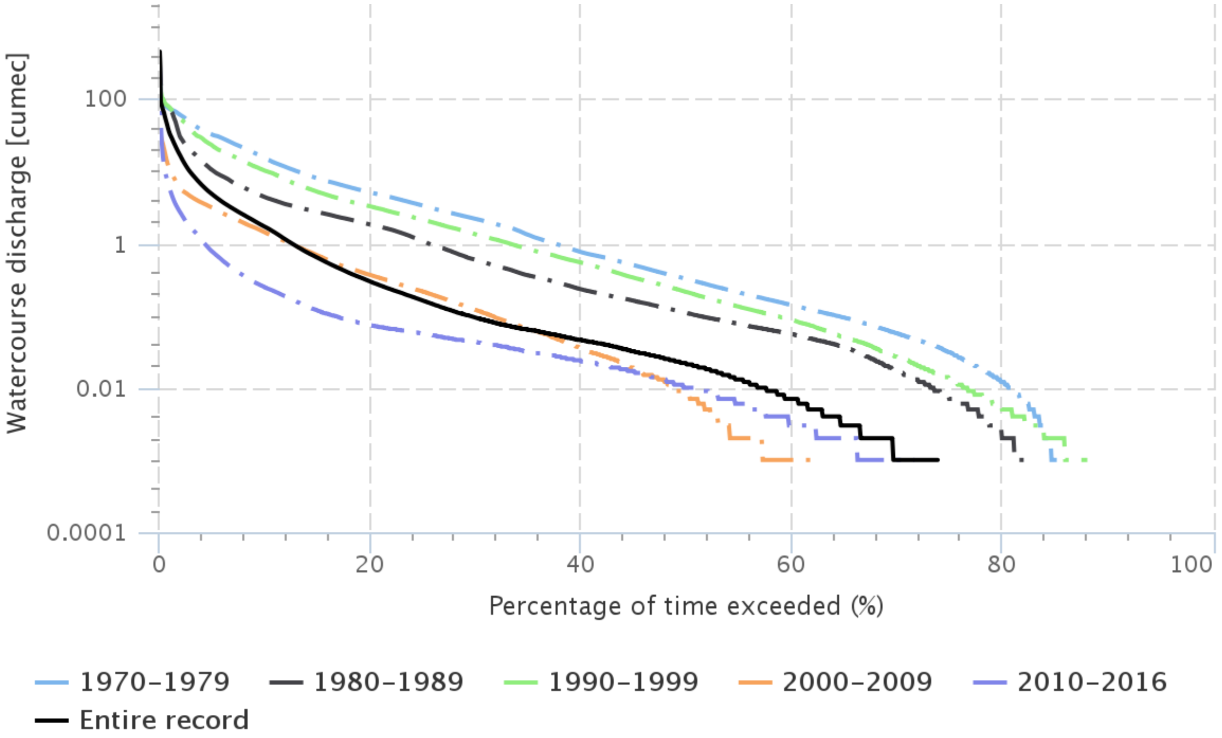

Figure 39 Flow duration curves for South Creek at Mulgoa Road (gauging station 212320) for the entire period and by decade

Source: Bureau of Meteorology (2016)

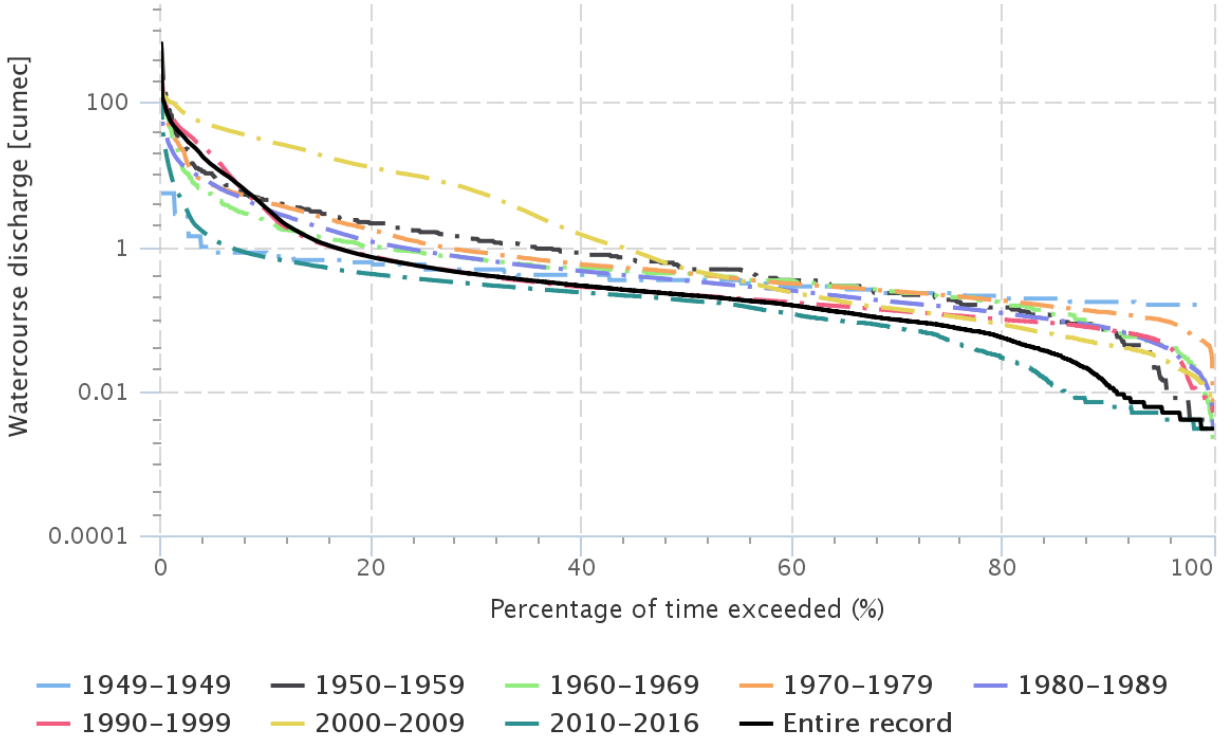

Figure 40 Flow duration curves for Macquarie Rivulet at Albion Park (gauging station 214003) for the entire period and by decade

Source: Bureau of Meteorology (2016)

1.1.5.2 *Surface water quality*

The Sydney Basin bioregion varies from relatively pristine wilderness areas within national parks in the northern and western parts of the Hawkesbury-Nepean river basin to highly modified urban environments around Sydney and Wollongong (see Figure 15 in Section 1.1.2), where the surface drainage network is highly engineered and the sources of contaminants highly variable. Treated wastewater, stormwater, runoff from disused mines and other industrial sites are sources of contaminants from the urbanised areas. In south-western Sydney, up onto the Southern Highlands and in the coastal strip south of Wollongong, runoff from agricultural lands is also a source of surface water contaminants.

Nutrients, particularly nitrogen and phosphorus, are of concern because elevated loads can lead to excessive algae and aquatic weed growth, which affects aquatic habitat and can limit commercial and recreational uses of the river. Diffuse sources, including urban, grazing, cropping, intensive horticulture, intensive animal production areas, contribute the majority (70 to 80%) of the total nutrient load to the lower Hawkesbury-Nepean river basin (Davis et al., 1998), with the highest rates around the Penrith-Windsor area and elevated rates southward towards Picton (NSW Department of Environment and Climate Change and Water, 2010). Point sources (predominantly sewage treatment plants (STPs)) contribute a much lower proportion of total nutrient loads in the Hawkesbury-Nepean river system. However, during dry weather they contribute the majority of nutrients because discharges are not driven by runoff events, but remain relatively constant year round. Over the last 20 years, upgrades to STPs, decommissioning of poorly performing plants and increasing wastewater recycling have resulted in significant reductions in nutrient exports from STPs (45% and 75% for TN and TP, respectively, between 1996 and 2008) (NSW Department of

Environment and Climate Change and Water, 2010). These reductions in nutrient loads from point sources suggest that the relative contribution from diffuse loads will increase to more than 80%. Trend analysis of nutrient levels in the Hawkesbury-Nepean river basin indicates that phosphorus have been generally declining throughout the river system, whereas nitrogen levels have decreased at many sites and increased at some others. Nitrogen levels often remain above ANZECC/ARMCANZ (2000) guidelines throughout the system.

WaterNSW is mandated to ensure a safe and reliable supply of water suitable for treatment to drinking water standards. To this end, it manages the water supply catchments and infrastructure to protect water quality. Protected and special areas are declared catchment areas where public access and activities are restricted to protect water quality (Figure 15 in Section 1.1.2). Three classes of protection zone have been defined: (i) special areas – no entry, (ii) special areas – restricted access and (iii) controlled areas – no entry. The no entry special areas include the reservoirs and surrounding land, except for Fitzroy Falls Reservoir and part of Lake Yarrunga, which allow for restricted access. Lake Burragorang has both a no entry zone around the reservoir enclosed by a more extensive second protection zone of restricted entry. Restricted entry prohibits vehicles, horses, pets and firearms within the zone. The controlled areas prohibit public access to water supply infrastructure, including land along the Warragamba pipelines and Upper Canal. In all, 365,000 ha of the water supply catchments are within protected and special areas. Underground coal mining predates the declaration of special areas and 8% of the special areas are currently undermined (NSW Chief Scientist and Engineer, 2014).

Water quality monitoring is undertaken by WaterNSW and an annual report has been published since 2000–01 by the Sydney Catchment Authority. The focus of monitoring is on ensuring the Australian Drinking Water Quality guidelines are met for a range of water quality parameters, including pathogens such as *Cryptosporidium* and *Giardia*, algae (e.g. cyanobacteria), nitrogen, phosphorus, cholorophyll-a, turbidity, toxins, heavy metals, pesticides and synthetic organic compounds. The monitoring program includes routine sampling and special sampling during wet weather and for research, using manual and automated sampling technologies. The safety limits for most substances dissolved in drinking water are set at about 1% of the amount that could potentially harm humans. Should levels exceed these limits, prompt response procedures are in place to ensure ongoing supply of safe water (Sydney Catchment Authority, 2014).

Analysis of water quality data between 2000 and 2009, reported in the *State of the Science – Catchment Impacts Summary Report* (Sydney Catchment Authority, 2011), indicated that 12 of the 19 catchments which flow into Greater Sydney water supply storages posed no risk to water quality except during very high flows. Five catchments were identified as high risk across a range of pollutant groups: Wollondilly, Kedumba (lower Coxs River), Kangaroo, Shoalhaven and the Upper Nepean rivers. All had excessive levels of nitrogen, phosphorus (except Shoalhaven), pathogens (except Shoalhaven) and metals (except Kedumba and Upper Nepean). Two catchments, Waratah Rivulet and the Cataract River, had some water quality issues relating to metals associated with mining activities. Turbidity and suspended sediments were not found to be a significant problem in any catchment, except during very high flows. Aluminium and iron, which are naturally occurring in groundwater discharges, were found to exceed ANZECC/ARMCANZ (2000) guidelines.

All development within Greater Sydney's drinking water catchments is required by the *State Environmental Planning Policy (Sydney Drinking Water Catchment) 2011* (SEPP) to have a sustainable neutral or beneficial effect on water quality. In May 2014, the NSW Chief Scientist and Engineer delivered a report to the NSW Government on the state's capacity to assess the cumulative impacts of activities which impact groundwater and surface water in the Sydney water supply catchments. The report found that there was insufficient data in a coherent form to enable a deep and reliable assessment of cumulative impact. WaterNSW has declared a set of principles for managing mining and coal seam gas impacts in declared catchment areas. Consistent with the SEPP, mining and coal seam gas activities must not result in a reduction in the quality of surface water and groundwater inflows (WaterNSW, 2015).

The salinity of Hawkesbury-Nepean water, as indicated by its electrical conductivity (EC), shows low salt concentrations (range 30 to 990 µS/cm, in Markich and Brown, 1998) throughout most of the river system until about 70 km or so from the coast (between where Colo River and Macdonald River meet the Hawkesbury) where the tidal influence begins. Water upstream of the Colo River is used for irrigation, but salt concentrations increase to levels that are detrimental to most irrigable crops downstream of this point. Some tributaries of the Nepean River have relatively high ECs at low flows, reflecting greater contribution of more saline groundwater at low flows, but the water is still generally suitable for most fruit and vegetable crops (NSW Environment Protection Authority, 1992). Analysis of EC data from the Hawkesbury-Nepean Environmental Monitoring Program suggest small increases in EC are occurring at the majority of monitoring sites, but levels remain well within ANZECC/ARMCANZ guidelines for lowland rivers (NSW Department of Environment and Climate Change, 2009).

1.1.5.3 Surface water flow

In the Sydney Basin bioregion, streamflow monitoring is undertaken by WaterNSW and DPI Water (formerly the NSW Office of Water). Figure 41 shows the location of DPI Water and WaterNSW streamflow gauges across the bioregion, including some discontinued sites.

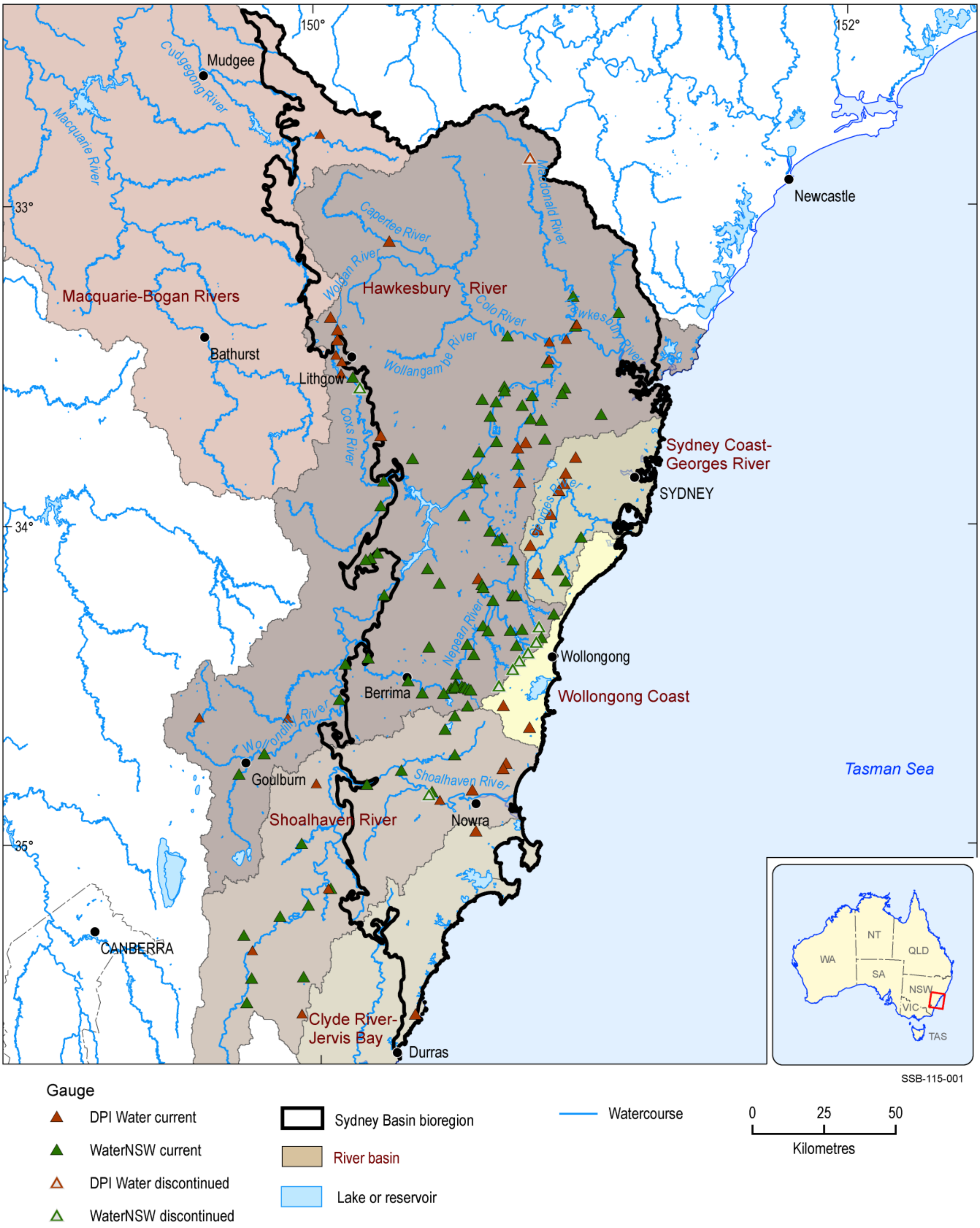

Figure 41 Stream gauges in the Sydney Basin bioregion and along rivers that flow into the bioregion

Data: Bureau of Meteorology (Dataset 1, Dataset 3)

1.1.5.3.1 Monthly and annual flow characteristics

Sydney Basin streamflow data were obtained for 28 gauging stations from DPI Water and 110 gauging stations from WaterNSW for the Sydney Basin Bioregional Assessment. Sixty-eight gauging stations had more than ten years of data since 1981 (Figure 42).

Figure 43 summarises the mean monthly flow characteristics for the Sydney Basin bioregion based on the streamflow data from the 68 gauging stations. On average, February has the highest proportion (0.14) of annual streamflow of all the months, although there is considerable variability around this. February is also the month with the highest mean monthly rainfall (Figure 18 in Section 1.1.2). A significant proportion (0.125) of total annual streamflow occurs on average in August, which tends to be one of the lowest rainfall months in the bioregion. It is not clear from mean monthly climate drivers for the bioregion (Figure 18 in Section 1.1.2) why August should have high streamflow, but it could relate to the characteristics of rainfall in August, including high rainfall variability, and catchment wetness meaning rapid runoff responses when rain does fall. It could also be driven up by the localised areas of higher rainfall in the area just south of Bowral and Wollongong in August, contributing to high flows in upper Nepean, Avon and Cordeaux catchments and the Kangaroo River. September through to January is typically a low-flow period (spring to summer), with relatively low variability. This is consistent with potential evapotranspiration (PET) being more than double precipitation (i.e. aridity index >2) during these months (Figure 18 in Section 1.1.2). Streamflow across the bioregion tends to be higher during autumn and winter as mean monthly PET approaches and drops below mean monthly precipitation.

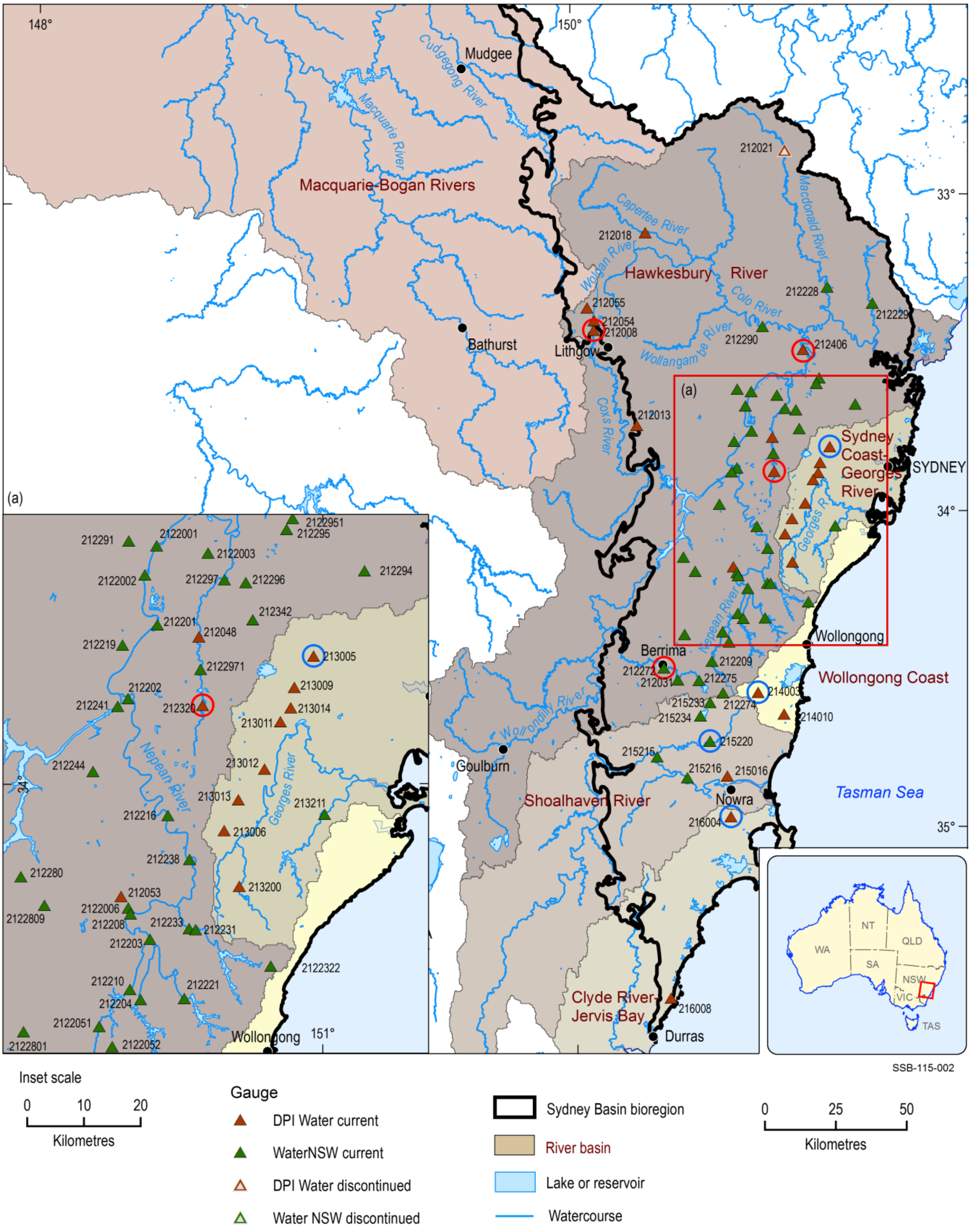

Figure 42 Streamflow gauges in the Sydney Basin bioregion and along rivers that flow into the bioregion that have at least ten years of daily flow data since 1981

Red rings identify stream gauges in the Hawkesbury-Nepean river basin that have annual streamflow data presented in Figure 44.
Blue rings identify stream gauges in the other river basins that have annual streamflow data presented in Figure 45.
Data: Bureau of Meteorology (Dataset 1, Dataset 3)

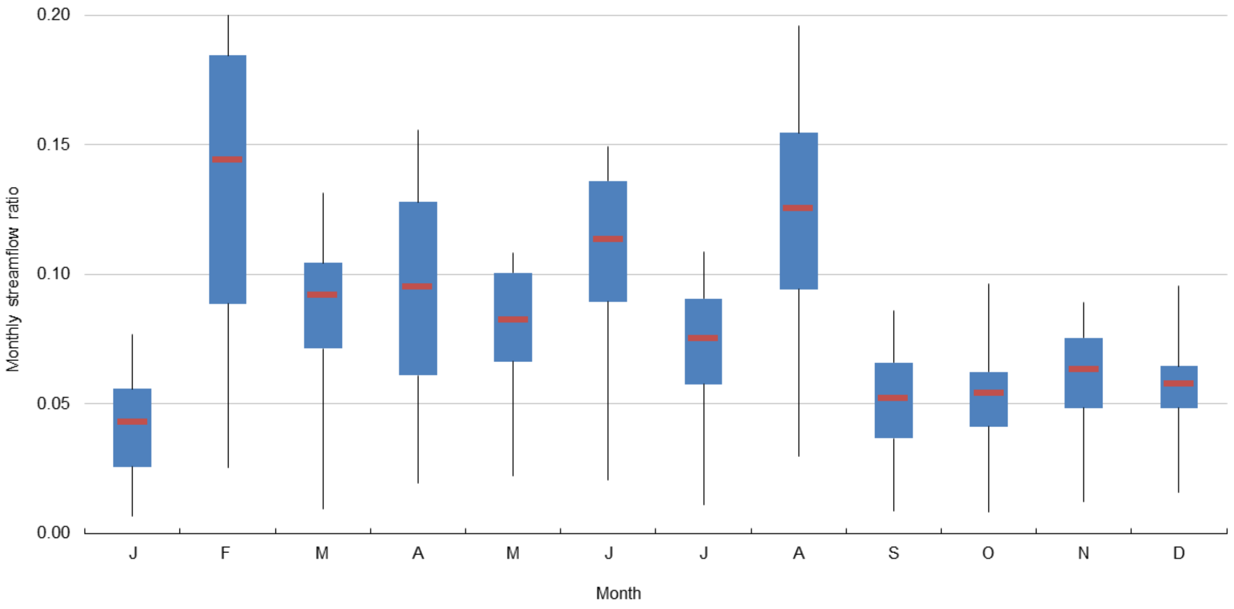

Figure 43 Monthly streamflow ratio (monthly mean divided by annual mean) distribution, summarised for 68 streamflow gauges within the Sydney Basin bioregion

Red lines correspond to monthly medians; blue boxes summarise the interquartile range (25th to 75th percentiles); black whiskers identify full range

Data: Sydney Catchment Authority (Dataset 4); NSW Office of Water (Dataset 5)

Table 17 summarises mean annual flows for a selection of gauging sites in each of the major river basins in the Sydney Basin bioregion. Selection was based on gauges with the most number of days of data and the start and end dates vary across the sites. Data are collected at sites with very small contributing areas (a few square kilometres) through to sites with large contributing areas (thousands of square kilometres), hence there is considerable variability in the mean annual flows. Many of the gauges, particularly in the Hawkesbury and Shoalhaven river basins, are downstream of dams and their flow regimes will differ from pre-dam flows. The release of environmental flows to maintain healthy water ways is a key objective of the Metropolitan Water Plan (NSW Government, 2010) in the Hawkesbury-Nepean river basin and will be reflected in the flow record of some gauging stations.

Annual time series have been generated for a number of gauging stations to illustrate some of the different flow characteristics of the rivers in the Sydney Basin bioregion (Figure 44 and Figure 45). Only years with >90% of daily streamflow values are used. A mean daily flow is calculated from the available flow data and multiplied by 365 to obtain an annual total. Gaps in the record reflect insufficient data, rather than zero-flow.

Annual streamflow is highly variable, but patterns are generally consistent with the bioregion-averaged annual precipitation (Figure 19a in Section 1.1.2). The size, location and physical characteristics of the catchments will contribute to local variations. The hydrographs tend to show relatively high flows through from mid-1980s to early 1990s, with 1990 having the highest flows at all sites for which data were available since 1980. However, where streamflow records are available from the 1970s, they indicate a period of higher streamflow at those sites than has been experienced in the 30 years since. However, the bioregion-averaged annual precipitation for this period is slightly lower than the mid-1980s to early 1990s period, which suggests that differences in the timing and magnitude of precipitation events varied in these periods. Annual streamflow volumes showed a decreasing trend from the early 1990s through to the mid- 2000s. The return to higher streamflow following the Millennium Drought has been variable across the bioregion, with some streams showing only moderate increases (e.g. at gauging stations 215220 and 216004) and others more significant increases (e.g. at gauging stations 212272, 213005 and 214003).

Table 17 Catchment areas and mean annual flow volumes for a subset of Sydney Basin bioregion stream gauging stations

River basin	Gauging station	Latitude	Longitude	Data length (days)	Catchment area (km²)	Mean annual flow (GL/y)
Hawkesbury	212008[a]	–33.425	150.0817	10980	199	20.30
	212018	–33.1233	150.28	10479	1030	26.17
	212048	–33.77	150.7617	9745	55	39.32
	212201[a]	–33.7483	150.6833	11726	327	595.20
	212202[a]	–33.865	150.6267	9571	386	190.39
	212203[a]	–34.245	150.6667	9195	126	95.34
	212208[a]	–34.205	150.63	8987	179	128.42
	212209	–34.4783	150.5333	10912	67	44.14
	212233[a]	–34.23	150.7433	11168	44	24.86
	212241[a]	–33.8683	150.6017	8734	1413	424.22
	212272[a]	–34.4967	150.3433	11900	60	59.84
	212274	–34.5767	150.57	9707	4	4.50
	212275[a]	–34.5367	150.4783	9356	35	29.71
	212280	–34.1467	150.42	10181	360	34.73
	212290	–33.42	150.725	10562	3305	376.14
	212295	–33.6	150.93	9119	120	22.75
	212320	–33.8783	150.7683	11699	90	8.76
Sydney Coast-Georges River	213005	–33.8	150.9817	10503	59	25.21
	213006	–34.075	150.81	10482	3	0.72
	213009	–33.85	150.945	9625	28	10.35
	213011	–33.9033	150.9183	8993	68	13.95
	213012	–33.9783	150.8867	8683	45	21.34
	213013	–34.0267	150.8367	9967	37	7.52
Wollongong Coast	214003	–34.5767	150.705	11837	35	15.46
Shoalhaven	215216[a]	–34.845	150.4317	8768	840	827.61
	215220	–34.73	150.52	11896	334	185.73
	215233	–34.6067	150.5217	11794	8	3.96
	215234[a]	–34.65	150.4833	9871	23	9.18
Clyde River-Jervis Bay	216004	–34.97	150.5983	11381	96	15.52

[a] downstream of a dam

Data: Sydney Catchment Authority (Dataset 4); NSW Office of Water (Dataset 5)

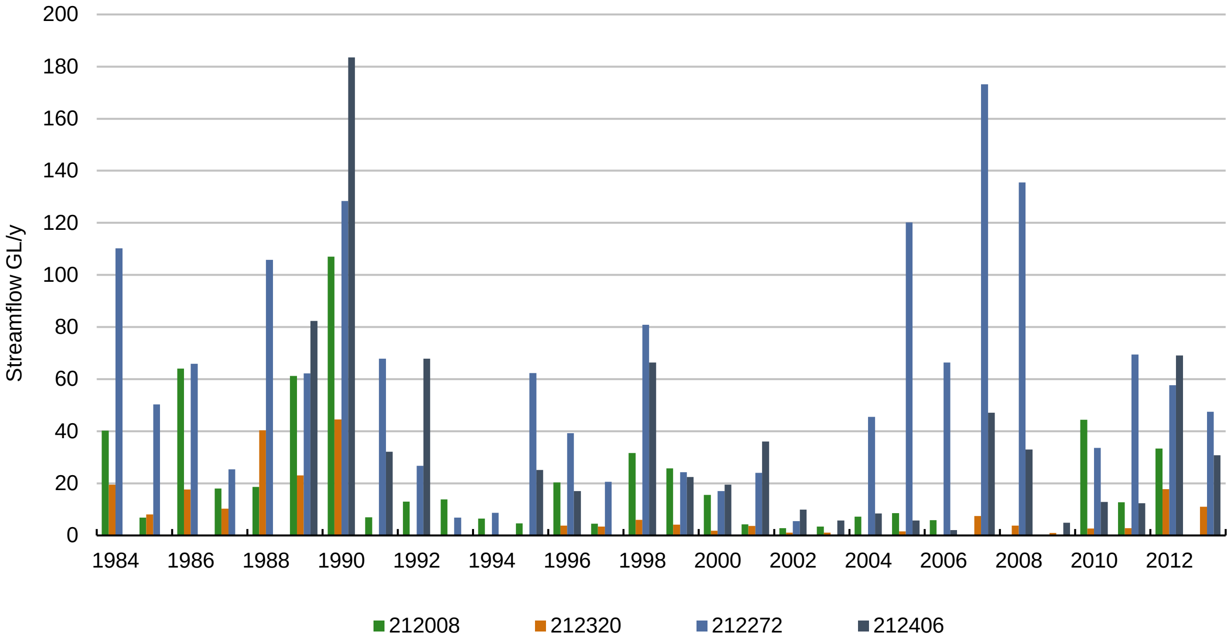

Figure 44 Annual streamflow volumes (1984 to 2013) at four gauging stations in the Hawkesbury river basin

212008 (Coxs River), 212272 (Wingecarribee River) and 212406 (Hawkesbury River) are located downstream of dams; 212406 is at Sackville, which is downstream of the tidal limit. 212320 (South Creek) records unimpaired flow. See Figure 42 for gauge locations.
Data: Sydney Catchment Authority (Dataset 4); NSW Office of Water (Dataset 5)

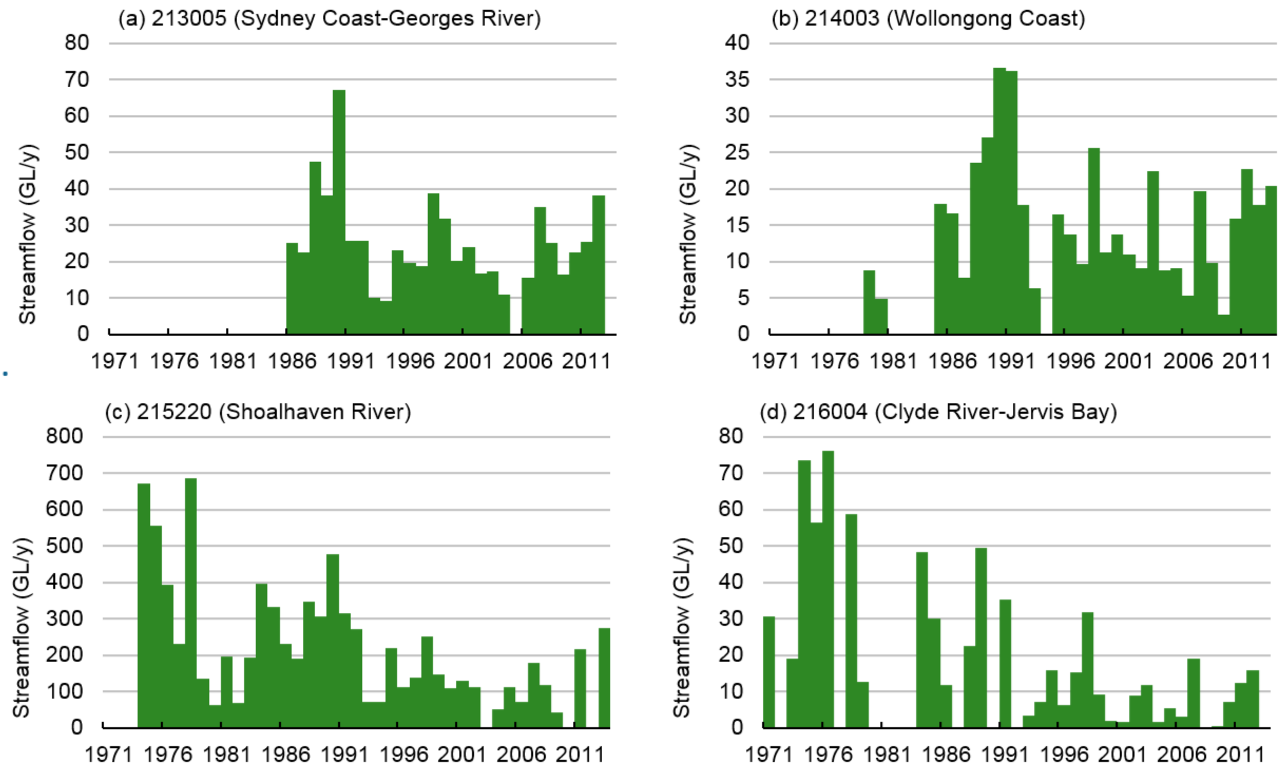

Figure 45 Annual streamflow volumes (1971 to 2013) for select gauges in four river basins

See Figure 42 for stream gauge locations.
Data: Sydney Catchment Authority (Dataset 4); NSW Office of Water (Dataset 5)

1.1.5.4 Water sharing plans

To maintain and protect the health of rivers and groundwater systems, the NSW government established water sharing plans (WSPs) for the state's unregulated and regulated rivers under NSW's *Water Management Act 2000*. The Act requires that water be allocated for the fundamental health of a water source and its dependent ecosystems, such as wetlands, floodplains and estuaries, as a first priority. These WSPs are reviewed every ten years.

There are three WSPs wholly within the Sydney Basin bioregion (Table 18). The WSP for the Greater Metropolitan Region Unregulated River Water Sources covers an area of 32,500 km^2 which includes most of the bioregion.

The Kangaroo River Water Source sits like an island within the larger area covered by the WSP for the Greater Metropolitan Unregulated River Water Sources. Its WSP commenced in 2004, well before the commencement of the WSP for the Greater Metropolitan Region Unregulated River Water Sources, in response to there being a high community dependence on water and a high risk to ecosystem values (NSW Department of Water and Energy, 2009). The 12 objectives specified in the plan reflect a range of environmental, economic, recreational and Indigenous values. DPI Water proposes to absorb the Kangaroo River Water Source into the WSP for Greater Metropolitan Region Unregulated River Water Sources in the near future.

Table 18 Water sharing plans for surface water resources in the Sydney Basin bioregion

Water sharing plan	Plan area	Water sources	Status
Greater Metropolitan Region Unregulated River Water Sources	Hawkesbury Shoalhaven (excl. Kangaroo River) Sydney Coast-Georges River Wollongong Coast	• Shoalhaven River • Illawarra rivers • Southern Sydney rivers • Northern Sydney rivers • Upper Nepean and upstream Warragamba rivers • Hawkesbury and lower Nepean rivers	Commenced 1 July 2011
Kangaroo River Water Source	Kangaroo River, including Brogers Creek, Barrengarry Creek and tributaries	• Kangaroo River	Commenced 1 July 2004. Extension to 1 July 2015 To be merged with WSP for the Greater Metropolitan Region Unregulated River water sources
Macquarie Bogan Unregulated and Alluvial Water Sources	Macquarie-Bogan unregulated water sources	• Upper Cudgegong River[a] • Turon Crudine River[a]	Commenced 4 October 2012

[a]other water sources covered by this water sharing plan are not within the Sydney Basin bioregion and are not included here

The Upper Cudgegong River and Turon Crudine River water sources are managed under the WSP for the Macquarie Bogan Unregulated and Alluvial Water Sources. Alluvial water sources include surface water and groundwater and are managed conjunctively under the plan. As the plan name indicates, flows in these water source areas are unregulated.

The Jervis Bay-Clyde river basin is not currently part of a WSP, but a draft WSP for the Clyde River unregulated and alluvial water sources has been prepared and gone to public exhibition. It is anticipated to commence sometime after mid-2016.

The WSPs specify the share components of water licence holders in the different water source areas. A share component translates into the maximum volume of water that is permitted to be taken in a year under a licence. Table 19 summarises the total volumes of take permitted to be extracted by water source area in each WSP area. The Greater Metropolitan Region Unregulated River Water Sources WSP area has licensed entitlements totalling just over 1,195,000 ML/y, with the majority of this for water in the water source areas that contribute to the major storages created by the Warragamba, Avon, Cataract, Cordeaux, Tallowa, Nepean and Prospect dams (Table 16).

Table 20 summarises the share component information given in Table 19 in terms of the use for which the water has been licensed. Most (~86%) of the water is for town water supply, predominantly for the Greater Sydney population; 11% is extracted from the unregulated river for unspecified purposes; and a small volume (2%) is used for power generation.

Table 19 Surface water entitlements (ML/y) by water source area

Water sharing plan	Water source	Estimated water share component (ML/y)
Greater Metropolitan Region Unregulated River Water Sources	Hawkesbury and lower Nepean rivers	120,772
	Illawarra rivers	3,125
	Northern Sydney rivers	1,854
	Shoalhaven River	363,659
	Southern Sydney rivers	36,949
	Upper Nepean and upstream Warragamba rivers	668,711
Kangaroo River Water Source	Kangaroo River	4,985
Macquarie Bogan Unregulated and Alluvial Water Sources	Upper Cudgegong River	6,452
	Turon Crudine River	328

Data: NSW Office of Water (Dataset 6)

Table 20 Licensed water use (ML/y)

Purpose	Estimated water share component (ML/y)
Town water supply	1,043,088
Power generation	29,021
Domestic and stock	1,744
Unregulated river (not specified)	132,982

Data: NSW Office of Water (Dataset 6)

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1.1.6 Surface water – groundwater interactions

Summary

The near-surface groundwater flows in the Sydney Basin bioregion are described within their geological settings. Groundwater flows in the central and eastern portion move laterally across different scales, from local to regional, and in general discharge into surface water bodies and rivers. In the north-west part of the bioregion the landscape is more rugged and incised, with local-scale flows driven by topography. Watercourses are net gaining with respect to groundwater under natural conditions.

Previous work in the vicinity of mines and borefields provides insight into natural and disturbed flow behaviour. Hydrological investigations of undisturbed streams and hanging swamps indicate that local, perched groundwater tables are the primary source of baseflow sustaining these surface features, and have little connection to deeper, larger-scale groundwater systems. Where a disturbance creates a linkage between flow scales and geological units, water flows are observed to be away from the surface, reducing baseflow and groundwater discharge.

1.1.6.1 Background

This section is not a comprehensive review of all aspects of surface water and groundwater and their connectivity within the Sydney Basin bioregion. Details of groundwater aquifers and flow are included in Section 1.1.3 (geology) and Section 1.1.4 (hydrogeology), while details of the bioregion's surface water stores and river flow are contained in Section 1.1.5 (hydrology). Where appropriate, cross references are made to these sections, rather than recapitulating details provided there.

Water courses in the Sydney Basin bioregion are generally considered to be gaining with respect to groundwater (Green et al., 2010). The general character of groundwater and surface water connections are described in this section according to their geological settings. These characterisations are greatly simplified relative to the full description of Sydney Basin geology.

The area dominated by the Hawkesbury Sandstone extends through the central and eastern sections of the bioregion, and is absent only south of Kiama and to the north and west of Lithgow (Figure 31 in Section 1.1.4). This region of the geological Sydney Basin is referred to as the Southern Coalfield (NSW RE, 2015) (Figure 23 in Section 1.1.3). Three main active groundwater groups have been defined by Green et al. (2010):

4. Alluvium at the surface, associated with major rivers, which has high sand content along major rivers like the Hawkesbury-Nepean but higher clay content on smaller local creeks.
5. Wianamatta Group, predominantly shales that produce groundwater confining layers, result in heavy clays when exposed and weathered at the surface, and have high connate salt stores due to their marine origin.
6. Hawkesbury Sandstone that thickens from west to east forming high plateaux and deep gorges.

Groundwater flows have been described by Green et al. (2010, Figure 3) as:

7. Shallow unconfined flows in upper level porous rocks that are topographically driven and discharging as hill-slope springs, seepages and baseflow to creeks
8. Intermediate flows in low yielding aquifers perched on less permeable material, likely discharging to mid-level valleys
9. Deep intermediate-regional flows in inter-layered and fractured rocks that are confined or semi-confined, discharging at the lowest levels of the landscape such as the Hawkesbury-Nepean River.

Within the Sydney Basin bioregion, the underground longwall mining operations west and north of Wollongong are in the Southern Coalfields (see Figure 7 in Section 1.2.2.1 of companion product 1.2 for the Sydney Basin bioregion (Hodgkinson et al., 2018)).

On the western side of the bioregion the topography becomes more rugged toward the Blue Mountains and Lachlan Fold Belt. This region of the geological Sydney Basin is referred to as the Western Coalfield (NSW RE, 2015) (Figure 23 in Section 1.1.3). It mainly occupies an extensive plateau of sandstone which is dissected by deep canyons and steep-sided valleys. The Illawarra Coal Measures outcrop at the surface along the western edges of the bioregion, and are deeper within some of the lower valleys (RW Corkery Pty Ltd, 2011). The upper geologic unit comprises layers of shale, sandstone and conglomerates mostly assigned to the Narrabeen Group, but it may be a sub-unit of the Hawkesbury Sandstone that lacks the usual geological markers used to identify it (Lee, 2009). The next layers form the Illawarra Coal Measures, with layers of interburden material and coal seams.

Rainfall recharge and groundwater discharge in these upland areas are tied to the highly dissected nature of the topography. Most flows in these highly dissected landscapes are considered local-scale, dominated by topography and specific local layering of low conductivity shale layers.

The west to east topography of the Sydney Basin bioregion starts in the Western Coalfields with relatively rugged terrain in the dissected sandstone and shale plateaux of the Blue Mountains plateau and the Illawarra plateau. Toward the Central Coalfields there is more undulating and flatter terrain along the coast, typically with a dramatic change in elevation between the two coalfields associated with the Lapstone Monocline (Figure 46). Groundwater flow paths are controlled topographically in the more upland areas, discharging locally to springs and streams. Over larger spatial scales, flow paths are longer and discharge at breaks-of-slope where the hillslopes meet the floodplains of major rivers. At the largest scales of flow, groundwater discharges into the alluvial deposits and floodplains of the major rivers and contributes baseflow (Figure 46). This regional recharge occurs around the northern and western margins of the Hawkesbury Sandstone (Figure 47).

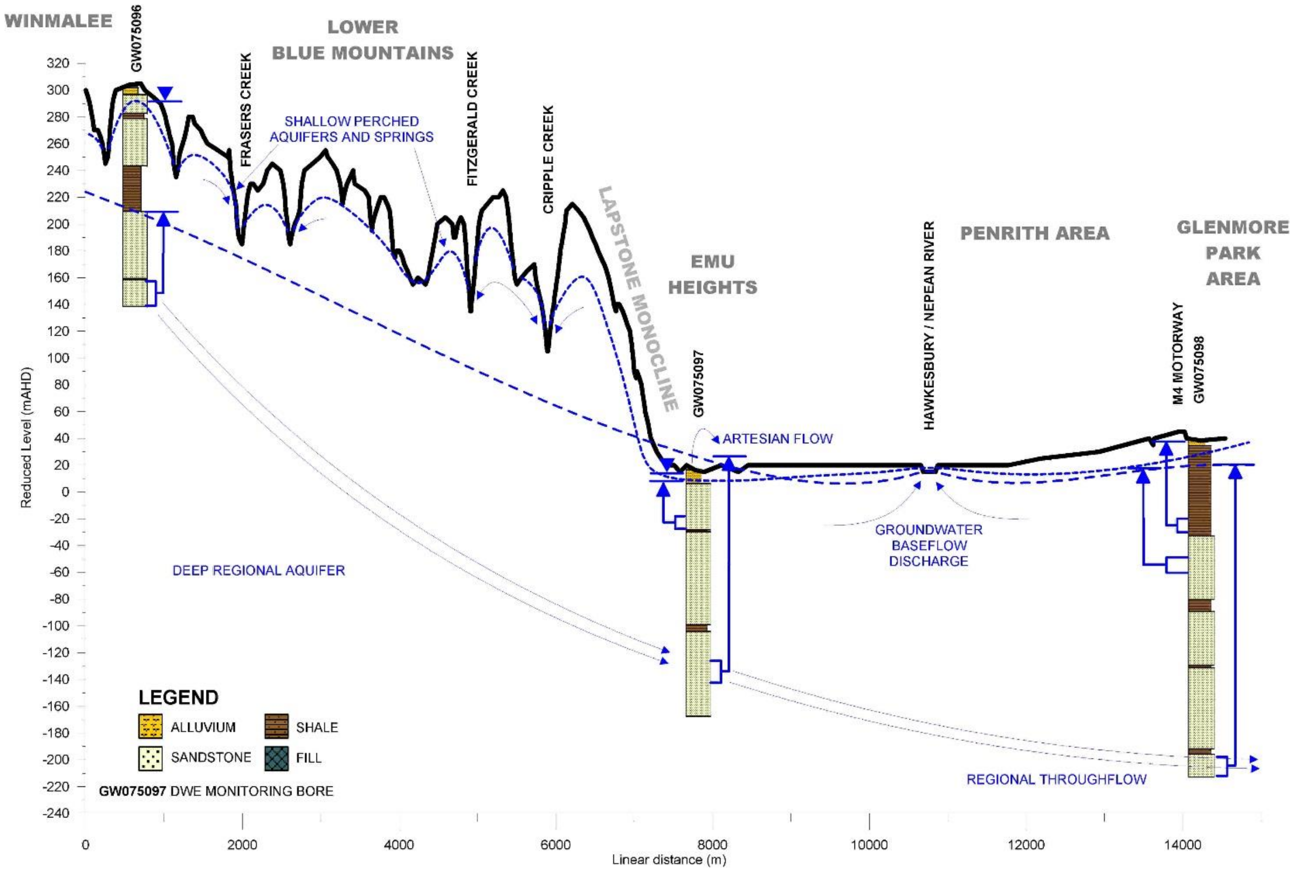

Figure 46 Groundwater levels and flow paths in a representative cross-section from the Blue Mountains Plateau to the Cumberland Lowlands

Source: Figure 3 in Green et al. (2010)

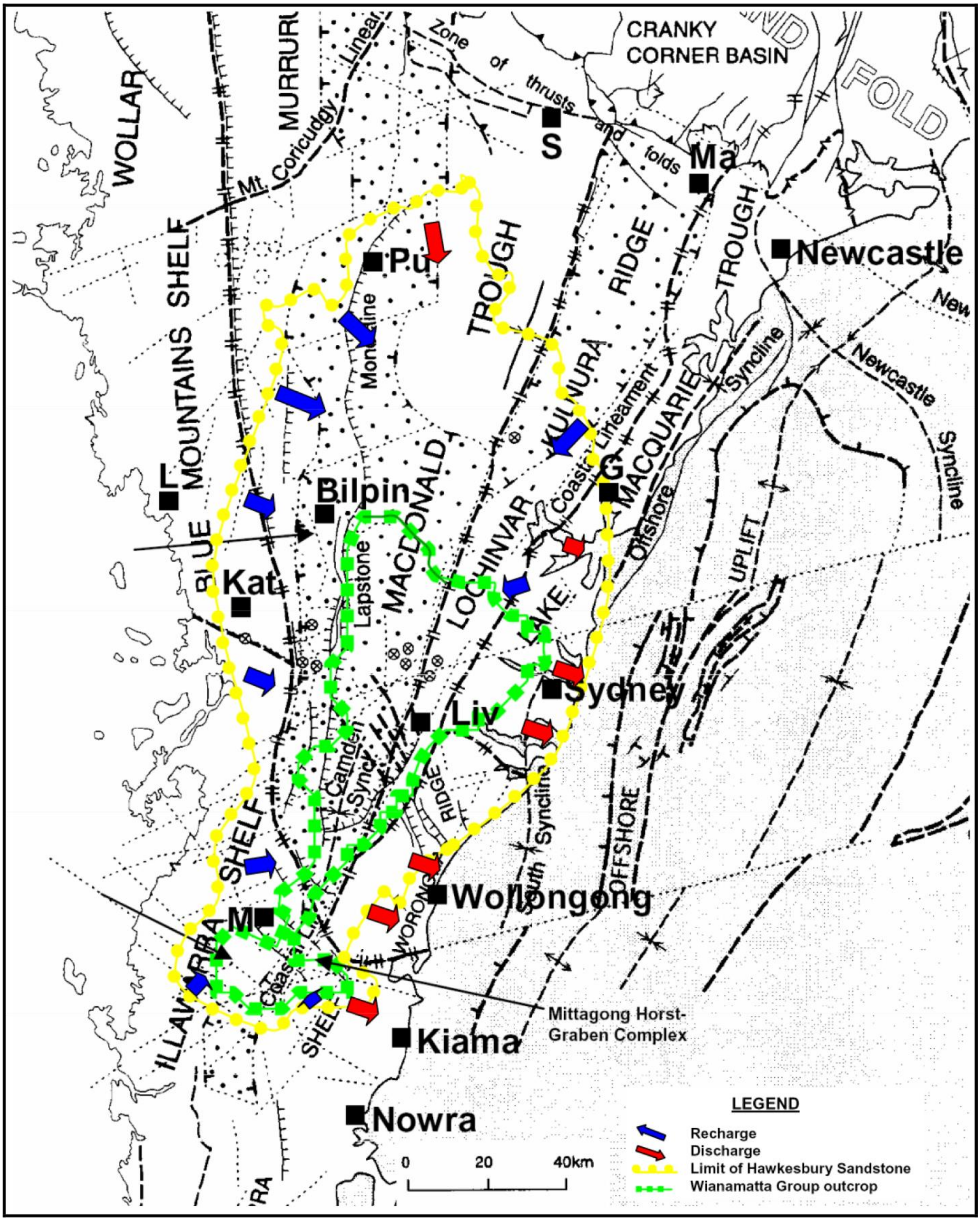

Figure 47 Regional-scale recharge and discharge areas in the geological Sydney Basin

Source: Figure 3 in Lee (2009)

1.1.6.2 Effects of mining on interactions with water courses

Studies of water courses near surface and underground mining operations are often hampered by a lack of pre-mining data collection. However, Jankowski (2007, 2009) has identified some general characteristics of systems in the Sydney Basin bioregion subject to mining disturbance. In an undisturbed state, groundwater flow is typically toward the stream as baseflow to a connected-gaining stream via an alluvial aquifer and the stream bed. Discharge supporting streamflow is often from springs, with local artesian head, or direct streambed connection in an area of significant vertical faulting. During mining operations there may be a reduction in the hydraulic gradient toward the stream but it remains a connected-gaining stream with reduced discharge. If there is sufficient dewatering of a surface mine, a reversal of the hydraulic gradient may result that causes the stream to become a connected-losing stream, meaning there is no longer any baseflow discharge and that runoff in the stream is lost. The impacts of a longwall mining operation can include changes to the strength and direction of the local groundwater gradient to the stream and associated streamflow changes. Structural changes that increase fracturing of streambed contact rocks can impact the wider catchment, with a reduction in surface flow to the stream, and increased losses through the streambed via new or expanded fracture zones. Where losses are so great that the groundwater table no longer intersects the streambed, the stream becomes a disconnected-losing stream.

Madden and Merrick (2009) summarised longwall mining effects as ‘The impact on groundwater systems from longwall mining is attributed to subsidence, strata movements and drainage.’ The first two of these are mechanisms that create new, or distort existing, groundwater pathways that tend to increase drainage away from surface features and reduce groundwater heads. The third mechanism involves drainage of water into underground mining voids. Water quality changes can occur whenever water from different layers is allowed to mix or drain due to new or altered flow paths.

Structural alterations from mining operations increase the complexity of the flow paths controlling surface water – groundwater interactions. Further, they almost exclusively result in decreased flow in creeks and potentially less groundwater discharge to other creeks in the immediate surface water catchment. It is not known how much losses of localised stream and creek flow are translated into river discharge in the intermediate and regional settings, but they must be considered as potentially impacting streamflow downstream from mining operations, at least within a reach down to a major storage reservoir. For example, Hawkes and Ross (2008) found that pumping alone in a 60-day test of the Hawkesbury Sandstone at Leonay, western Sydney, did not influence shallow monitoring bores in the surficial Cranebrook Formation. This suggests that unless connectivity is pre-existing, or is generated by anthropogenic or natural forces, local and regional groundwater are not always locally connected.

The Reynolds Inquiry (1976) found that bord and pillar mining under reservoirs at a minimum depth of suitable cover of 60m is unlikely to cause sufficient disturbance of the strata to increase any existing seepage from reservoirs. Subsequent investigations, including those involving longwall mining operations, have not updated the minimum depth of suitable cover, instead reporting continued uncertainty around the potential impact of subsidence upon surface water features including rivers and significant streams (McNally and Evans, 2007; NSWDP Southern Coalfields Enquiry, 2008).

1.1.6.3 Pumping interactions with upland swamps

Commonwealth of Australia (2014) describes three different peat swamp conceptual models: headwater swamps, valley infill swamps, and hanging swamps (see Section 1.1.7.3.2). Headwater swamps, which predominate on the Woronora Plateau (Southern Coalfield), are local depressions on eroded ridgelines that have filled with sand and later peat. They are mostly less than 10 ha in area and have a base layer less than 1.5 m thick; some swamps have a thin clay or silt layer directly above Hawkesbury Sandstone bedrock (Tomkins and Humphreys, 2006). Their water regime is dominated by rainfall and surface water runoff, but they can be connected to a shallow, typically ephemeral, perched aquifer. Two long pumping trials on swamps associated with borefields have been conducted to investigate linkages between headwater swamps and the local groundwater system (URS, 2007, 2008; Ross and Carosone, 2009). Results indicated that the perched water levels supporting the swamps were not connected to the underlying groundwater in the sandstone. Due to the characteristic shallow depths of headwater swamps, tilting and cracking of underlying sandstone caused by longwall mining is a threat despite their peat base.

The other two types of peat swamp have a stronger groundwater connection (Commonwealth of Australia, 2014). Valley infill swamps occur in steeper, more incised valleys of second and third order streams. They are recharged by rainfall, runoff and groundwater. Groundwater sources are typically perched, but can sometimes be regional. Swamps with a connection to a regional groundwater system are more likely to be permanently wet. Hanging swamps occur on steep valley sides and cliffs and are more common in the Blue Mountains and on the Newnes Plateau (Western Coalfield), but have also been identified on the Woronora Plateau. They are sustained by groundwater discharge from seepage faces caused by low permeability layers forcing water sideways along cracks and joints. Source aquifers occur within the higher permeability parts of the sandstone beds. Both of these swamp types are expected to be more vulnerable to subsidence than headwater swamps because they occur in steeper terrain. While swamps with at least local groundwater connection have experienced changes in their hydrology due to longwall mining, i.e. valley infill and hanging swamps (Tomkins and Humphreys, 2006; NSWDP Southern Coalfields Inquiry, 2008), no such observations have yet been reported for headwater swamps.

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1.1.7 Ecology

Summary

The Sydney Basin bioregion features a shale/clay basin surrounded by sandstone plateaux as well as rolling hills and coastal alluvial plains. It also exhibits some of the highest levels of species diversity in Australia largely as a result of the variety of rock types, topography and climates in the bioregion. It includes lagoons, estuaries and coastal lake systems, as well as a variety of vegetation types such as rainforest, wet and dry sclerophyll forest, and hanging swamps. The Wollemi National Park is home to several endemic species including the Wollemi pine. The Sydney Basin bioregion contains approximately 50 endangered or vulnerable plant communities, 26 endangered populations, nine endangered or vulnerable fungi, 222 endangered or vulnerable plants and 154 endangered or vulnerable animals listed under NSW's *Threatened Species Conservation Act 1995* (the TSC Act). Under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act), 133 flora species and 117 fauna species are listed either as critically endangered, endangered, vulnerable and/or migratory. Two hundred and three surface water features and 310 vegetation ecosystems are classified as groundwater-dependent ecosystems.

1.1.7.1 Ecological systems

As described in Section 1.1.1.1, the Sydney Basin bioregion aligns closely, but not exactly, with the Sydney Basin bioregion of the Interim Biogeographic Regionalisation for Australia (IBRA) classification (SEWPaC, 2012) – it also includes parts of the NSW South Western Slopes and South Eastern Highlands IBRA bioregions. The main IBRA subregions that occur within the Sydney Basin bioregion (as defined for use in the Sydney Basin Bioregional Assessment) are Wollemi, Yengo, Cumberland, Burragorang, Ettrema, Sydney Cataract, Jervis, Pittwater, Illawarra and Moss Vale; these account for nearly 92% of the bioregion. The Capertee Valley and Capertee Uplands IBRA subregions account for a further 7.1% of the bioregion. The vegetation characteristics of key IBRA subregions are described in detail in Table 21 (see also Figure 6 in Section 1.1.1.1) based on Morgan (2001); details of geology, landforms and soils can be found in Table 7 in Section 1.1.2.1.1.

The Sydney Basin bioregion is one of the most species diverse in Australia largely as a result of the variety of rock types, topography and climates in the bioregion. It includes lagoons, estuaries and coastal lake systems. It contains large areas of World Heritage and wilderness-listed national parks and includes a variety of vegetation types such as rainforest, wet and dry sclerophyll forest, and hanging swamps.

Table 21 Characteristic vegetation of the main Interim Biogeographic Regionalisation for Australia subregions in the Sydney Basin bioregion

IBRA[a] subregion	Vegetation
Burragorang	Heath, shrubland and woodland with black ash, hard-leaved scribbly gum, Sydney peppermint and red bloodwood on sandstone similar to other parts of the Basin. Deane's gum, turpentine, blue-leaved stringybark immediately below escarpment passing to grey gum, narrow-leaved ironbark and thin-leaved stringybark on bouldery slopes. River oak along main streams below the plateaux.
Capertee Uplands	Woodlands support rough-barked apple, red stringybark, red box, yellow box, Blakely's red gum with shrubby understorey and wallaby grass in open valleys. Scribbly gum, red stringybark, red box and broad-leaved ironbark on talus slopes. Black ash and Sydney peppermint on sandstone peaks. Dwarf casuarina, tea tree, and sedge on pagoda margins.
Cataract	Red bloodwood and black ash woodland with abundant shrubs on sandstone with extensive gahnia, banksia in hanging swamps. Coastal dune sequence of tea-tree, coast wattle, smooth-barked apple, blackbutt and swamp mahogany on barrier system. Mangroves and salt marsh on Towra Point and up the Georges River estuary.
Cumberland	Grey box, forest red gum, narrow-leaved ironbark woodland with some spotted gum on the shale hills. Hard-leaved scribbly gum, rough-barked apple and old man banksia on alluvial sands and gravels. Broad-leaved apple, cabbage gum and forest red gum with abundant swamp oak on river flats. Tall spike rush, and juncus with Parramatta red gum in lagoons and swamps.
Ettrema	Very prominent 'contour' vegetation pattern. Lichens, mosses and low heath patches on rock, woodlands with dwarfed red bloodwood, black ash, tall heath and sedgeland on soil benches. Better soils have messmate and brown barrel. Gullies support rainforest elements with turpentine plumwood, coachwood, lilly pilly and mountain pepper.
Illawarra	Mixed warm temperate and subtropical rainforest complexes on rich shale soils and alluvium under the escarpment. Coachwood, native tamarind, cabbage tree palm, Port Jackson fig, cheese tree, with soft tree fern and rough tree fern understorey. Adjacent tall forests; Sydney peppermint, brown barrel, yellow stringybark coastal white box. Coastal dunes; coast wattle, tea-tree, banksia, and blackbutt. Common reed in fresh swamps and lakes, mangroves and limited saltmarsh in estuaries.
Jervis	Coastal forests on shale dominated by spotted gum, blackbutt, black ash, and bangalay. Rainforest elements on trachyte, watergum along streams. Open understorey with macrozamia. Sand dunes have barrier sequence of tea-tree, banksia, wattles merging to protected forests and scrubs with smooth-barked apple, red bloodwood, forest oak, bangalay and blackbutt. Gahnia sedgelands with black wattle in steep wet gullies. Common reed swamps and sedgeland in wide valleys on shale and behind dunes. Swamp oak, salt marsh and mangrove sequence in estuaries.
Moss Vale	Tall forest of narrow-leaved peppermint, Sydney peppermint, monkey gum, black ash, messmate, coastal white box, and brown barrel on shale and basalts. Extensive sedgelands and hanging swamps on sandstone. Wingecarribee raised sphagnum bog. Sydney peppermint, narrow-leaved peppermint, and gully ash on trachyte domes.
Pittwater	Shale caps support tall forest of Sydney blue gum and blackbutt or turpentine and grey ironbark. Sandstone plateau; Sydney peppermint, smooth-barked apple, scribbly gum, red bloodwood, yellow bloodwood, with diverse shrubs and patches of heath. Blackbutt, turpentine, coachwood and water gum in deep sheltered gullies. Spotted gum, Deane's gum, bangalow palm, and forest oak on Narrabeen sandstone lower slopes. Banksia, tea-tree heath on dunes. Bangalay, swamp mahogany, cabbage tree palm, swamp oak, common reed and cumbungi in fresh swamps. Mangrove and saltmarsh communities in calm estuaries.
Wollemi	Red bloodwood, yellow bloodwood, rough-barked apple, smooth-barked apple, hard-leaved scribbly gum, and grey gum with diverse shrubs and heaths on plateau. Smooth-barked apple, Sydney peppermint, blue-leaved stringybark, and turpentine and gully rainforests in gullies and canyon heads. Ribbon gum and Blaxland's stringybark on basalt. River oak along main streams.

IBRA[a] subregion	Vegetation
Yengo	Red bloodwood, yellow bloodwood, rough-barked apple, smooth-barked apple, hard-leaved scribbly gum, and grey gum with diverse shrubs and heaths on plateau. Smooth-barked apple, Sydney peppermint, blue-leaved stringybark, and turpentine with rainforest species in gullies. Hard-leaved scribbly gum, rough-barked apple and Parramatta red gum with sedge swamps on Mellong Range sand. River mangrove and grey mangrove along margins of upper Hawkesbury estuary, freshwater reed swamps with sedges and paperbarks.

[a]Interim Biogeographic Regionalisation for Australia (IBRA; Environment Australia, 2000)
Data: NSW National Parks and Wildlife Service (2003)

1.1.7.2 *Terrestrial species and communities*

Eucalypt forest and woodland assemblages are the dominant vegetation communities in the Sydney Basin bioregion occupying more than 50% of the area (Figure 48), with 26% of the bioregion modified (including for intensive and agricultural uses) and 6% covered by heath. The following description of the terrestrial species and communities of the Sydney Basin IBRA bioregion is based on NSW National Parks and Wildlife Service (2003). Species diversity is very high, related to an assortment of topography, geology and climate combinations.

Young coastal dunes support tea-tree (*Leptospermum laevigatum*), wattle (*Acacia longifolia*) and banksias (*Banksia aemula*, *Banksia serrata*, *Banksia integrifolia*), often with grass tree (*Xanthorroea* sp.) and *Lomandra longifolia*. Older dunes support vegetation communities dominated by old man banksia (*Banksia serrata*), smooth-barked apple (*Angophora costata*), red bloodwood (*Corymbia gummifera*) and blackbutt (*Eucalyptus pilularis*) with a diverse shrub layer. The oldest dunes support a mature coastal forest community. Coastal forest occupying shale-derived soils is characterised by Sydney blue gum (*Eucalyptus saligna*), blackbutt, turpentine, grey ironbark (*Eucalyptus paniculata*), spotted gum, black ash and bangalay (*Eucalyptus botryoides*), and often have an open understorey, with macrozamia (*Macrozamia communis*) and cabbage tree palm. Estuaries are characterised by swamp oak (*Casuarina glauca*), common reed (*Phragmites australis*), saltmarsh and mangroves.

Rainforests are characterised by coachwood (*Ceratopetalum apetalum*), native tamarind (*Diploglottus australis*), white cherry (*Schizomeria ovata*), cheese tree (*Glochidion ferdinandi*), lilly pilly (*Acmena smithii*), blackwood (*Acacia melanoxylon*) and Port Jackson fig (*Ficus rubiginosa*), with tree ferns (*Dicksonia antarctica* and *Cyathea australis*) common in the understorey. Adjacent tall forests are dominated by peppermints (*Eucalyptus piperita* and *Eucalyptus radiata*) and messmate (*Eucalyptus obliqua*), other eucalypt species (*Eucalyptus fastigata*, *Eucalyptus muellerana*, *Eucalyptus quadrangulata*, *Eucalyptus deanei*), turpentine (*Syncarpia glomulifera*), bangalow palm (*Archontophoenix cunninghamiana*), cabbage tree palm (*Livistonia australis*), forest oak (*Allocasuarina torulosa*) and water gum (*Tristania laurina*). Species composition and the structural form of the vegetation communities occupying extensive sandstone plateaux vary with altitude and rainfall. Common trees include red bloodwood, yellow bloodwood (*Corymbia eximia*), rough-barked apple (*Angophora floribunda*), smooth-barked apple, hard-leaved scribbly gum (*Eucalyptus sclerophylla*), grey gum (*Eucalyptus punctata*), black ash (*Eucalyptus sieberi*), Sydney peppermint, blue-leaved stringybark (*Eucalyptus agglomerata*), turpentine, brown stringybark (*Eucalyptus capitellata*) and northern grey ironbark (*Eucalyptus siderophloia*). Drier, lowland environments such as the Cumberland Plain support forests and woodlands dominated by forest red gum (*Eucalyptus tereticornis*) and other eucalpyts (*Eucalyptus maculata*, *Eucalyptus haemastoma*, *Eucalyptus moluccana*, *Eucalyptus melliodora*, *Eucalyptus conica*, *Eucalyptus crebra*, *Eucalyptus fibrosa*), rough-barked apple, yellow bloodwood and extensive stands of swamp oak.

Riparian vegetation is dominated by river oak (*Casuarina cunninghamiana*) with water gum occupying the wetter, more protected environments. Swamp vegetation ranges from monocultures of common reed to complex prickly-leaved tea-tree (*Melaleuca stypheloides*) and paperbark (*Melaleuca quinquenervia*) associations, with swamp mahogany (*Eucalyptus robusta*), swamp oak, sedges, rushes and *Juncus* sp. Hanging swamps can be found on sandstone and dunes, with the dominant species being *Gahnia aspera* and *Banksia robur*. A raised sphagnum bog (*Sphagnum* sp.) is located at Wingecarribee.

Wollemi National Park is the largest reserve in the Sydney Basin IBRA bioregion, and protects many threatened species including locally endemic species such as *Apatophyllum constablei*, *Acacia asparagoides*, *Eucalyptus bensonii* and *Rupicola decumbens*, and the recently discovered Wollemi pine (*Wollemia nobilis*). Mellong Swamp in the Wollemi National Park has a unique plant community that provides important habitat for reptiles and invertebrates. Other important vegetation communities include yellow box - ironbark woodlands in the northern escarpments of the bioregion. These are thought to provide important habitat for species such as the regent honeyeater (*Xanthomyza phrygia*).

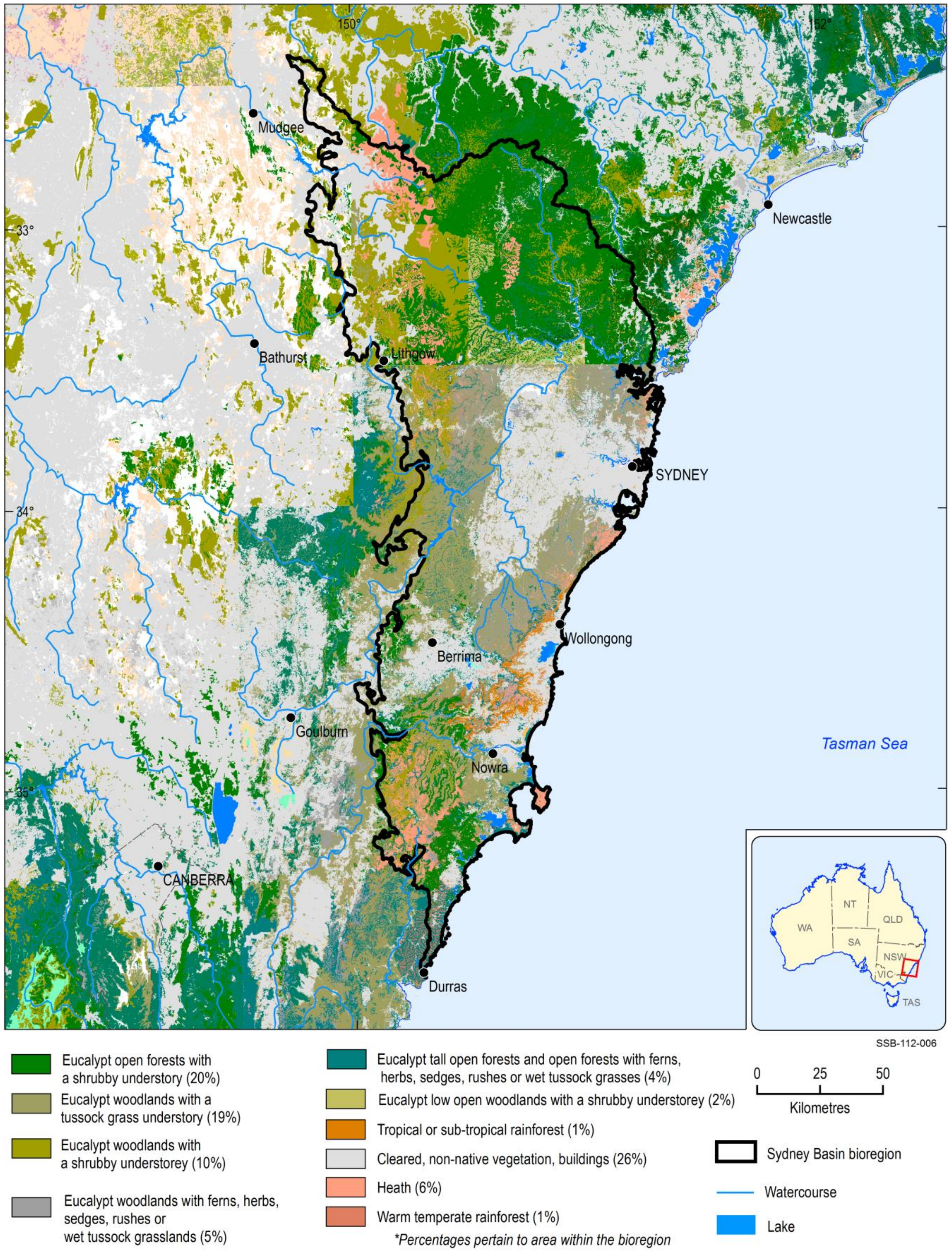

Figure 48 Dominant vegetation communities in the Sydney Basin bioregion

Data: Department of the Environment (Dataset 1)

A search of the *BioNet Atlas of NSW Wildlife* (NSW Environment and Heritage, 2014) found that the IBRA subregions listed in Table 21 contained 50 endangered or vulnerable plant communities

(Table 22), 26 endangered populations (Table 23), 154 endangered or vulnerable animals (Table 24), nine endangered or vulnerable fungi (Table 25) and 222 endangered or vulnerable plants (Table 26), all listed under the *NSW Conservation Act 1995* (the TSC Act). Threatened and endangered animals included 9 amphibians, 93 birds, one gastropod, three insects, 40 mammals and eight reptiles. A further 452 plants and 692 animals had ‘protected status’. Threatened species include the brush-tailed rock wallaby (*Petrogale penicillata*), koala (*Phascolarctos cinereus*), yellow-bellied glider (*Petaurus australis*), brush-tailed phascogale (*Phascogale tapoatafa*), tiger quoll (*Dasyurus maculatus*), broadheaded snake (*Hoplocephalus bungaroides*), glossy black cockatoo (*Calyptorhynchus lathami*), turquoise parrot (*Neophema pulchella*) and powerful owl (*Ninox strenua*). Under the Commonwealth’s *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), 133 flora (Table 25, Table 26) and 117 fauna species are listed (Table 24). Twenty-one endangered ecological communities (Table 22) and two endangered populations (Table 23) were also listed under the EPBC Act. General threats to the terrestrial communities and species in the bioregion include broad-scale vegetation clearing, loss of remnants, stock grazing, weed invasion and urbanisation.

Table 22 Endangered ecological communities within the Sydney Basin bioregion

Endangered ecological communities (EEC) as listed under either the TSC Act[a] that are known or predicted to lie within the Greater Sydney, Central Tablelands, Hunter and South East LLSs[c] and one or more of the IBRA[d] subregions listed in Table 21. Where an EEC is also listed under the EPBC Act[b] as a Threatened Ecological Community under another name, this has also been indicated.

Community name (as listed under the TSC Act)[e]	TSC Act	EPBC Act
Agnes Banks Woodland in the Sydney Basin Bioregion	Endangered	Not Listed
Bangalay Sand Forest of the Sydney Basin and South East Corner bioregions	Endangered	Not Listed
Blue Gum High Forest in the Sydney Basin Bioregion	Endangered	Critically Endangered
Blue Mountains Basalt Forest in the Sydney Basin Bioregion	Endangered	Not Listed
Blue Mountains Shale Cap Forest in the Sydney Basin Bioregion	Endangered	Critically Endangered
Blue Mountains Swamps in the Sydney Basin Bioregion	Vulnerable	Endangered
Castlereagh Scribbly Gum Woodland in the Sydney Basin Bioregion	Vulnerable	Endangered
Castlereagh Swamp Woodland Community	Endangered	Not Listed
Coastal Saltmarsh in the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Vulnerable
Coastal Upland Swamp in the Sydney Basin Bioregion	Endangered	Endangered
Cooks River/Castlereagh Ironbark Forest in the Sydney Basin Bioregion	Endangered	Critically Endangered
Cumberland Plain Woodland in the Sydney Basin Bioregion	Endangered	Critically Endangered
Duffys Forest Ecological Community in the Sydney Basin Bioregion	Endangered	Not Listed
Eastern Suburbs Banksia Scrub in the Sydney Basin Bioregion	Endangered	Endangered
Elderslie Banksia Scrub Forest in the Sydney Basin Bioregion	Endangered	Not Listed
Freshwater Wetlands on Coastal Floodplains of the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Not Listed
Genowlan Point Allocasuarina nana Heathland	Endangered	Not Listed
Hygrocybeae Community of Lane Cove Bushland Park in the Sydney Basin Bioregion	Endangered	Not Listed
Illawarra Lowlands Grassy Woodland in the Sydney Basin Bioregion	Endangered	Not Listed
Illawarra Subtropical Rainforest in the Sydney Basin Bioregion	Endangered	Not Listed
Kurnell Dune Forest in the Sutherland Shire and City of Rockdale	Endangered	Not Listed
Littoral Rainforest in the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Critically Endangered
Lowland Rainforest in the NSW North Coast and Sydney Basin Bioregions	Endangered	Critically Endangered
Maroota Sands Swamp Forest	Endangered	Not Listed
Melaleuca armillaris Tall Shrubland in the Sydney Basin Bioregion	Endangered	Not Listed
Milton Ulladulla Subtropical Rainforest in the Sydney Basin Bioregion	Endangered	Not Listed
Moist Shale Woodland in the Sydney Basin Bioregion	Endangered	Critically Endangered
Montane Peatlands and Swamps of the New England Tableland, NSW North Coast, Sydney Basin, South East Corner, South Eastern Highlands and Australian Alps bioregions	Endangered	Endangered

Community name (as listed under the TSC Act)[e]	TSC Act	EPBC Act
Mount Gibraltar Forest in the Sydney Basin Bioregion	Endangered	Endangered
Newnes Plateau Shrub Swamp in the Sydney Basin Bioregion	Endangered	Endangered
OHares Creek Shale Forest	Endangered	Not Listed
Pittwater and Wagstaffe Spotted Gum Forest in the Sydney Basin Bioregion	Endangered	Not Listed
River-Flat Eucalypt Forest on Coastal Floodplains of the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Not Listed
Robertson Basalt Tall Open-forest in the Sydney Basin Bioregion	Endangered	Endangered
Robertson Rainforest in the Sydney Basin Bioregion	Endangered	Not Listed
Shale Gravel Transition Forest in the Sydney Basin Bioregion	Endangered	Critically Endangered
Shale Sandstone Transition Forest in the Sydney Basin Bioregion	Endangered	Critically Endangered
Southern Highlands Shale Woodlands in the Sydney Basin Bioregion	Endangered	Not Listed
Southern Sydney sheltered forest on transitional sandstone soils in the Sydney Basin Bioregion	Endangered	Not Listed
Sun Valley Cabbage Gum Forest in the Sydney Basin Bioregion	Endangered	Not Listed
Swamp Oak Floodplain Forest of the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Not Listed
Swamp Sclerophyll Forest on Coastal Floodplains of the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Not Listed
Sydney Freshwater Wetlands in the Sydney Basin Bioregion	Endangered	Not Listed
Sydney Turpentine-Ironbark Forest	Endangered	Critically Endangered
Tableland Basalt Forest in the Sydney Basin and South Eastern Highlands Bioregions	Endangered	Not Listed
Tablelands Snow Gum, Black Sallee, Candlebark and Ribbon Gum Grassy Woodland in the South Eastern Highlands, Sydney Basin, South East Corner and NSW South Western Slopes Bioregions	Endangered	Not Listed
The Shorebird Community occurring on the relict tidal delta sands at Taren Point	Endangered	Not Listed
Themeda grassland on seacliffs and coastal headlands in the NSW North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Not Listed
Western Sydney Dry Rainforest in the Sydney Basin Bioregion	Endangered	Critically Endangered
White Box Yellow Box Blakelys Red Gum Woodland	Endangered	Critically Endangered

[a] NSW's *Threatened Species Conservation Act 1995* (TSC Act)
[b] the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)
[c] local land services areas (NSW Government, 2014)
[d] Interim Biogeographic Regionalisation for Australia (IBRA), (Environment Australia, 2000)
[e] typology and punctuation are given as they are used in the legislation.
Data: NSW Environment and Heritage (2014)

Table 23 Endangered populations within the Sydney Basin bioregion

Endangered populations as listed under the TSC Act[a] or EPBC Act[b] that are known or predicted to lie within the Sydney Basin bioregion.

Scientific name[c]	Common name and/or description[c]	TSC Act	EPBC Act
Acacia prominens	Gosford Wattle, Hurstville and Kogarah Local Government Areas	Endangered	Not Listed
Allocasuarina diminuta subsp. *mimica*	*Allocasuarina diminuta* subsp. *mimica* L.A.S.Johnson population in the Sutherland and Liverpool local government areas	Endangered	Not Listed
Callitris endlicheri	Black Cypress Pine, Woronora Plateau population	Endangered	Not Listed
Callocephalon fimbriatum	Gang-gang Cockatoo population in the Hornsby and Ku-ring-gai Local Government Areas	Endangered	Not Listed
Chorizema parviflorum	*Chorizema parviflorum Benth*. in the Wollongong and Shellharbour Local Government Areas	Endangered	Not Listed
Darwinia fascicularis subsp. *oligantha*	*Darwinia fascicularis* subsp. *oligantha* population in the Baulkham Hills and Hornsby Local Government Areas	Endangered	Not Listed
Dillwynia tenuifolia	*Dillwynia tenuifolia Sieber* ex D.C. in the Baulkham Hills local government area	Endangered	Not Listed
Dillwynia tenuifolia	*Dillwynia tenuifolia*, Kemps Creek	Endangered	Not Listed
Epthianura albifrons	White-fronted Chat population in the Sydney Metropolitan Catchment Management Area	Endangered	Not Listed
Eucalyptus aggregata	*Eucalyptus aggregata* H.Deane & Maiden population in the Wingecarribee local government area	Endangered	Not Listed
Eucalyptus langleyi	*Eucalyptus langleyi* population north of the Shoalhaven River in the Shoalhaven local government area	Endangered	Vulnerable
Eucalyptus macarthurii	Paddys River Box, Camden Woollybutt	Endangered	Not Listed
Eudyptula minor	Little Penguin in the Manly Point	Endangered	Not Listed
Gossia acmenoides	*Gossia acmenoides* population in the Sydney Basin Bioregion south of the Georges River	Endangered	Not Listed
Keraudrenia corollata var. *denticulate*	*Keraudrenia corollata* var. *denticulata* in the Hawkesbury local government area	Endangered	Not Listed
Lespedeza juncea subsp. *sericea*	*Lespedeza juncea* subsp. *sericea* in the Wollongong Local Government Area	Endangered	Not Listed
Marsdenia viridiflora subsp. *viridiflora*	*Marsdenia viridiflora* R. Br. subsp. *viridiflora* population in the Bankstown, Blacktown, Camden, Campbelltown, Fairfield, Holroyd, Liverpool and Penrith local government areas	Endangered	Not Listed
Menippus darcyi	*Menippus darcyi* population in the Sutherland Shire	Endangered	Not Listed
Perameles nasuta	Long-nosed Bandicoot population in inner western Sydney	Endangered	Not Listed
Petauroides volans	Greater Glider population in the Eurobodalla local government area	Endangered	Not Listed
Petaurus norfolcensis	Squirrel Glider on Barrenjoey Peninsula, north of Bushrangers Hill	Endangered	Not Listed
Phascolarctos cinereus	Koala in the Pittwater Local Government Area	Endangered	Vulnerable

Scientific name[c]	Common name and/or description[c]	TSC Act	EPBC Act
Pomaderris prunifolia	*Pomaderris prunifolia* in the Parramatta, Auburn, Strathfield and Bankstown Local Government Areas	Endangered	Not Listed
Prostanthera saxicola	*Prostanthera saxicola* population in Sutherland and Liverpool local government areas	Endangered	Not Listed
Pultenaea villifera	*Pultenaea villifera Sieber* ex DC. population in the Blue Mountains local government area	Endangered	Not Listed
Wahlenbergia multicaulis	Tadgell's Bluebell in the local government areas of Auburn, Bankstown, Baulkham Hills, Canterbury, Hornsby, Parramatta and Strathfield	Endangered	Not Listed

[a] NSW's *Threatened Species Conservation Act 1995* (TSC Act)

[b] the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)

[c] typology and punctuation are given as they are used in the legislation.

Data: NSW Environment and Heritage (2014)

Table 24 Threatened animal species within the Sydney Basin bioregion

Threatened animal species listed under either the TSC Act[a] or the EPBC Act[b] known to live within the Sydney Basin bioregion. 'Migratory' refers to species listed under the China, Japan or Korea Australia Migratory Bird Agreement. Typology and punctuation are given as they are used in the legislation.

Common name	Scientific name	TSC Act	EPBC Act
Antipodean Albatross	*Diomedea antipodensis*	Vulnerable	Vulnerable
Arctic Jaeger	*Stercorarius parasiticus*	Not Listed	Migratory
Asian Dowitcher	*Limnodromus semipalmatus*	Not Listed	Migratory
Australasian Bittern	*Botaurus poiciloptilus*	Endangered	Endangered
Australian Fur-seal	*Arctocephalus pusillus doriferus*	Vulnerable	Not Listed
Australian Painted Snipe	*Rostratula australis*	Endangered	Endangered
Baird's Sandpiper	*Calidris bairdii*	Not Listed	Migratory
Barking Owl	*Ninox connivens*	Vulnerable	Not Listed
Barn Swallow	*Hirundo rustica*	Not Listed	Migratory
Barred Cuckoo-shrike	*Coracina lineata*	Vulnerable	Not Listed
Bar-tailed Godwit	*Limosa lapponica*	Not Listed	Migratory
Bathurst Copper Butterfly	*Paralucia spinifera*	Endangered	Vulnerable
Beach Stone-curlew	*Esacus magnirostris*	Endangered	Not Listed
Black Bittern	*Ixobrychus flavicollis*	Vulnerable	Not Listed
Black Falcon	*Falco subniger*	Vulnerable	Not Listed
Black-breasted Buzzard	*Hamirostra melanosternon*	Vulnerable	Not Listed
Black-browed Albatross	*Thalassarche melanophris*	Vulnerable	Vulnerable
Black-chinned Honeyeater (eastern subspecies)	*Melithreptus gularis gularis*	Vulnerable	Not Listed
Black-necked Stork	*Ephippiorhynchus asiaticus*	Endangered	Not Listed
Black-tailed Godwit	*Limosa limosa*	Vulnerable	Migratory
Black-winged Petrel	*Pterodroma nigripennis*	Vulnerable	Not Listed
Blue Mountains Water skink	*Eulamprus leuraensis*	Endangered	Endangered
Blue Whale	*Balaenoptera musculus*	Endangered	Endangered
Blue-billed Duck	*Oxyura australis*	Vulnerable	Not Listed
Booroolong Frog	*Litoria booroolongensis*	Endangered	Endangered
Broad-billed Sandpiper	*Limicola falcinellus*	Vulnerable	Migratory
Broad-headed Snake	*Hoplocephalus bungaroides*	Endangered	Vulnerable
Brown Booby	*Sula leucogaster*	Not Listed	Migratory
Brown Treecreeper (eastern subspecies)	*Climacteris picumnus victoriae*	Vulnerable	Not Listed
Brush-tailed Bettong (South-East Mainland)	*Bettongia penicillata penicillata*	Endangered	Extinct
Brush-tailed Phascogale	*Phascogale tapoatafa*	Vulnerable	Not Listed

Common name	Scientific name	TSC Act	EPBC Act
Brush-tailed Rock-wallaby	*Petrogale penicillata*	Endangered	Vulnerable
Buff-breasted Sandpiper	*Tryngites subruficollis*	Not Listed	Migratory
Bush Stone-curlew	*Burhinus grallarius*	Endangered	Not Listed
Caspian Tern	*Hydroprogne caspia*	Not Listed	Migratory
Cattle Egret	*Ardea ibis*	Not Listed	Migratory
Citrine Wagtail	*Motacilla citreola*	Not Listed	Migratory
Comb-crested Jacana	*Irediparra gallinacea*	Vulnerable	Not Listed
Common Greenshank	*Tringa nebularia*	Not Listed	Migratory
Common Noddy	*Anous stolidus*	Not Listed	Migratory
Common Redshank	*Tringa totanus*	Not Listed	Migratory
Common Sandpiper	*Actitis hypoleucos*	Not Listed	Migratory
Common Tern	*Sterna hirundo*	Not Listed	Migratory
Corben's Long-eared Bat	*Nyctophilus corbeni*	Vulnerable	Vulnerable
Cotton Pygmy-Goose	*Nettapus coromandelianus*	Endangered	Not Listed
Cumberland Plain Land Snail	*Meridolum corneovirens*	Endangered	Not Listed
Curlew Sandpiper	*Calidris ferruginea*	Endangered	Critically Endangered
Diamond Firetail	*Stagonopleura guttata*	Vulnerable	Not Listed
Dugong	*Dugong dugon*	Endangered	Not Listed
Dural Woodland Snail	*Pommerhelix duralensis*	Not Listed	Endangered
Eastern Bentwing-bat	*Miniopterus schreibersii oceanensis*	Vulnerable	Not Listed
Eastern Bristlebird	*Dasyornis brachypterus*	Endangered	Endangered
Eastern Cave Bat	*Vespadelus troughtoni*	Vulnerable	Not Listed
Eastern Chestnut Mouse	*Pseudomys gracilicaudatus*	Vulnerable	Not Listed
Eastern Curlew	*Numenius madagascariensis*	Not Listed	Critically Endangered
Eastern False Pipistrelle	*Falsistrellus tasmaniensis*	Vulnerable	Not Listed
Eastern Freetail-bat	*Mormopterus norfolkensis*	Vulnerable	Not Listed
Eastern Grass Owl	*Tyto longimembris*	Vulnerable	Not Listed
Eastern Ground Parrot	*Pezoporus wallicus wallicus*	Vulnerable	Not Listed
Eastern Osprey	*Pandion cristatus*	Vulnerable	Not Listed
Eastern Pygmy-possum	*Cercartetus nanus*	Vulnerable	Not Listed
Eastern Quoll	*Dasyurus viverrinus*	Endangered	Not Listed
Eastern Reef Egret	*Egretta sacra*	Not Listed	Migratory
Flame Robin	*Petroica phoenicea*	Vulnerable	Not Listed
Flesh-footed Shearwater	*Ardenna carneipes*	Vulnerable	Migratory

Common name	Scientific name	TSC Act	EPBC Act
Fork-tailed Swift	*Apus pacificus*	Not Listed	Migratory
Freckled Duck	*Stictonetta naevosa*	Vulnerable	Not Listed
Gang-gang Cockatoo	*Callocephalon fimbriatum*	Vulnerable	Not Listed
Giant Barred Frog	*Mixophyes iteratus*	Endangered	Endangered
Giant Burrowing Frog	*Heleioporus australiacus*	Vulnerable	Vulnerable
Giant Dragonfly	*Petalura gigantea*	Endangered	Not Listed
Gibson's Albatross	*Diomedea gibsoni*	Vulnerable	Vulnerable
Gilbert's Whistler	*Pachycephala inornata*	Vulnerable	Not Listed
Glossy Black-Cockatoo	*Calyptorhynchus lathami*	Vulnerable	Not Listed
Glossy Ibis	*Plegadis falcinellus*	Not Listed	Migratory
Golden-tipped Bat	*Kerivoula papuensis*	Vulnerable	Not Listed
Gould's Petrel	*Pterodroma leucoptera leucoptera*	Vulnerable	Endangered
Great Knot	*Calidris tenuirostris*	Vulnerable	Migratory
Greater Broad-nosed Bat	*Scoteanax rueppellii*	Vulnerable	Not Listed
Greater Sand-plover	*Charadrius leschenaultii*	Vulnerable	Migratory
Green and Golden Bell Frog	*Litoria aurea*	Endangered	Vulnerable
Green Turtle	*Chelonia mydas*	Vulnerable	Vulnerable
Green-thighed Frog	*Litoria brevipalmata*	Vulnerable	Not Listed
Grey Falcon	*Falco hypoleucos*	Endangered	Not Listed
Grey Plover	*Pluvialis squatarola*	Not Listed	Migratory
Grey Ternlet	*Procelsterna cerulea*	Vulnerable	Not Listed
Grey-crowned Babbler (eastern subspecies)	*Pomatostomus temporalis temporalis*	Vulnerable	Not Listed
Grey-headed Albatross	*Thalassarche chrysostoma*	Not Listed	Endangered
Grey-headed Flying-fox	*Pteropus poliocephalus*	Vulnerable	Vulnerable
Grey-tailed Tattler	*Tringa brevipes*	Not Listed	Migratory
Hooded Plover	*Thinornis rubricollis*	Endangered	Not Listed
Hooded Robin (south-eastern form)	*Melanodryas cucullata cucullata*	Vulnerable	Not Listed
Humpback Whale	*Megaptera novaeangliae*	Vulnerable	Vulnerable
Kermadec Petrel (west Pacific subspecies)	*Pterodroma neglecta neglecta*	Vulnerable	Vulnerable
Koala	*Phascolarctos cinereus*	Vulnerable	Vulnerable
Large-eared Pied Bat	*Chalinolobus dwyeri*	Vulnerable	Vulnerable
Latham's Snipe	*Gallinago hardwickii*	Not Listed	Migratory
Leatherback Turtle	*Dermochelys coriacea*	Endangered	Endangered
Lesser Frigatebird	*Fregata ariel*	Not Listed	Migratory

Common name	Scientific name	TSC Act	EPBC Act
Lesser Sand-plover	*Charadrius mongolus*	Vulnerable	Migratory
Little Bentwing-bat	*Miniopterus australis*	Vulnerable	Not Listed
Little Curlew	*Numenius minutus*	Not Listed	Migratory
Little Eagle	*Hieraaetus morphnoides*	Vulnerable	Not Listed
Little Lorikeet	*Glossopsitta pusilla*	Vulnerable	Not Listed
Little Shearwater	*Puffinus assimilis*	Vulnerable	Not Listed
Little Stint	*Calidris minuta*	Not Listed	Migratory
Little Tern	*Sternula albifrons*	Endangered	Migratory
Little Whip Snake	*Suta flagellum*	Vulnerable	Not Listed
Littlejohn's Tree Frog	*Litoria littlejohni*	Vulnerable	Vulnerable
Loggerhead Turtle	*Caretta caretta*	Endangered	Endangered
Long-nosed Bandicoot, North Head	*Perameles nasuta*	Endangered	Not Listed
Long-nosed Potoroo	*Potorous tridactylus*	Vulnerable	Vulnerable
Long-tailed Jaeger	*Stercorarius longicaudus*	Not Listed	Migratory
Long-toed Stint	*Calidris subminuta*	Not Listed	Migratory
Magpie Goose	*Anseranas semipalmata*	Vulnerable	Not Listed
Major Mitchell's Cockatoo	*Lophochroa leadbeateri*	Vulnerable	Not Listed
Marsh Sandpiper	*Tringa stagnatilis*	Not Listed	Migratory
Masked Booby	*Sula dactylatra*	Vulnerable	Migratory
Masked Owl	*Tyto novaehollandiae*	Vulnerable	Not Listed
New Holland Mouse	*Pseudomys novaehollandiae*	Not Listed	Vulnerable
New Zealand Fur-seal	*Arctocephalus forsteri*	Vulnerable	Not Listed
Northern Giant-Petrel	*Macronectes halli*	Vulnerable	Vulnerable
Olive Whistler	*Pachycephala olivacea*	Vulnerable	Not Listed
Orange-bellied Parrot	*Neophema chrysogaster*	Endangered	Critically Endangered
Oriental Plover	*Charadrius veredus*	Not Listed	Migratory
Oriental Pratincole	*Glareola maldivarum*	Not Listed	Migratory
Pacific Golden Plover	*Pluvialis fulva*	Not Listed	Migratory
Painted Honeyeater	*Grantiella picta*	Vulnerable	Not Listed
Pale-headed Snake	*Hoplocephalus bitorquatus*	Vulnerable	Not Listed
Parma Wallaby	*Macropus parma*	Vulnerable	Not Listed
Pectoral Sandpiper	*Calidris melanotos*	Not Listed	Migratory
Pied Oystercatcher	*Haematopus longirostris*	Endangered	Not Listed
Pink Robin	*Petroica rodinogaster*	Vulnerable	Not Listed
Pomarine Jaeger	*Stercorarius pomarinus*	Not Listed	Migratory

Common name	Scientific name	TSC Act	EPBC Act
Powerful Owl	*Ninox strenua*	Vulnerable	Not Listed
Providence Petrel	*Pterodroma solandri*	Vulnerable	Migratory
Purple-crowned Lorikeet	*Glossopsitta porphyrocephala*	Vulnerable	Not Listed
Rainbow Bee-eater	*Merops ornatus*	Not Listed	Migratory
Red Goshawk	*Erythrotriorchis radiatus*	Endangered	Vulnerable
Red Knot	*Calidris canutus*	Not Listed	Migratory
Red-backed Button-quail	*Turnix maculosus*	Vulnerable	Not Listed
Red-crowned Toadlet	*Pseudophryne australis*	Vulnerable	Not Listed
Red-necked Stint	*Calidris ruficollis*	Not Listed	Migratory
Red-tailed Tropicbird	*Phaethon rubricauda*	Vulnerable	Not Listed
Regent Honeyeater	*Anthochaera phrygia*	Endangered	Endangered
Regent Parrot (eastern subspecies)	*Polytelis anthopeplus monarchoides*	Endangered	Vulnerable
Ringed Plover	*Charadrius hiaticula*	Not Listed	Migratory
Rose-crowned Fruit-Dove	*Ptilinopus regina*	Vulnerable	Not Listed
Rosenberg's Goanna	*Varanus rosenbergi*	Vulnerable	Not Listed
Ruddy Turnstone	*Arenaria interpres*	Not Listed	Migratory
Ruff	*Philomachus pugnax*	Not Listed	Migratory
Rufous Bettong	*Aepyprymnus rufescens*	Vulnerable	Not Listed
Sanderling	*Calidris alba*	Vulnerable	Migratory
Scarlet Robin	*Petroica boodang*	Vulnerable	Not Listed
Sharp-tailed Sandpiper	*Calidris acuminata*	Not Listed	Migratory
Short-tailed Shearwater	*Ardenna tenuirostris*	Not Listed	Migratory
Shy Albatross	*Thalassarche cauta*	Vulnerable	Vulnerable
Sooty Albatross	*Phoebetria fusca*	Vulnerable	Vulnerable
Sooty Owl	*Tyto tenebricosa*	Vulnerable	Not Listed
Sooty Oystercatcher	*Haematopus fuliginosus*	Vulnerable	Not Listed
Sooty Shearwater	*Ardenna grisea*	Not Listed	Migratory
Sooty Tern	*Onychoprion fuscata*	Vulnerable	Not Listed
South Polar Skua	*Stercorarius maccormicki*	Not Listed	Migratory
Southern Brown Bandicoot (eastern)	*Isoodon obesulus obesulus*	Endangered	Endangered
Southern Giant Petrel	*Macronectes giganteus*	Endangered	Endangered
Southern Myotis	*Myotis macropus*	Vulnerable	Not Listed
Southern Right Whale	*Eubalaena australis*	Endangered	Endangered
Speckled Warbler	*Chthonicola sagittata*	Vulnerable	Not Listed
Sperm Whale	*Physeter macrocephalus*	Vulnerable	Not Listed
Spotted Harrier	*Circus assimilis*	Vulnerable	Not Listed

Common name	Scientific name	TSC Act	EPBC Act
Spotted-tailed Quoll	*Dasyurus maculatus*	Vulnerable	Endangered
Square-tailed Kite	*Lophoictinia isura*	Vulnerable	Not Listed
Squirrel Glider	*Petaurus norfolcensis*	Vulnerable	Not Listed
Star Finch	*Neochmia ruficauda*	Endangered	Endangered
Streaked Shearwater	*Calonectris leucomelas*	Not Listed	Migratory
Striated Fieldwren	*Calamanthus fuliginosus*	Endangered	Not Listed
Stuttering Frog	*Mixophyes balbus*	Endangered	Vulnerable
Superb Fruit-Dove	*Ptilinopus superbus*	Vulnerable	Not Listed
Superb Parrot	*Polytelis swainsonii*	Vulnerable	Vulnerable
Swift Parrot	*Lathamus discolor*	Endangered	Endangered
Tasmanian Bettong	*Bettongia gaimardi*	Endangered	Extinct
Terek Sandpiper	*Xenus cinereus*	Vulnerable	Migratory
Turquoise Parrot	*Neophema pulchella*	Vulnerable	Not Listed
Varied Sittella	*Daphoenositta chrysoptera*	Vulnerable	Not Listed
Wallum Froglet	*Crinia tinnula*	Vulnerable	Not Listed
Wandering Albatross	*Diomedea exulans*	Endangered	Endangered
Wandering Tattler	*Tringa incana*	Not Listed	Migratory
Wedge-tailed Shearwater	*Ardenna pacificus*	Not Listed	Migratory
Western Sandpiper	*Calidris mauri*	Not Listed	Migratory
Whimbrel	*Numenius phaeopus*	Not Listed	Migratory
White Tern	*Gygis alba*	Vulnerable	Not Listed
White-bellied Sea-Eagle	*Haliaeetus leucogaster*	Not Listed	Migratory
White-bellied Storm-Petrel	*Fregetta grallaria*	Vulnerable	Vulnerable
White-footed Dunnart	*Sminthopsis leucopus*	Vulnerable	Not Listed
White-fronted Chat	*Epthianura albifrons*	Vulnerable	Not Listed
White-tailed Tropicbird	*Phaethon lepturus*	Not Listed	Migratory
White-throated Needletail	*Hirundapus caudacutus*	Not Listed	Migratory
White-winged Black Tern	*Chlidonias leucopterus*	Not Listed	Migratory
Wilson's Storm-Petrel	*Oceanites oceanicus*	Not Listed	Migratory
Wompoo Fruit-Dove	*Ptilinopus magnificus*	Vulnerable	Not Listed
Wood Sandpiper	*Tringa glareola*	Not Listed	Migratory
Yellow Wagtail	*Motacilla flava*	Not Listed	Migratory
Yellow-bellied Glider	*Petaurus australis*	Vulnerable	Not Listed
Yellow-bellied Sheathtail-bat	*Saccolaimus flaviventris*	Vulnerable	Not Listed

[a] NSW's *Threatened Species Conservation Act 1995* (TSC Act)
[b] the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)
Data: NSW Environment and Heritage (2014)

Table 25 Threatened fungi species within the Sydney Basin bioregion

Threatened fungi species listed under the TSC Act[a] that are known or predicted to lie within the Sydney Basin bioregion – none were listed under the EPBC Act[b]. Typology and punctuation are given as they are used in the legislation.

Scientific name	TSC Act
Camarophyllopsis kearneyi	Endangered
Hygrocybe anomala var. ianthinomarginata	Vulnerable
Hygrocybe aurantipes	Vulnerable
Hygrocybe austropratensis	Endangered
Hygrocybe collucera	Endangered
Hygrocybe griseoramosa	Endangered
Hygrocybe lanecovensis	Endangered
Hygrocybe reesiae	Vulnerable
Hygrocybe rubronivea	Vulnerable

[a] NSW's *Threatened Species Conservation Act 1995* (TSC Act)
[b] the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)
Data: NSW Environment and Heritage (2014)

Table 26 Threatened plant species known to occur within the Sydney Basin bioregion

Threatened plant species listed under either the TSC Act[a] or the EPBC Act[b] known to live within the Sydney Basin bioregion. Typology and punctuation are given as they are used in the legislation.

Common name[c]	Scientific name	TSC Act	EPBC Act
	Acacia baueri subsp. *aspera*	Vulnerable	Not Listed
	Acacia gordonii	Endangered	Endangered
	Acrophyllum australe	Vulnerable	Vulnerable
Albatross Mallee	*Eucalyptus langleyi*	Vulnerable	Vulnerable
	Allocasuarina glareicola	Endangered	Endangered
	Amperea xiphoclada var. *pedicellata*	Endangered	Extinct
	Ancistrachne maidenii	Vulnerable	Not Listed
Angus's Onion Orchid	*Microtis angusii*	Endangered	Endangered
	Asterolasia buxifolia	Endangered	Not Listed
	Asterolasia elegans	Endangered	Endangered
Austral Pillwort	*Pilularia novae-hollandiae*	Endangered	Not Listed
Austral Toadflax	*Thesium australe*	Vulnerable	Vulnerable
Australian Saltgrass	*Distichlis distichophylla*	Endangered	Not Listed
	Baeckea kandos	Endangered	Endangered
Bargo Geebung	*Persoonia bargoensis*	Endangered	Vulnerable
Bauer's Midge Orchid	*Genoplesium baueri*	Endangered	Endangered
Beadle's Grevillea	*Grevillea beadleana*	Endangered	Endangered
Biconvex Paperbark	*Melaleuca biconvexa*	Vulnerable	Vulnerable
Black Gum	*Eucalyptus aggregata*	Vulnerable	Not Listed
Black-eyed Susan	*Tetratheca juncea*	Vulnerable	Vulnerable
Black-hooded Sun Orchid	*Thelymitra atronitida*	Endangered	Not Listed
Bluegrass	*Dichanthium setosum*	Vulnerable	Vulnerable
Bomaderry Zieria	*Zieria baeuerlenii*	Endangered	Endangered
Botany Bay Bearded Orchid	*Pterostylis* sp. Botany Bay	Endangered	Endangered
Bristly Shield Fern	*Lastreopsis hispida*	Endangered	Not Listed
Broad-leaved Sally	*Eucalyptus aquatica*	Vulnerable	Vulnerable
Broken Back Ironbark	*Eucalyptus fracta*	Vulnerable	Not Listed
Brown Pomaderris	*Pomaderris brunnea*	Endangered	Vulnerable
Budawangs Bush-pea	*Pultenaea baeuerlenii*	Vulnerable	Vulnerable
Budawangs Cliff-heath	*Budawangia gnidioides*	Vulnerable	Vulnerable
Buttercup Doubletail	*Diuris aequalis*	Endangered	Vulnerable
Bynoe's Wattle	*Acacia bynoeana*	Endangered	Vulnerable
Caley's Grevillea	*Grevillea caleyi*	Endangered	Endangered

Common name[c]	Scientific name	TSC Act	EPBC Act
Tree-fern Calomnion	*Calomnion complanatum*	Endangered	Not Listed
Cambage Kunzea	*Kunzea cambagei*	Vulnerable	Vulnerable
Camden White Gum	*Eucalyptus benthamii*	Vulnerable	Vulnerable
Camfield's Stringybark	*Eucalyptus camfieldii*	Vulnerable	Vulnerable
Capertee Stringybark	*Eucalyptus cannonii*	Vulnerable	Not Listed
Carrington Falls Grevillea	*Grevillea rivularis*	Endangered	Endangered
Carrington Falls Pomaderris	*Pomaderris walshii*	Endangered	Not Listed
Chef's Cap Correa	*Correa baeuerlenii*	Vulnerable	Vulnerable
Clandulla Geebung	*Persoonia marginata*	Vulnerable	Vulnerable
Coast Groundsel	*Senecio spathulatus*	Endangered	Not Listed
Cotoneaster Pomaderris	*Pomaderris cotoneaster*	Endangered	Endangered
Coveny's Zieria	*Zieria covenyi*	Endangered	Endangered
Creek Triplarina	*Triplarina imbricata*	Endangered	Endangered
Dark Greenhood	*Pterostylis nigricans*	Vulnerable	Not Listed
	Darwinia biflora	Vulnerable	Vulnerable
	Darwinia glaucophylla	Vulnerable	Not Listed
	Darwinia peduncularis	Vulnerable	Not Listed
Deane's Boronia	*Boronia deanei*	Vulnerable	Vulnerable
Deane's Paperbark	*Melaleuca deanei*	Vulnerable	Vulnerable
Dense Cord-rush	*Baloskion longipes*	Vulnerable	Vulnerable
	Derwentia blakelyi	Vulnerable	Not Listed
	Deyeuxia appressa	Endangered	Endangered
	Dillwynia tenuifolia	Vulnerable	Not Listed
	Diuris bracteata	Endangered	Extinct
Downy Wattle	*Acacia pubescens*	Vulnerable	Vulnerable
Dwarf Kerrawang	*Commersonia prostrata*	Endangered	Endangered
Dwarf Mountain Pine	*Pherosphaera fitzgeraldii*	Endangered	Endangered
Dwarf Phyllota	*Phyllota humifusa*	Vulnerable	Vulnerable
East Lynne Midge Orchid	*Genoplesium vernale*	Vulnerable	Vulnerable
Eastern Australian Underground Orchid	*Rhizanthella slateri*	Vulnerable	Endangered
Elusive Bush-pea	*Pultenaea elusa*	Endangered	Endangered
	Epacris hamiltonii	Endangered	Endangered
	Epacris purpurascens var. *purpurascens*	Vulnerable	Not Listed
Ettrema Mallee	*Eucalyptus sturgissiana*	Vulnerable	Not Listed
	Eucalyptus copulans	Endangered	Endangered

Common name[c]	Scientific name	TSC Act	EPBC Act
	Eucalyptus sp. Cattai	Endangered	Not Listed
	Eucalyptus sp. Howes Swamp Creek	Endangered	Endangered
	Euphrasia bowdeniae	Vulnerable	Vulnerable
Evans Grevillea	*Grevillea evansiana*	Vulnerable	Vulnerable
Evans Sedge	*Lepidosperma evansianum*	Vulnerable	Not Listed
Few-seeded Bossiaea	*Bossiaea oligosperma*	Vulnerable	Vulnerable
Fletcher's Drumsticks	*Isopogon fletcheri*	Vulnerable	Vulnerable
Flockton Wattle	*Acacia flocktoniae*	Vulnerable	Vulnerable
	Grevillea divaricata	Endangered	Not Listed
	Grevillea obtusiflora	Endangered	Endangered
	Grevillea parviflora subsp. *supplicans*	Endangered	Not Listed
	Grevillea shiressii	Vulnerable	Vulnerable
Grove's Paperbark	*Melaleuca groveana*	Vulnerable	Not Listed
	Gyrostemon thesioides	Endangered	Not Listed
Hairy Geebung	*Persoonia hirsuta*	Endangered	Endangered
	Haloragodendron lucasii	Endangered	Endangered
Hartman's Sarcochilus	*Sarcochilus hartmannii*	Vulnerable	Vulnerable
Heath Wrinklewort	*Rutidosis heterogama*	Vulnerable	Vulnerable
	Hibbertia puberula	Endangered	Not Listed
Hibbertia sp. Bankstown	*Hibbertia* sp. Bankstown	Endangered	Critically Endangered
	Hibbertia stricta subsp. *furcatula*	Endangered	Not Listed
	Hibbertia superans	Endangered	Not Listed
Hoary Sunray	*Leucochrysum albicans* var. *tricolor*	Not Listed	Endangered
	Hypsela sessiliflora	Endangered	Extinct
Illawarra Greenhood	*Pterostylis gibbosa*	Endangered	Endangered
Illawarra Irene	*Irenepharsus trypherus*	Endangered	Endangered
Illawarra Socketwood	*Daphnandra johnsonii*	Endangered	Endangered
Illawarra Zieria	*Zieria granulata*	Endangered	Endangered
Jervis Bay Leek Orchid	*Prasophyllum affine*	Endangered	Endangered
Julian's Hibbertia	*Hibbertia* sp. *Turramurra*	Endangered	Not Listed
Juniper-leaved Grevillea	*Grevillea juniperina* subsp. *juniperina*	Vulnerable	Not Listed
Kanangra Wattle	*Acacia clunies-rossiae*	Vulnerable	Not Listed
Kangaloon Sun Orchid	*Thelymitra kangaloonica*	Endangered	Critically Endangered
	Kennedia retrorsa	Vulnerable	Vulnerable
Klaphake's Sedge	*Carex klaphakei*	Endangered	Not Listed
Kowmung Hakea	*Hakea dohertyi*	Endangered	Endangered

Common name[c]	Scientific name	TSC Act	EPBC Act
	Kunzea rupestris	Vulnerable	Vulnerable
	Lasiopetalum joyceae	Vulnerable	Vulnerable
Leafless Tongue Orchid	*Cryptostylis hunteriana*	Vulnerable	Vulnerable
Leafy Peppercress	*Lepidium foliosum*	Endangered	Not Listed
	Leionema lachnaeoides	Endangered	Endangered
	Leptospermum deanei	Vulnerable	Vulnerable
Lesser Creeping Fern	*Arthropteris palisotii*	Endangered	Not Listed
	Leucopogon fletcheri subsp. *fletcheri*	Endangered	Not Listed
Magenta Lilly Pilly	*Syzygium paniculatum*	Endangered	Vulnerable
Matted Bush-pea	*Pultenaea pedunculata*	Endangered	Not Listed
	Maundia triglochinoides	Vulnerable	Not Listed
Megalong Valley Bottlebrush	*Callistemon megalongensis*	Endangered	Not Listed
	Micromyrtus blakelyi	Vulnerable	Vulnerable
	Micromyrtus minutiflora	Endangered	Vulnerable
Mittagong Geebung	*Persoonia glaucescens*	Endangered	Vulnerable
Monga Tea Tree	*Leptospermum thompsonii*	Vulnerable	Vulnerable
Mount Vincent Mint-bush	*Prostanthera stricta*	Vulnerable	Vulnerable
Musty Leek Orchid	*Prasophyllum pallens*	Vulnerable	Not Listed
Narrabarba Wattle	*Acacia constablei*	Vulnerable	Vulnerable
Narrow-leaf Finger Fern	*Grammitis stenophylla*	Endangered	Not Listed
Narrow-leafed Wilsonia	*Wilsonia backhousei*	Vulnerable	Not Listed
Narrow-leaved Black Peppermint	*Eucalyptus nicholii*	Vulnerable	Vulnerable
Needle Geebung	*Persoonia acerosa*	Vulnerable	Vulnerable
Netted Bottle Brush	*Callistemon linearifolius*	Vulnerable	Not Listed
Nielsen Park She-oak	*Allocasuarina portuensis*	Endangered	Endangered
Nodding Geebung	*Persoonia nutans*	Endangered	Endangered
Nowra Heath Myrtle	*Triplarina nowraensis*	Endangered	Endangered
	Olearia cordata	Vulnerable	Vulnerable
Orara Boronia	*Boronia umbellata*	Vulnerable	Vulnerable
Parris' Bush-pea	*Pultenaea parrisiae*	Vulnerable	Vulnerable
	Persoonia hindii	Endangered	Not Listed
	Persoonia laxa	Endangered	Extinct
	Persoonia mollis subsp. *maxima*	Endangered	Endangered
	Phebalium bifidum	Endangered	Not Listed
	Philotheca ericifolia	Not Listed	Vulnerable
	Pimelea curviflora var. *curviflora*	Vulnerable	Vulnerable

Common name[c]	Scientific name	TSC Act	EPBC Act
Pretty Beard Orchid	*Calochilus pulchellus*	Endangered	Not Listed
Prickly Bush-pea	*Pultenaea aristata*	Vulnerable	Vulnerable
	Pterostylis chaetophora	Vulnerable	Not Listed
	Pterostylis ventricosa	Endangered	Not Listed
	Pterostylis vernalis	Endangered	Critically Endangered
	Pultenaea parviflora	Endangered	Vulnerable
	Pultenaea sp. Genowlan Point	Endangered	Critically Endangered
	Pultenaea sp. Olinda	Endangered	Not Listed
Rainforest Cassia	*Senna acclinis*	Endangered	Not Listed
Round-leafed Wilsonia	*Wilsonia rotundifolia*	Endangered	Not Listed
Rylstone Bell	*Leionema sympetalum*	Vulnerable	Vulnerable
Sand Doubletail	*Diuris arenaria*	Endangered	Not Listed
Sand Spurge	*Chamaesyce psammogeton*	Endangered	Not Listed
Seaforth Mintbush	*Prostanthera marifolia*	Endangered	Critically Endangered
Silky Pomaderris	*Pomaderris sericea*	Endangered	Vulnerable
Silky Swainson-pea	*Swainsona sericea*	Vulnerable	Not Listed
Silver-leafed Gum	*Eucalyptus pulverulenta*	Vulnerable	Vulnerable
Singleton Mint Bush	*Prostanthera cineolifera*	Vulnerable	Vulnerable
Slaty Leek Orchid	*Prasophyllum fuscum*	Endangered	Vulnerable
Small Pale Grass-lily	*Caesia parviflora* var. *minor*	Endangered	Not Listed
Small-flower Grevillea	*Grevillea parviflora* subsp. *parviflora*	Vulnerable	Vulnerable
Smooth Bush-Pea	*Pultenaea glabra*	Vulnerable	Vulnerable
	Solanum amourense	Endangered	Not Listed
	Solanum celatum	Endangered	Not Listed
Somersby Mintbush	*Prostanthera junonis*	Endangered	Endangered
Sparse Heath	*Epacris sparsa*	Vulnerable	Vulnerable
Spider orchid	*Dendrobium melaleucaphilum*	Endangered	Not Listed
Spiked Rice-flower	*Pimelea spicata*	Endangered	Endangered
Spreading Guinea Flower	*Hibbertia procumbens*	Endangered	Not Listed
Square Raspwort	*Haloragis exalata* subsp. *exalata*	Vulnerable	Vulnerable
Sublime Point Pomaderris	*Pomaderris adnata*	Endangered	Not Listed
Sunshine Wattle	*Acacia terminalis* subsp. *terminalis*	Endangered	Endangered
Superb Midge Orchid	*Genoplesium superbum*	Endangered	Not Listed
Swamp Everlasting	*Xerochrysum palustre*	Not Listed	Vulnerable
Sydney Plains Greenhood	*Pterostylis saxicola*	Endangered	Endangered
Tall Knotweed	*Persicaria elatior*	Vulnerable	Vulnerable

Common name[c]	Scientific name	TSC Act	EPBC Act
Tallong Midge Orchid	*Genoplesium plumosum*	Endangered	Endangered
Tangled Bedstraw	*Galium australe*	Endangered	Not Listed
	Tetratheca glandulosa	Vulnerable	Not Listed
Thick Lip Spider Orchid	*Caladenia tessellata*	Endangered	Vulnerable
Thick-leaf Star-hair	*Astrotricha crassifolia*	Vulnerable	Vulnerable
	Prostanthera askania	Endangered	Endangered
	Velleia perfoliata	Vulnerable	Vulnerable
Velvet Zieria	*Zieria murphyi*	Vulnerable	Vulnerable
Villous Mint-bush	*Prostanthera densa*	Vulnerable	Vulnerable
Wallangarra White Gum	*Eucalyptus scoparia*	Endangered	Vulnerable
Warty Zieria	*Zieria tuberculata*	Vulnerable	Vulnerable
Waterfall Greenhood	*Pterostylis pulchella*	Vulnerable	Vulnerable
White-flowered Wax Plant	*Cynanchum elegans*	Endangered	Endangered
Wingecarribee Gentian	*Gentiana wingecarribiensis*	Endangered	Endangered
Wingecarribee Leek Orchid	*Prasophyllum uroglossum*	Endangered	Endangered
Wingello Grevillea	*Grevillea molyneuxii*	Vulnerable	Endangered
Wollemi Mint-bush	*Prostanthera cryptandroides* subsp. *cryptandroides*	Vulnerable	Vulnerable
Woronora Beard-heath	*Leucopogon exolasius*	Vulnerable	Vulnerable
	Xanthosia scopulicola	Vulnerable	Not Listed
Yellow Loosestrife	*Lysimachia vulgaris* var. *davurica*	Endangered	Not Listed
	Zannichellia palustris	Endangered	Not Listed
	Zieria involucrata	Endangered	Vulnerable

[a] NSW's *Threatened Species Conservation Act 1995* (the TSC Act)
[b] the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act)
[c] many plant species are not known by common names
Data: NSW Environment and Heritage (2014)

1.1.7.3 Aquatic species and communities

1.1.7.3.1 Wetlands

Several wetlands in the Sydney Basin bioregion (as defined for use in the Sydney Basin Bioregional Assessment) are regarded as being bioregionally significant. In the south of the bioregion, Swan Lake provides important breeding habitat for prawns and fish and is a key feeding and roosting area for waterfowl. Lake Conjola provides nesting habitat for a number of threatened shorebirds including the endangered little tern (*Sterna albifrons*) and hooded plover (*Thinornis rubricollis*) as well as the vulnerable pied oystercatcher (*Haematopus longirostris*). Both lakes also support significant areas of seagrass.

Narrabeen Lagoon and Deep Creek support the state-listed (TSC Act) threatened black bittern (*Ixobrychus flavicollis*), Australasian bittern (*Botaurus poiciloptilus*), osprey (*Pandion haliaetus*) and glossy black cockatoo (*Calyptorhynchus lathami*). The Australian bittern is also a nationally listed (EPBC Act) threatened species. Brundee Swamp also provides habitat for the Australasian bittern.

Bakers Lagoon, near Richmond, supports a range of important species listed under the TSC Act including the vulnerable freckled duck, Australasian bittern, black-tailed godwit (*Limosa limosa*), black bittern and the endangered black-necked stork (*Ephippiorhynchus asiaticus*). The black-tailed godwit is also listed as a threatened migratory species under the EPBC Act.

The Sydney Basin bioregion is densely populated and disturbances and threats to the wetlands are many and varied. They include impacts from urban, agricultural and industrial development such as decreased water quality resulting from runoff from urban areas, industrial areas, agricultural lands and rubbish tips, as well as stormwater and wet weather overflows. Potential spills from shipping and industries can also pose a serious risk to wetland health. Other threats include feral animals and exotic weeds, changed fire regimes, sedimentation, salinity, weir construction and mining development.

1.1.7.3.2 Groundwater-dependent ecosystems

Within the Sydney Basin bioregion, flora and fauna species and communities are dependent on sources of water in addition to rainfall to survive. These sources might include surface water from streams and wetlands or groundwater either directly from subsurface aquifers, river baseflow or through springs. Such species and communities are referred to as groundwater-dependent ecosystems (Figure 49). Richardson et al. (2011) define groundwater-dependent ecosystems as ‘natural ecosystems that require access to groundwater to meet all or some of their water requirements on a permanent or intermittent basis so as to maintain their communities of plants and animals, ecosystem processes and ecosystem services’. The *National Atlas of Groundwater Dependent Ecosystems* (Bureau of Meteorology, 2012) highlights 125 rivers, 75 wetlands, two springs, one lake and 310 vegetation communities as groundwater-dependent ecosystems in the Sydney Basin bioregion.

Within the groundwater dependent ecosystems (GDEs), upland swamps are of particular interest because of their high vulnerability to impacts from longwall mining (Krogh, 2012). Upland swamps have high plant species diversity (Keith and Myerscough, 1993) and have an important role in catchment hydrodynamics and the maintenance of potable water supplies (Krogh, 2007). Upland swamps in the Sydney Basin bioregion generally develop on gentle slopes, within or adjacent to low-order streams where stream-power is relatively low (Tomkins and Humphreys, 2006). The swamp substrate consists of coarse-grained, quartzose sand and peat, often bound at the surface by a peaty mat (Keith and Myerscough 1993; Tomkins and Humphreys, 2006). Any activity that results in conversion of perched watertable flows into subsurface flows (including damage to confining aquicludes, aquitards and peat substrates as a result of longwall mining) will significantly change the water balance of upland swamps and may pose an irreversible threat to the integrity of the swamp ecosystems (Benson and Baird, 2012). Upland swamps in the Sydney Basin bioregion are listed in the EPBC Act as two threatened ecological communities (TEC).

The ‘Temperate Highland Peat Swamps on Sandstone’ TEC incorporates the ‘Montane Peatlands and Swamps of the New England Tableland, NSW North Coast, Sydney Basin, South East Corner, South Eastern Highlands and Australian Alps bioregions’, the ‘Newnes Plateau Shrub Swamp in the

Sydney Basin Bioregion', and the 'Blue Mountains Swamps in the Sydney Basin Bioregion' ecological communities (Table 22). Of the 3000 ha of this TEC, approximately 1300 ha are reserved in the Blue Mountains National Park, with the rest in a mix of freehold, state forests, and crown land (TSSC, 2005). Nationally threatened plant species and animal species known to inhabit this TEC include the Blue Mountains Water Skink (*Eulamprus leuraensis*), Giant Burrowing Frog (*Heleioporus australiacus*), Wingecarribee Leek Orchid (*Prasophyllum uroglossum*), and Wingecarribee Gentian (*Gentiana wingecarribiensis*). The swamps of this ecological community occur across a range of locations in the landscape, from 'hanging swamps' to depressions in the landscape, or along watercourses. Hanging swamps occur on sloping rock and/or cliff faces, and are particularly vulnerable to changes in water regime because they rely predominantly on groundwater discharge to sustain them. The discharging groundwater is most likely derived from perched watertables that develop over impervious geological layers. Water supply to hanging swamps is particularly vulnerable to fracturing caused by subsidence, which can reduce their water holding capacity or modify the groundwater flow paths that naturally replenish them. Hanging swamps have been identified in the Blue Mountains, on the Newnes Plateau and in the Bargo and Cataract gorges on the Woronora Plateau (Commonwealth of Australia, 2014). Blue Mountains and Newnes Plateau hanging swamps contain open heath vegetation communities that are dominated by shrubs or sedges (Commonwealth of Australia, 2014). Two threatened vegetation species, *Epacris hamiltonii* (endangered under the TSC Act and the EPBC Act) and *Pherosphaera fitzgeraldii,* are reported to depend on continual seepage from hanging swamps (Blue Mountains City Council, 2009). Hanging swamps provide unique habitat for the giant dragonfly (*Petalura gigantea*) and the red-crowned toadlet (*Pseudophyrne australis*), in addition to the giant burrowing frog and Blue Mountains Water Skink.

The 'Coastal Upland Swamps in the Sydney Basin Bioregion' TEC is listed under the same name on the New South Wales list of endangered ecological communities (Table 22). The community occurs primarily on poorly permeable sandstone plateaux in the low relief headwater valleys of streams and on sandstone benches with abundant seepage moisture, mainly at elevations of 200 to 450 mASL (Keith and Myerscough, 1993). In the south of the bioregion it primarily occurs on the Woronora Plateau, and in the north of the bioregion, it is mainly on the Somersby-Hornsby plateaux. Vegetation types include open graminoid heath, sedgeland and tall scrub (TSSC, 2014). Coastal Upland Swamp in the Sydney Basin bioregion provides habitat to a wide variety of birds, mammals, amphibians, reptiles and invertebrate species. Threatened species that have been recorded in the community include prickly bush-pea (*Pultenaea aristata*), giant burrowing frog, red-crowned toadlet, Rosenberg's goanna (*Varanus rosenbergi*), the green and golden bell frog (*Litoria aurea*), the eastern ground parrot (*Pezoporus wallicus wallicus*) and the giant dragonfly (NSW Environment and Heritage, 2012).

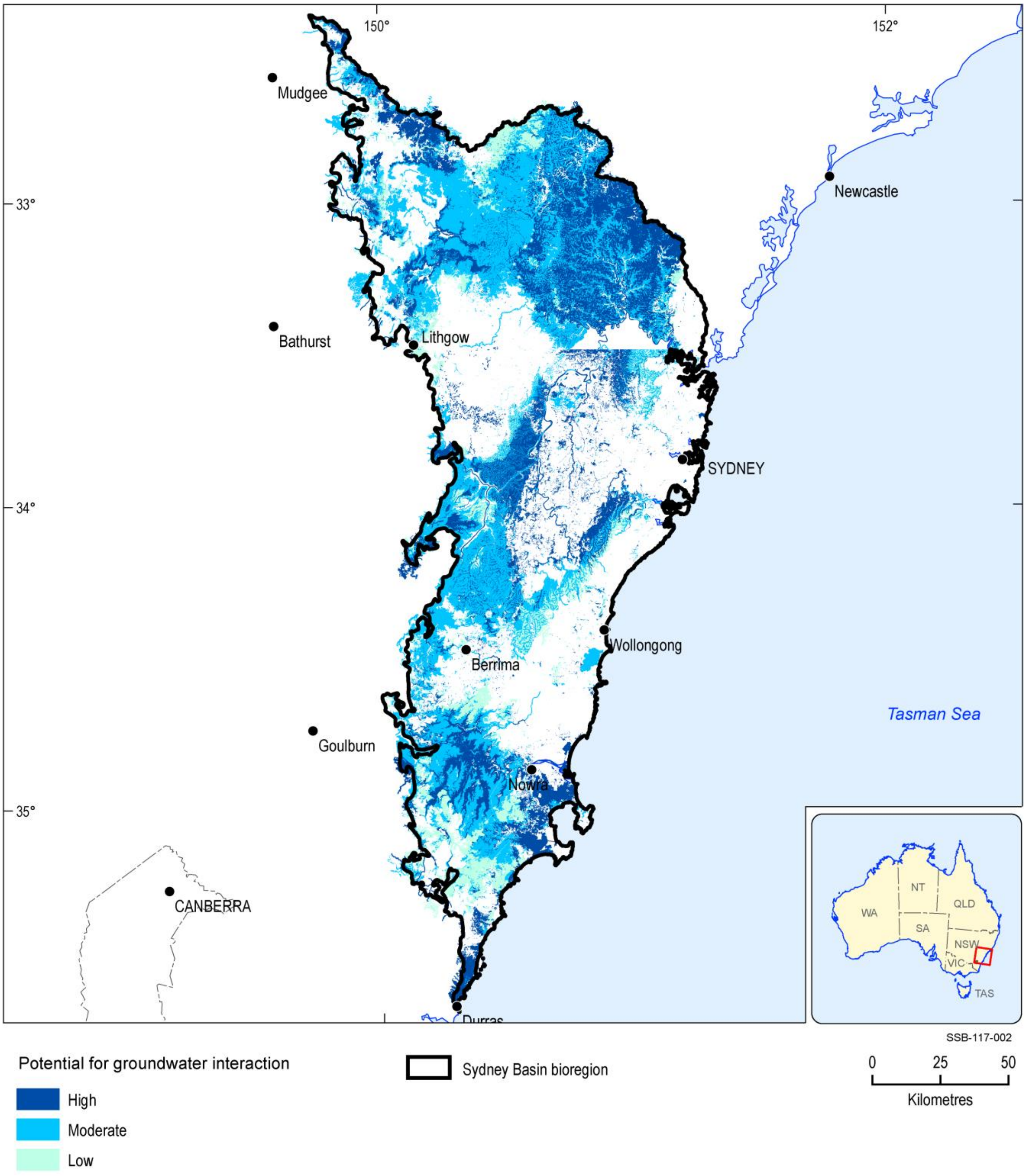

Figure 49 Surface and subsurface groundwater-dependent ecosystems within the Sydney Basin bioregion

As identified in *The National Atlas of Groundwater Dependent Ecosystems* (Bureau of Meteorology, 2013)
Data: Bioregional Assessment Programme (Dataset 2)

1.1.7.3.3 Freshwater species

Three endangered, or critically endangered, freshwater species are listed under NSW’s *Fisheries Management Act 1994*. The Macquarie perch (*Macquaria australasica*) is present in both lake and river habitats in the Hawkesbury-Nepean region. The purple spotted gudgeon (*Mogurnda* *adspersa)* is a benthic species found in slow moving streams or billabongs and it is thought to be present in the Tweed, Richmond and Brunswick River catchments. The Fitzroy Falls spiny crayfish is restricted to a few locations along the Wildes Meadow Creek in the NSW Southern Highlands. It prefers flowing water and is threatened by reservoir construction and predation by the introduced yabbie (*Cherax destructor*).

1.1.7.4 Environmental flows

Two of the objectives of NSW's *Water Sharing Plan for the Greater Metropolitan Unregulated River Water Sources 2011* pertain to environmental objectives: Objective (C) is to 'protect, preserve, maintain and enhance the important river flow dependent and high priority groundwater-dependent ecosystems of these water sources' and Objective (O) is to 'implement Government decisions on environmental flow regimes for the Upper Nepean and Upstream Warragamba Water Source, the Hawkesbury and Lower Nepean Rivers Water Source, the Southern Sydney Rivers Water Source and the Shoalhaven River Water Source'. Their purpose is to maintain the overall health of rivers in the region and to protect wetlands, lakes, estuaries and floodplains that rely on river flow to sustain them (NSW Office of Water, 2011).

Environmental flows are allocated based on the premise that ecosystem health will be maintained by setting annual extraction limits and 'cease-to-pump' levels which prevent pumping when river levels are low. Daily releases of environmental flows from a number of water storages that feed into the Shoalhaven, Upper Nepean, Upstream Warragamba, Hawkesbury and Lower Nepean rivers are also specified in the water sharing plan, for example:

- Fitzroy Falls Reservoir and Tallowa Dam into Shoalhaven River
- Wingecarribee and Thompsons Creek reservoirs; Pheasants Nest and Broughtons Pass weirs; Lake Lyall; Lake Wallace; Cordeaux, Cataract, Nepean and Avon dams into the Upper Nepean and Upstream Warragamba water source
- Menangle, Camden, Sharpes, Cobbity, Mount Hunter Rivulet, Brownlow Hill, Theresa Park, Wallacia weirs that flow into the Hawkesbury and Lower Nepean rivers.

The environmental flow protection rules developed for the water sharing plan consider the occurrence of threatened frogs, macro-invertebrates, birds, fish, aquatic and riparian vegetation species, as well as endangered ecological communities and threatened populations. However, there has been minimal research or monitoring to ensure that the water sharing plan achieves its environmental objectives. An existing program is underway to better understand whether current environmental flow provisions sustain the target ecosystems in unregulated rivers (Brooks et al., 2010).

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