Australian Government

BIOREGIONAL ASSESSMENTS

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

Context statement for the Hunter subregion

Product 1.1 for the Hunter subregion from the Northern Sydney Basin Bioregional Assessment

24 April 2015

A scientific collaboration between the Department of the Environment, 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 direct, indirect and cumulative 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. The Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia are collaborating to undertake bioregional assessments. For more information, visit <http://www.bioregionalassessments.gov.au>.

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ISBN-PDF 978-1-925315-00-4

Citation

McVicar TR, Pinetown KL, Hodgkinson JH, Barron OV, Rachakonda PK, Zhang YQ, Dawes WR, Macfarlane C, Holland KL, Marvanek SP, Wilkes PG, Li LT and Van Niel TG (2015) Context statement for the Hunter subregion. Product 1.1 for the Hunter subregion from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia.

Authorship is listed in relative order of contribution.

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Cover photograph

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

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v20150428

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Contents

Figures

Tables

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Acknowledgements

This technical product was reviewed by several groups:

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The authors acknowledge and thank John Laurie and Bob Nicoll (Geoscience Australia) for creating Figure 33.

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.

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 direct, indirect and cumulative 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, 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:

- 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.

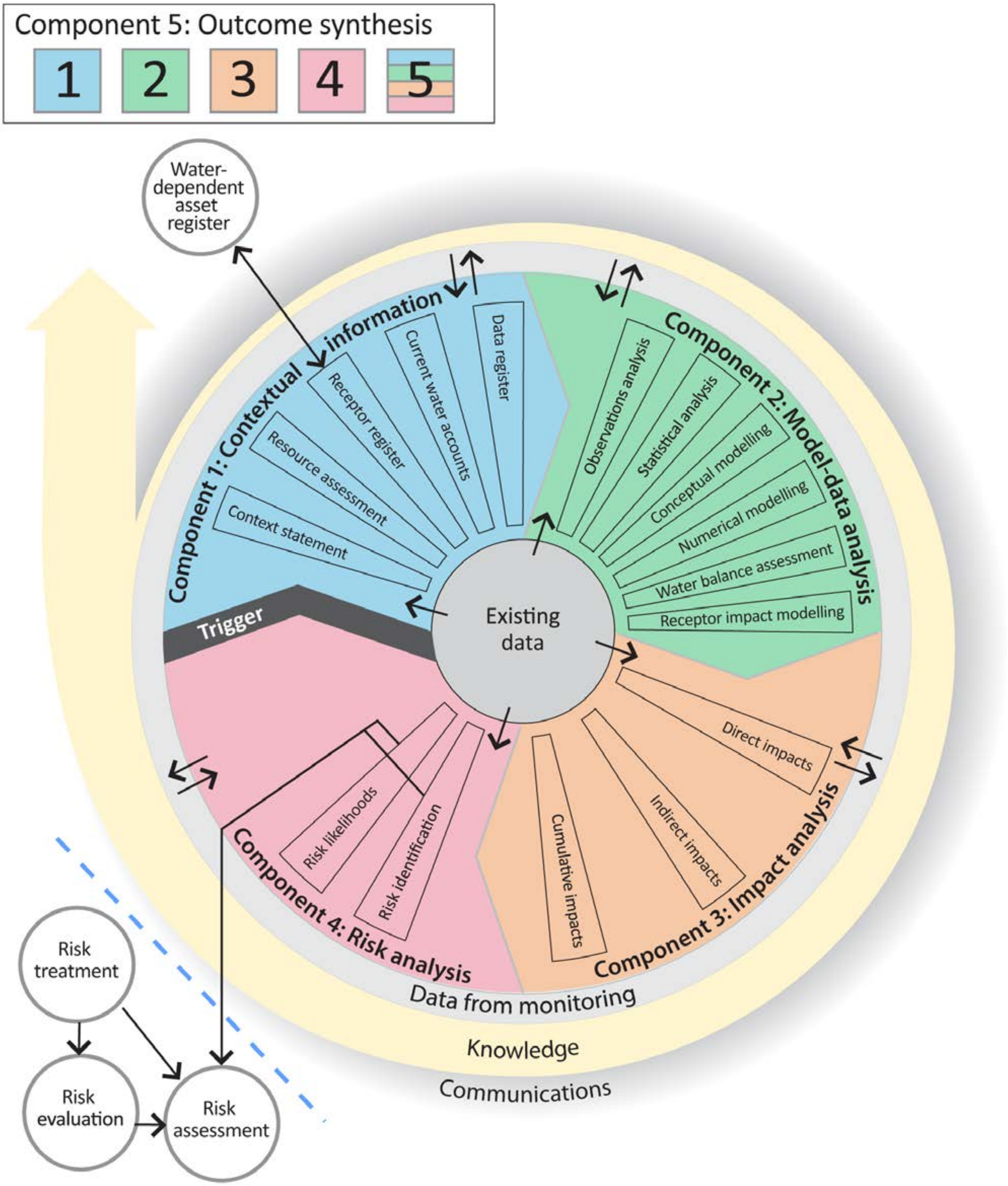

Figure 1 Schematic diagram of the bioregional assessment methodology

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

For transparency and to ensure consistency across all BAs, submethodologies have been developed to supplement the key approaches outlined in the *Methodology for bioregional assessments of the impact of coal seam gas and coal mining development on water resources* (Barrett et al., 2013). This series of submethodologies aligns with technical products as presented in Table 1. The submethodologies are not intended to be 'recipe books' nor to provide step-by-step instructions; rather they provide an overview of the approach to be taken. In some instances, methods applied for a particular BA may need to differ from what is proposed in the submethodologies – in this case an explanation will be supplied. Overall, the submethodologies are intended to provide a rigorously defined foundation describing how BAs are undertaken.

Table 1 Methodologies and associated technical products listed in Table 2

Code	Proposed title	Summary of content	Associated technical product
M01	*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	All
M02	*Compiling water-dependent assets*	Describes the approach for determining water-dependent assets	1.3 Description of the water-dependent asset register
M03	*Assigning receptors and impact variables to water-dependent assets*	Describes the approach for determining receptors associated with water-dependent assets	1.4 Description of the receptor register
M04	*Developing a coal resource development pathway*	Specifies the information that needs to be collected and reported in product 1.2 (i.e. known coal and coal seam gas resources as well as current and potential resource developments). Describes the process for determining the coal resource development pathway (reported in product 2.3)	1.2 Coal and coal seam gas resource assessment 2.3 Conceptual modelling
M05	*Developing the conceptual model for causal pathways*	Describes the development of the conceptual model for causal pathways, which summarises how the 'system' operates and articulates the links between coal resource developments and impacts on receptors	2.3 Conceptual modelling
M06	*Surface water modelling*	Describes the approach taken for surface water modelling across all of the bioregions and subregions. It covers the model(s) used, as well as whether modelling will be quantitative or qualitative.	2.6.1 Surface water numerical modelling
M07	*Groundwater modelling*	Describes the approach taken for groundwater modelling across all of the bioregions and subregions. It covers the model(s) used, as well as whether modelling will be quantitative or qualitative. It also considers surface water – groundwater interactions, as well as how the groundwater modelling is constrained by geology.	2.6.2 Groundwater numerical modelling

Code	Proposed title	Summary of content	Associated technical product
M08	*Receptor impact modelling*	Describes how to develop the receptor impact models that are required to assess the potential impacts from coal seam gas and large coal mining on receptors. Conceptual, semi-quantitative and quantitative numerical models are described.	2.7 Receptor impact modelling
M09	*Propagating uncertainty through models*	Describes the approach to sensitivity analysis and quantifying uncertainty in the modelled hydrological response to coal and coal seam gas development	2.3 Conceptual modelling 2.6.1 Surface water numerical modelling 2.6.2 Groundwater numerical modelling 2.7 Receptor impact modelling
M10	*Risk and cumulative impacts on receptors*	Describes the process to identify and analyse risk	3 Impact analysis 4 Risk analysis
M11	*Hazard identification*	Describes the process to identify potential water-related hazards from coal and coal seam gas development	2 Model-data analysis 3 Impact analysis 4 Risk analysis
M12	*Fracture propagation and chemical concentrations*	Describes the likely extent of both vertical and horizontal fractures due to hydraulic stimulation and the likely concentration of chemicals after production of coal seam gas	2 Model-data analysis 3 Impact analysis 4 Risk analysis

Each submethodology is available online at <http://www.bioregionalassessments.gov.au>. Submethodologies might be added in the future.

Technical products

The outputs of the BAs include a suite of technical products variously presenting information about the ecology, hydrology, hydrogeology and geology of a bioregion and the potential direct, indirect and cumulative 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 information flow within a BA. 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 rectangles in both Figure 2 and Table 2 indicate the information included in this technical product.

This technical product is delivered as a report (PDF). Additional material is also provided, as specified by the BA methodology:

- all unencumbered data syntheses and databases
- unencumbered tools, model code, procedures, routines and algorithms
- unencumbered forcing, boundary condition, parameter and initial condition datasets
- the workflow, comprising a record of all decision points along the pathway towards completion of the BA, gaps in data and modelling capability, and provenance of data.

The PDF of this technical product, and the additional material, are available online at <http://www.bioregionalassessments.gov.au>.

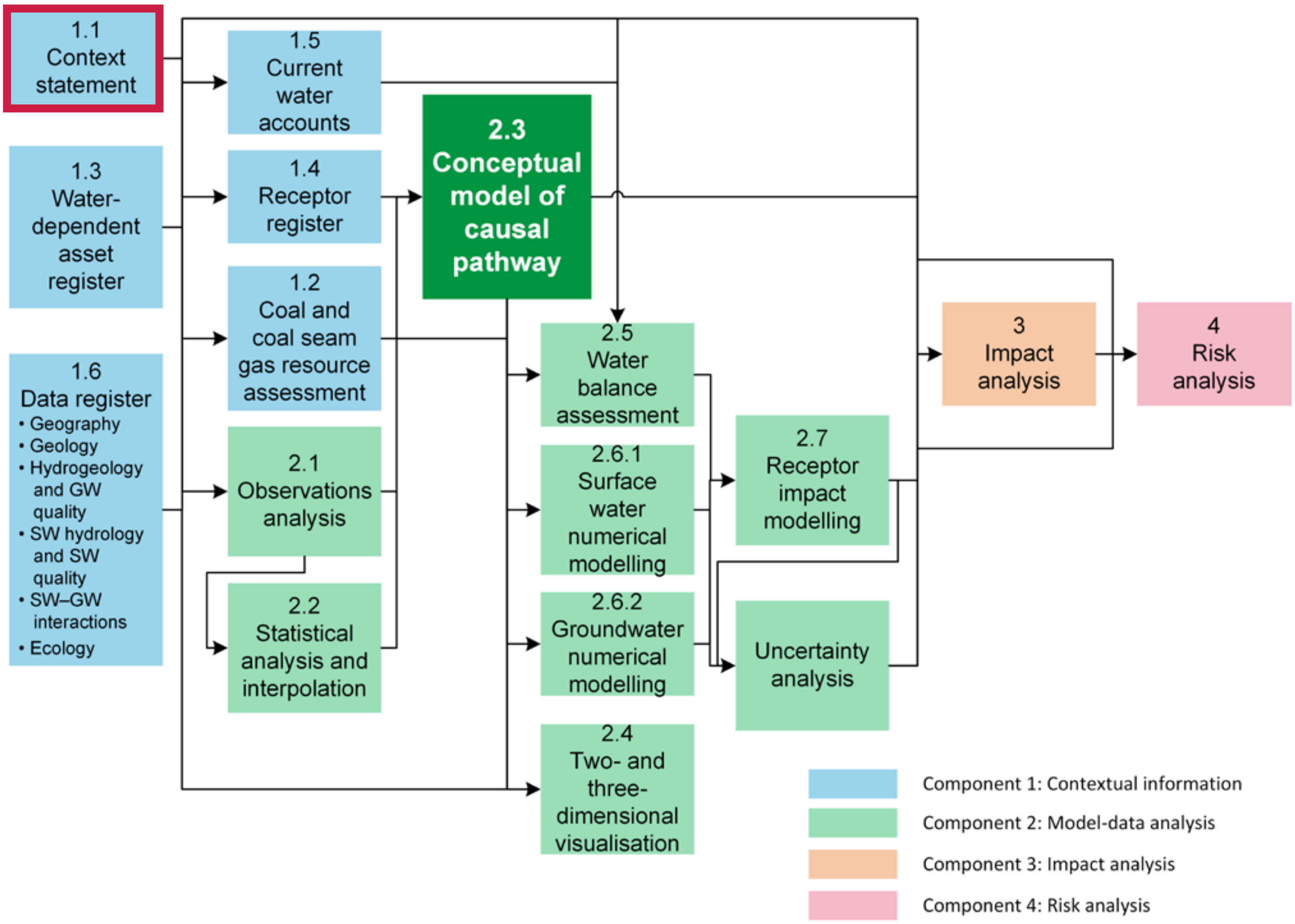

Figure 2 The simple decision tree indicates the flow of information through a bioregional assessment

The red rectangle indicates the information included in this technical product.

Table 2 Technical products being delivered as part of the Northern Sydney Basin Bioregional Assessment

For each subregion in the Northern Sydney Basin Bioregional Assessment, technical products will be delivered as data, summaries and reports (PDFs) as indicated by ■ in the last column of Table 2. The red rectangle indicates the information covered in this technical product. A suite of other technical and communication products – such as maps, registers and factsheets – will also be developed through the bioregional assessments.

Component	Product code	Information	Section in the BA methodology[a]	Report
Component 1: Contextual information for the Hunter subregion	1.1	Context statement	2.5.1.1, 3.2	■
	1.2	Coal and coal seam gas resource assessment	2.5.1.2, 3.3	■
	1.3	Description of the water-dependent asset register	2.5.1.3, 3.4	■
	1.4	Description of the receptor register	2.5.1.4, 3.5	■
	1.5	Current water accounts and water quality	2.5.1.5	■
	1.6	Data register	2.5.1.6	
Component 2: Model-data analysis for the Hunter subregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2	■
	2.3	Conceptual modelling	2.5.2.3, 4.3	■
	2.4	Two- and three-dimensional representations	4.2	[b]
	2.5	Water balance assessment	2.5.2.4	■
	2.6.1	Surface water numerical modelling	4.4	■
	2.6.2	Groundwater numerical modelling	4.4	■
	2.7	Receptor impact modelling	2.5.2.6, 4.5	■
Component 3: Impact analysis for the Hunter subregion	3	Impact analysis	5.2.1	■
Component 4: Risk analysis for the Hunter subregion	4	Risk analysis	2.5.4, 5.3	■
Component 5: Outcome synthesis for the Northern Sydney Basin bioregion	5	Outcome synthesis	2.5.5	■

[a] Barrett et al. (2013)

[b] The two- and three-dimensional representations will be delivered in products such as 2.3, 2.6.1 and 2.6.2.

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 'look and feel' 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.
- 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 Northern Sydney Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Contact <bioregionalassessments@bom.gov.au> to access metadata (including copyright, attribution and licensing information) for all datasets cited or used to make figures in this product. At a later date, this information, as well as all unencumbered datasets, will be published online

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 24 April 2015, <http://www.environment.gov.au/coal-seam-gas-mining/pubs/methodology-bioregional-assessments.pdf>.

1.1 Context statement for the Hunter subregion

The context statement brings together what is currently known about the geography, ecology, hydrology, geology and hydrogeology of a subregion or bioregion. 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. Information is collated that is relevant to interpret the impact analysis, risk analysis and outcomes of the bioregional assessment.

The context statement includes materially relevant characteristics of a subregion or 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.

No new analysis or modelling is presented in the context statement; rather it draws on existing information. Thus, some figures are reproduced from other sources and the look and feel 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 Hunter subregion is part of the Northern Sydney Basin bioregion (Figure 3). The Northern Sydney Basin bioregion is located north-west of Sydney in eastern Australia. The bioregion adjoins the Northern Inland Catchments bioregion in the north-east and the Sydney Basin bioregion in the south. The Northern Sydney Basin bioregion covers an area of about 17,390 km^2.

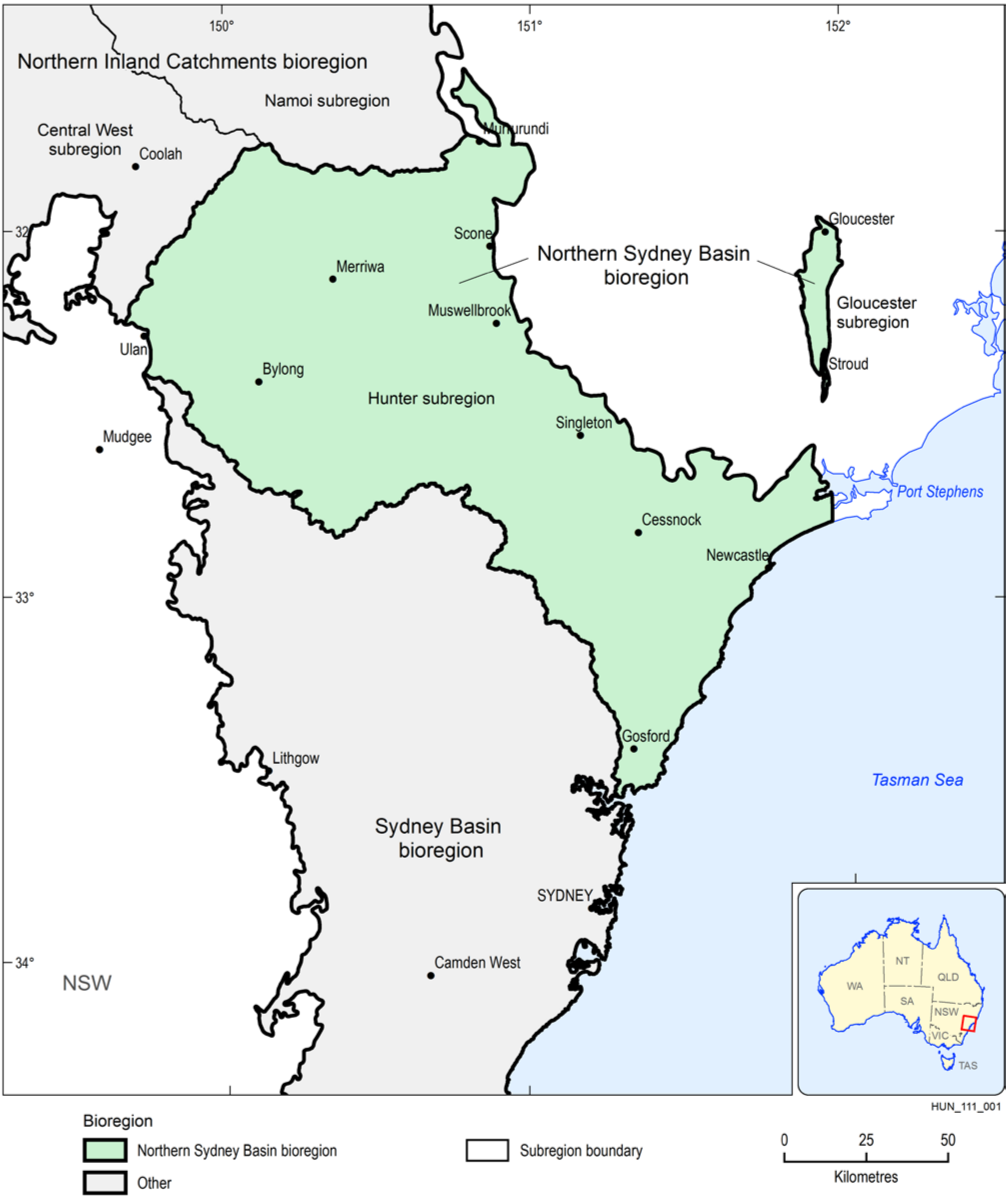

Figure 3 Hunter and Gloucester subregions in the Northern Sydney Basin bioregion

The adjacent Sydney Basin bioregion and subregions within the Northern Inland Catchments bioregion are also shown.

The Hunter subregion covers about 17,045 km^2. The Hunter subregion is defined from four data sources, being: (i) the geological Sydney Basin (Tadros, 1995), (ii) the geological Werrie Basin (Carey, 1934; DMR, 2002), (iii) the Hunter Central-Coast surface water catchments (Geoscience Australia, 2006) and (iv) the Australian coastline derived from the 1:250,000 topographic dataset (Geoscience Australia, 2006). These are shown in Figure 4.

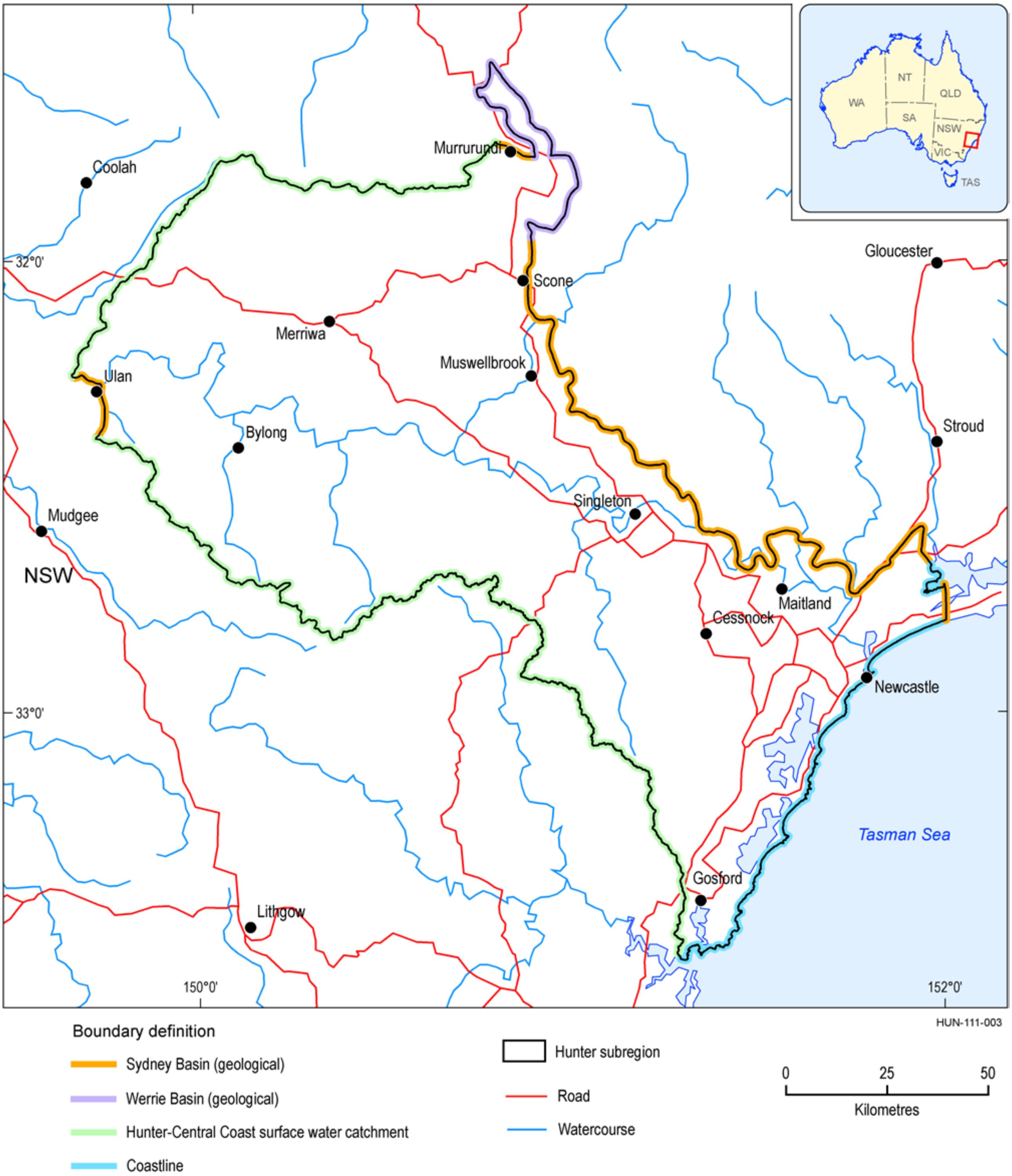

Figure 4 Boundary definitions of the Hunter subregion

Data: (i) Sydney Basin, Tadros (2005), (ii) Werrie Basin, Geoscience Australia (Dataset 1), (iii) the coastline and the Hunter-Central Coast surface water catchment boundaries, Geoscience Australia (Dataset 2)

The Werrie Basin is a transitional basin between the Sydney and Gunnedah geological basins and, due to its relatively small size, the Werrie Basin is not currently included in the Australian Geological Provinces Database (Geoscience Australia, 2013). As this feature is so small and ill defined, in some geological circles it is termed the Werrie Syncline. Definition of the Hunter subregion used a spatially disconnected part of the Gunnedah Basin (Geoscience Australia, 2009) with a boundary that closely resembles other more detailed definitions of the Werrie Basin (Carey, 1934; DMR, 2002).

The Hunter Central-Coast surface water catchments conform to the boundary of the area formerly managed by the Hunter-Central Rivers Catchment Management Authority (CMA; DIPNR, 2003). It was this CMA boundary that was used when the Hunter subregion was defined in 2012. From 1 January 2014, all CMAs in NSW transitioned into local land services (LLS) regions (NSW Government, 2014) and part of the Central-Coast portion of the Hunter subregion is now part of the Greater Sydney LLS region (Figure 5). However, as it was included in the Hunter-Central Rivers CMA boundary when the Hunter subregion was defined in 2012, it is maintained as part of the Hunter subregion.

1.1.1.1 *Definitions used*

There are a number of jurisdictional boundaries used in this context statement, including (i) 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 Hunter subregion are characterised below.

The Hunter subregion contains parts of five LLS regions (NSW Government, 2014) (Table 3 and Figure 5). Over 80% of the Hunter subregion is composed of the Hunter LLS region, with most of the remaining subregion area being accounted for by the Central Tablelands and Greater Sydney LLS regions, covering approximately 13 and 6.5% respectively (Table 3 and Figure 5).

Table 3 Local land services regions contained in the Hunter subregion

LLS[a] name	Area (ha)	Area in Hunter subregion (ha)	Percentage of LLS[a] in Hunter subregion (%)	Percentage of Hunter subregion (%)
Hunter	3,300,596	1,366,407	41.4%	80.2%
Greater Sydney	1,249,672	108,968	8.7%	6.4%
Central Tablelands	3,134,665	219,216	7.0%	12.9%
North West	8,244,281	9,482	0.1%	0.6%
Central West	9,161,893	332	0.0%	0.0%

These data are in descending order based on the ‘Percentage of LLS in Hunter subregion’ column.
[a] Local land services region
Data: NSW Trade and Investment (Dataset 3)

The Hunter subregion contains parts of 13 IBRA subregions (SEWPaC, 2012) (Figure 6 and Table 4). There are three IBRA subregions that are essentially wholly contained (i.e. >90%) in the Hunter subregion: Wyong, Hunter and Kerrabee. Almost 60% of the Liverpool Range IBRA subregion and 30% of the Yengo IBRA subregion are contained in the Hunter subregion. The names and relevant statistics for the eight remaining IBRA subregions contained within the Hunter subregion are provided in Table 4.

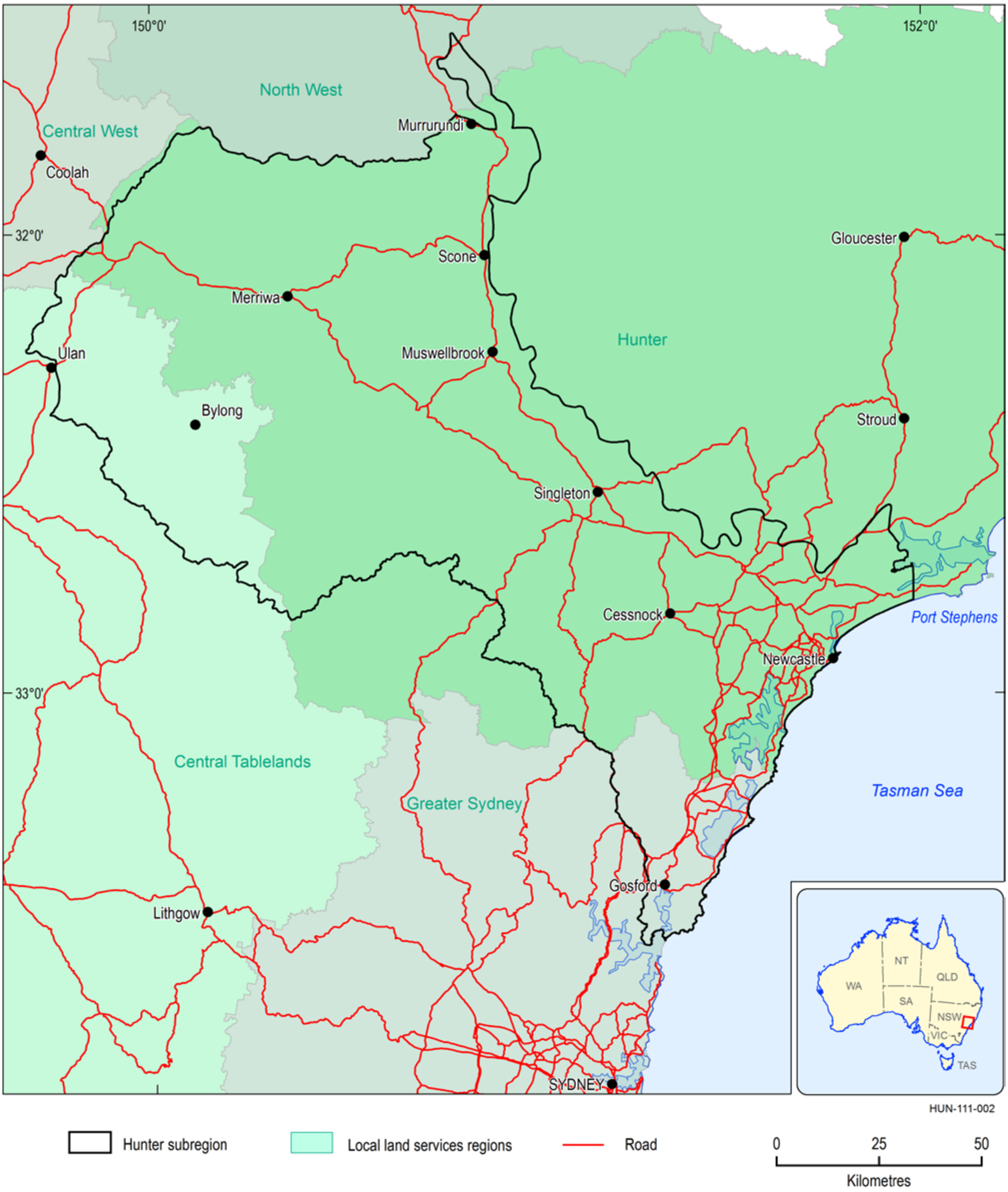

Figure 5 Local land services regions relative to the Hunter subregion

Data: NSW Trade and Investment (Dataset 3)

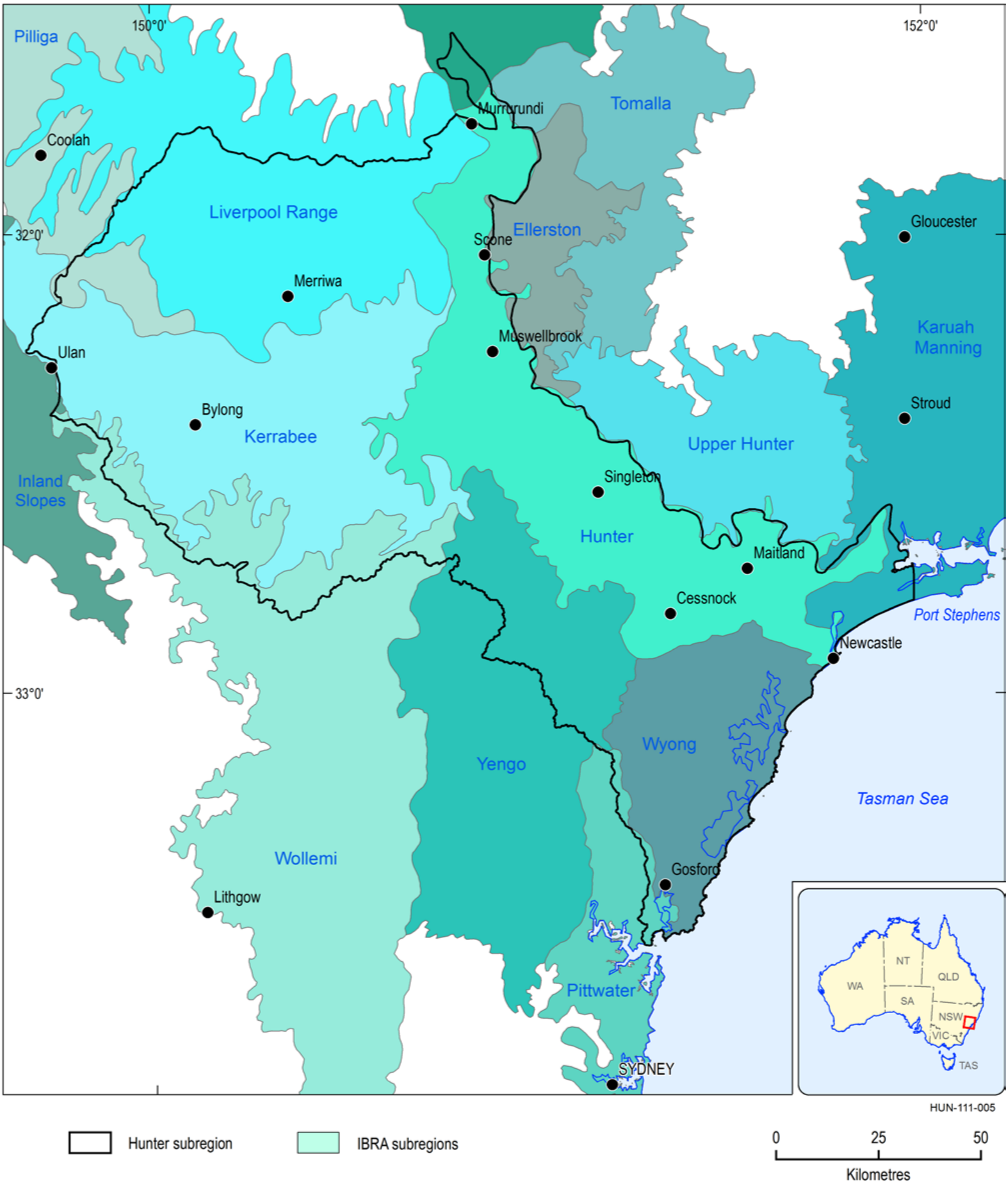

Figure 6 Interim Biogeographic Regionalisation for Australia (IBRA) subregions relative to the Hunter subregion

Data: SEWPaC (Dataset 4)

Table 4 Interim Biogeographic Regionalisation for Australia (IBRA) subregions contained in the Hunter subregion

IBRA subregion name	IRBA subregion code[a]	Area (ha)	Area in BA Hunter subregion (ha)	Percentage of IBRA subregion in Hunter subregion (%)	Percentage of Hunter region (%)
Wyong	SYB06	211,494	211,473	100.0%	12.4%
Hunter	SYB02	461,515	445,126	96.4%	26.1%
Kerrabee	SYB01	437,384	403,528	92.3%	23.7%
Liverpool Range	BBS26	521,960	310,592	59.5%	18.2%
Yengo	SYB05	461,327	138,468	30.0%	8.1%
Wollemi	SYB04	687,622	97,213	14.1%	5.7%
Pittwater	SYB07	148,389	14,856	10.0%	0.9%
Karuah Manning	NNC17	602,423	32,312	5.4%	1.9%
Ellerston	NNC15	113,183	3,252	2.9%	0.2%
Pilliga	BBS24	1,732,137	36,031	2.1%	2.1%
Peel	NAN04	1,430,562	8,720	0.6%	0.5%
Upper Hunter	NNC16	232,750	1,392	0.6%	0.1%
Tomalia	NNC14	227,615	841	0.4%	0.0%

These data are in descending order based on the ‘Percentage of IBRA subregion in Hunter subregion’ column.
Data: SEWPaC (Dataset 4)
[a] There are four main IBRA bioregions within the Hunter subregion, each represented by the alpha part of the IBRA subregion code: (i) SYB – Sydney Basin, (ii) BBS – the Brigalow Belt South, (iii) NNC – NSW North Coast and (iv) NAN – Nandewar.

The Hunter subregion contains parts of 16 NSW LGAs (Australian Bureau of Statistics, 2011) (Figure 7 and Table 5). There are three LGAs that are essentially wholly contained (i.e. >99%) in the Hunter subregion: Wyong, Lake Macquarie and Newcastle. Then in descending order of percentage of the LGA in the subregion there is Muswellbrook (92%), Maitland, Cessnock, Port Stephens, Upper Hunter Shire, Singleton (49%), with approximately a quarter of the Gosford and Mid-Western Regional LGAs also being included in the Hunter subregion. The remaining LGAs (i.e. Liverpool Plains, Dungog, Great Lakes, Warrumbungle Shire and Hawkesbury) each contribute less than 2% of the Hunter subregion.

Figure 7 Local government areas relative to the Hunter subregion

Data: ABS (Dataset 5)

Table 5 Local government areas (LGAs) contained in the Hunter subregion

LGA name[a]	Area (ha)	Area in Hunter subregion (ha)	Percentage of LGA in Hunter subregion (%)	Percentage of Hunter subregion (%)
Wyong (A)	73,980	73,854	99.8%	4.4%
Lake Macquarie (C)	64,799	64,674	99.8%	3.9%
Newcastle (C)	18,677	18,629	99.7%	1.1%
Muswellbrook (A)	340,499	313,029	91.9%	18.6%
Maitland (C)	39,152	32,980	84.2%	2.0%
Cessnock (C)	196,541	158,542	80.7%	9.4%
Port Stephens (A)	85,847	52,214	60.8%	3.1%
Upper Hunter Shire (A)	809,606	470,507	58.1%	28.0%
Singleton (A)	489,283	239,793	49.0%	14.3%
Gosford (C)	93,989	23,978	25.5%	1.4%
Mid-Western Regional (A)	875,279	219,266	25.1%	13.1%
Liverpool Plains (A)	508,231	9,482	1.9%	0.6%
Dungog (A)	225,002	1,376	0.6%	0.1%
Great Lakes (A)	337,333	507	0.2%	0.0%
Warrumbungle Shire (A)	1,237,108	335	0.0%	0.0%
Hawkesbury (C)	277,464	15	0.0%	0.0%

These data are in descending order based on the ‘Percentage of LGA in Hunter subregion’ column.

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

Data: ABS (Dataset 5)

The combined LGA area is approximately 23,965 ha smaller than the Hunter subregion area because a number of water bodies are not included in the spatial definitions of the LGAs. Denoted as ‘name (associated LGA) and area (ha)’, these are: (i) Lake Macquarie (Lake Macquarie) 10,897 ha, (ii) Tuggerah Lake (Wyong) 5865 ha, (iii) Brisbane Water (Gosford) 2449 ha, (iv) Budgewoi Lake (Wyong) 1369 ha, (v) Lake Munmorah (Wyong) 785 ha and (vi) Newcastle Harbour (i.e. Fullarton Cove/Hunter River) 2600 ha.

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Datasets

Dataset 1 Geoscience Australia (2009) HUN bioregion boundary definition sources. Bioregional Assessment Source Dataset. Viewed 30 March 2015, <http://data.bioregionalassessments.gov.au/dataset/3052c699-3b0d-4504-95e3-18598147c5ae>.

Dataset 2 Geoscience Australia (2006) Geoscience Australia GEODATA TOPO Series – 1:1 Million to 1:10 Million scale, Bioregional Assessment Source Dataset. Viewed 30 March 2015, <http://data.bioregionalassessments.gov.au/dataset/310c5d07-5a56-4cf7-a5c8-63bdb001cd1a>.

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Dataset 4 SEWPaC (2012) Hunter bioregion (IBRA Version 7). Bioregional Assessment Source Dataset. Viewed 30 March 2015, <http://data.bioregionalassessments.gov.au/dataset/e73c01b3-c5ef-4fea-8402-2b816d7533b5>.

Dataset 5 ABS (2011) Hunter Local Government Areas. Bioregional Assessment Source Dataset. Viewed 30 March 2015, <http://data.bioregionalassessments.gov.au/dataset/45cf9e06-6114-4d68-b5c9-ae0b0ee9d8db>.

1.1.2 Geography

Summary

The Northern Sydney Basin bioregion covers an area of about 17,390 km^2, of which the Hunter subregion covers about 17,045 km^2. It is located just north of Sydney, NSW. The Hunter subregion is primarily defined by the geological Sydney Basin and the river basins of the Hunter River and the Macquarie-Tuggerah Lakes, which are in part defined by ridge lines associated with the Hunter Range, Liverpool Range and Great Dividing Range. It is approximately 230 km north–south and 210 km east–west. Elevation in the subregion ranges from sea level to 1241 mAHD (metres above Australian Height Datum), and it is mostly undulating with relative low slopes in the northern part of the subregion (along the Hunter River and its tributaries), with relatively rugged terrain found in the southern part of the subregion primarily associated with the heavily dissected rock outcrops of the Triassic Hawkesbury Sandstone.

The Hunter Estuary wetland is a nationally and internationally significant wetland. Soils are mainly Tenosol (30.0%), Kurosol (27.3%) and Ferrosol (13.1%); another seven soil types are also present. Pre-European vegetation was dominated by eucalypt forest and approximately 40% of the subregion retains this vegetation cover. In the remaining parts of the subregion much of the vegetation has been cleared. A wide range of land uses occur in the subregion; grazing is the most widespread (covering 40% of the subregion). Vegetation height exceeds 40 m in the forests.

There are numerous rivers in the subregion dominated by the Hunter River and many others which drain the Barrington Tops, and the Goulburn River and Growee River that drain the remnant native forests in the south-western part of the subregion associated with the Hunter Range. From a groundwater perspective it is essentially a closed system, with the majority of groundwater resources associated with alluvial and aeolian aquifers. Fractured rock aquifers are of less importance due to marginal water quality.

About 838,000 people live in the subregion, including the important regional urban centres of Newcastle, Central Coast, Maitland and Cessnock. Water for these towns is extracted from local rivers and groundwater systems and there are several major dams in the subregion. Three of these dams produce hydro-power; however a much more significant proportion of NSW's electricity requirement is generated by coal-fired power stations located in the Hunter subregion, which are fueled by coal mined within the subregion.

The climate is sub-tropical on the coast becoming more temperate inland, characterised by summer dominant precipitation. Mean precipitation over the last 30 years (1982 to 2012) for the subregion was 793 mm/year with a mean potential evapotranspiration (PET) of 1728 mm/year; considerable spatial variation across the subregion and temporal variation is 'hidden' in such subregion-averages. There were no distinctive precipitation trends over this period but there was a decreasing trend for PET due to declining rates of wind speed, net radiation and vapour pressure deficit offsetting PET increases associated with rising air

temperatures. Future precipitation may decrease and accordingly there may be a decrease in runoff generation from the Hunter subregion.

1.1.2.1 *Physical geography*

The centre of the Hunter subregion is located approximately 150 km north of Sydney in NSW, while the distance from the southern extent of the subregion to the Sydney GPO is only 36 km. It contains the agriculturally productive and key coal producing Hunter Valley and the Central Coast area, including Lake Macquarie, Tuggerah Lake and Brisbane Water. The subregion contains the major coastal cities of Newcastle in the north and Gosford in the south. Inland, towns such as Ulan border the western extent of the subregion and Murrurundi is located in the north. There are two features of high international conservation value including: (i) part of the Greater Blue Mountains World Heritage Area and (ii) the Hunter Estuary, a nationally and an internationally significant wetland listed under the Ramsar Convention on Wetlands (McCauley, 2006, Section 3.3 Land Use; NSW National Parks and Wildlife Service, 2003). The subregion is proximal to another two areas that also have significant international and local conservation value: (i) the Barrington Tops World Heritage Area (located directly north of the subregion) and (ii) the Myall Lakes National Park (located north-east of the subregion). In addition to these nationally and internationally recognised areas, the Hunter Valley is of great ecological significance as: (i) it represents the major break in the Great Dividing Range providing a link between coastal and inland NSW and (ii) it contains an area of overlap between tropical and temperate zones known as the MacPherson–Macleay Overlap (Burbidge, 1960) in which the limits of many taxa are found. For more details see Section 1.1.7 below.

The Hunter subregion is primarily defined by geological features (the Sydney Basin and the Hunter-Mooki fault) and ridge lines associated with the Hunter, Liverpool and Great Dividing ranges defining surface water catchments; see Section 1.1.1 for full details. It is approximately 230 km north–south and 210 km east–west. The 1:250,000 topographic dataset (Geoscience Australia, 2006) shows that several mountain ranges ring the subregion, including the Hunter, Liverpool and Great Dividing ranges. Land-surface elevation ranges from sea level to 1241 m (Australian Height Datum (AHD), Figure 8); it exceeds 1550 m (AHD) in the nearby Barrington Tops (located outside the subregion). The highest point in the subregion is East Bluff (1241 m), located in the Liverpool Range. Figure 9 shows that in the subregion the land surface slopes (calculated using ~90 m resolution grid cell – that is the 3 second Shuttle Radar Topography Mission (SRTM; Farr et al., 2007) data) are flat to moderate in the undulating northern part of the subregion (along the Hunter River and its tributaries), with relatively rugged terrain found in the southern part of the subregion primarily associated with the heavily dissected rock outcrops of the Triassic Hawkesbury Sandstone. The maximum slope in the subregion is 69 degrees, with some steep slopes being encountered in surrounding mountain areas. There are distinct break-of-slopes where the mountains and valley meet (Figure 9).

Figure 10 shows that from a surface water perspective the Hunter subregion is primarily composed of the Hunter river basin (87.5% of the subregion). River basins of the Macquarie and Tuggerah lakes comprise 10.7% of the subregion and the remaining 2% of the subregion comprises the Lower Karuah basin (1.3%) and the Upper Namoi basin (0.5%). Within the river basins of the Macquarie and Tuggerah lakes there are several natural coastal lakes including (i) Lake Macquarie,

(ii) Tuggerah Lake, (iii) Brisbane Water, (iv) Budgewoi Lake and (v) Lake Munmorah that are important water bodies for recreation and habitat.

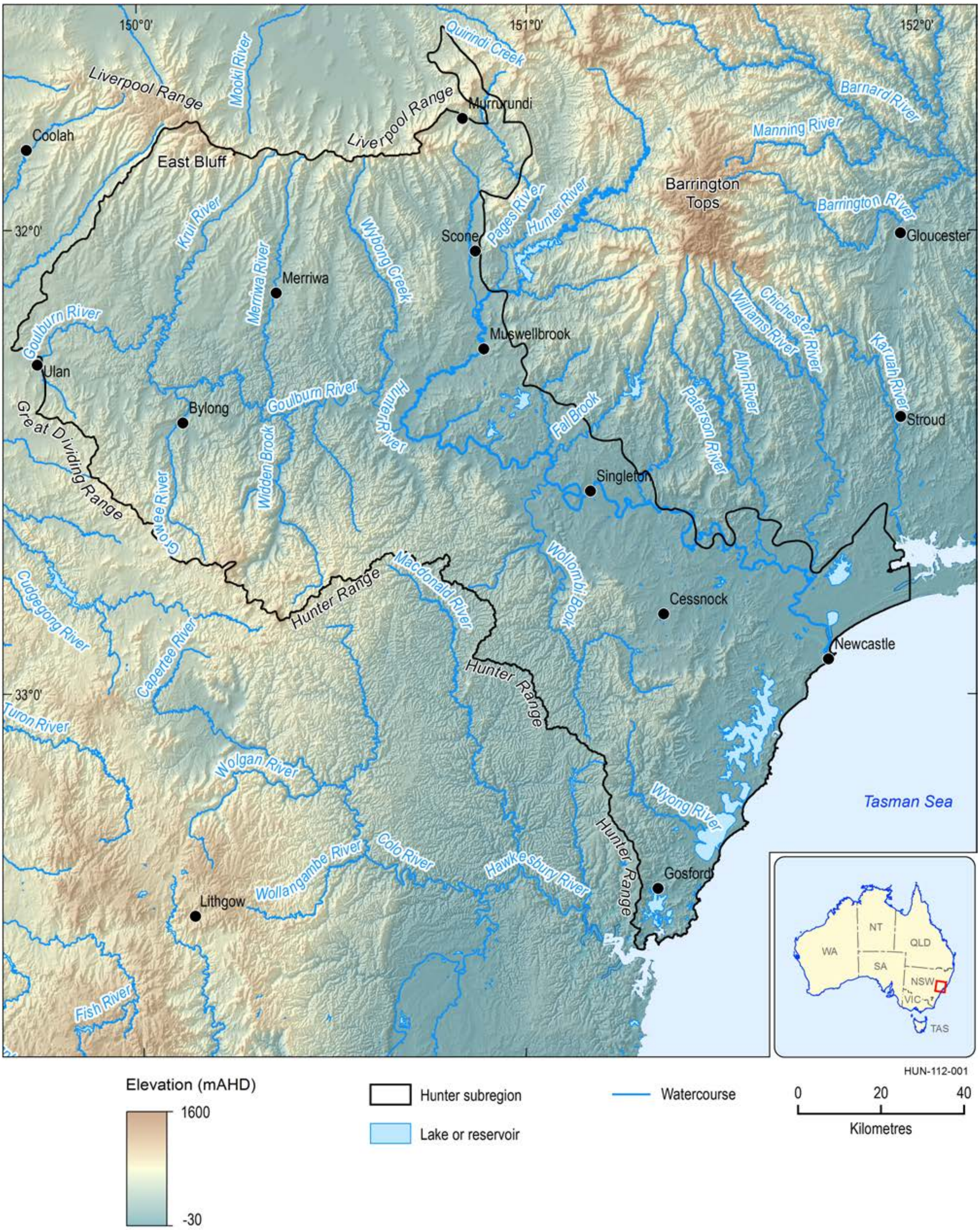

Figure 8 Surface elevation and mountain ranges of the Hunter subregion

Data: Geoscience Australia (Dataset 1), Geoscience Australia (Dataset 2), Geoscience Australia (Dataset 3)

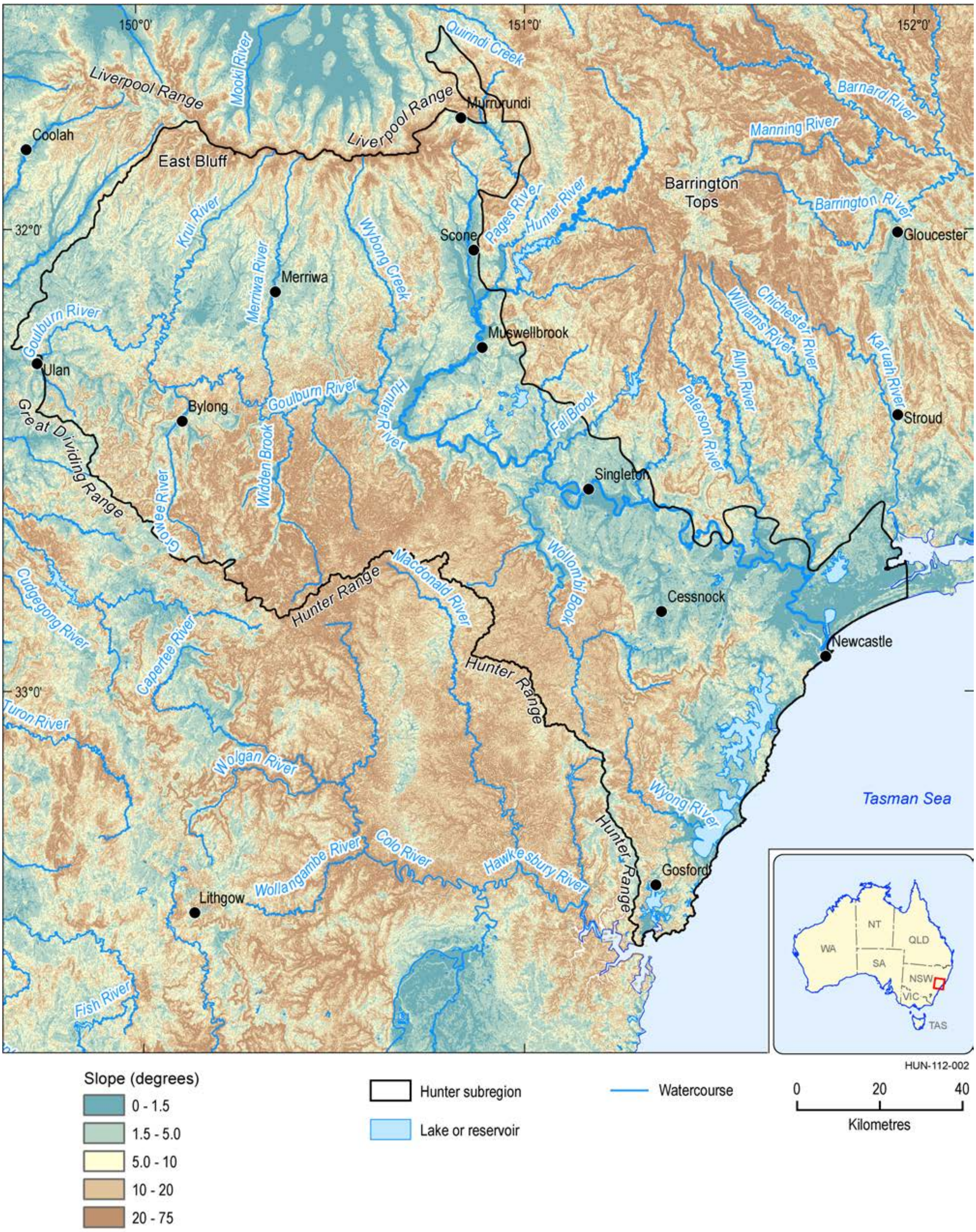

Figure 9 Land surface slopes of the Hunter subregion

Data: CSIRO (Dataset 4)

Figure 10 Major river basins and selected surface water bodies of the Hunter subregion

The hydrogeological systems in the Hunter subregion are associated with Permian-Triassic rock aquifers, alluvial aquifers along major rivers and creeks and aeolian sands aquifer in the coastal zone of the subregion. The Hunter Valley represents a regional groundwater discharge zone and a dividing streamline for groundwater flow. Similarly to surface water, the main regional groundwater fluxes (south from Hunter-Mooki thrust fault, which forms the northern boundary of the geological Sydney Basin, and the Hunter subregion; see the previous section) largely follow the subregion topography from the upland towards the river channels with overall discharge towards the Tasman Sea. Interactions between surface water and groundwater in alluvial aquifers are important processes which determine quantity and quality of groundwater resources in the subregion. There are a series of connected alluvial deposits along the Hunter River and its tributaries, which form an important water resource. In water sharing plans the local alluvial aquifer is considered a separate water source for agriculture (DPI, 2005; 2013) with the Kingdom Ponds and Dart Brook alluvial aquifers, located in the north-west of the region, being the major groundwater resources. The Tomago Sandbeds are an important water resource for the Newcastle region (Woolley et al., 1995) being one of three main water supplies for this region. This aquifer provides a buffer against the effects of drought and could supply up to 30% of the water supply to areas of the lower Hunter River and Lake Macquarie. Other groundwater resources are largely dependent on the bedrock’s secondary permeability associated with fractures (Kellett et al., 1989). Water quality (salinity) limits use of groundwater found in Permian formations. Within the deeper strata of the Hunter subregion there is limited potential for groundwater interactions with groundwater systems to the south (the southern parts of the geological Sydney Basin that comprise the Sydney Basin Bioregional Assessment) and/or to the west (the geological Gunnedah Basin), but the volumetric fluxes between these basins are likely to be minimal. For more details about the hydrogeological systems see Section 1.1.4.

Figure 11 shows the locations of wetlands and groundwater-dependent ecosystems in the Hunter subregion (Serov et al., 2012). The Hunter Estuary wetland is a nationally and internationally significant wetland listed under the Ramsar Convention on Wetlands. This wetland is a key site for migratory and resident shorebirds providing roosting and feeding resources to a large seasonal population of shorebirds and as a waylay site for transient migrants. Over 250 species of birds have been recorded within this Ramsar site, including 45 species listed under international migratory conservation agreements. In addition, the Hunter Estuary wetland provides habitat for three species nationally recognised as threatened: the green and golden bell frog, the red goshawk and the Australasian bittern; it also provides habitat for waterbirds such as ducks and herons during periods of inland drought. There are some important springs located in the Hunter subregion (Figure 11) which are key water sources for local ecosystems. Many of the rivers in the subregion have riparian vegetation along the banks, which provide important habitat for a variety of species. For more details about the ecology of the Hunter subregion see Section 1.1.7.

The Hunter subregion is comprised of seven physiographic classes of the Australian Soil Resource Information System (ASRIS) (Figure 12). The main ASRIS classes are (i) Hunter Valley (covering 4946 km^2 or 29.0% of the subregion), (ii) Hawkesbury-Shoalhaven Plateaus (covering 3980 km^2 or 23.4% of the subregion), (iii) Merriwa Plateau (covering 3973 km^2 or 23.2% of the subregion) and (iv) Goulburn Corridor (covering 3485 km^2 or 20.4% of the subregion). The descriptions of all classes present in the subregion are provided in Table 6.

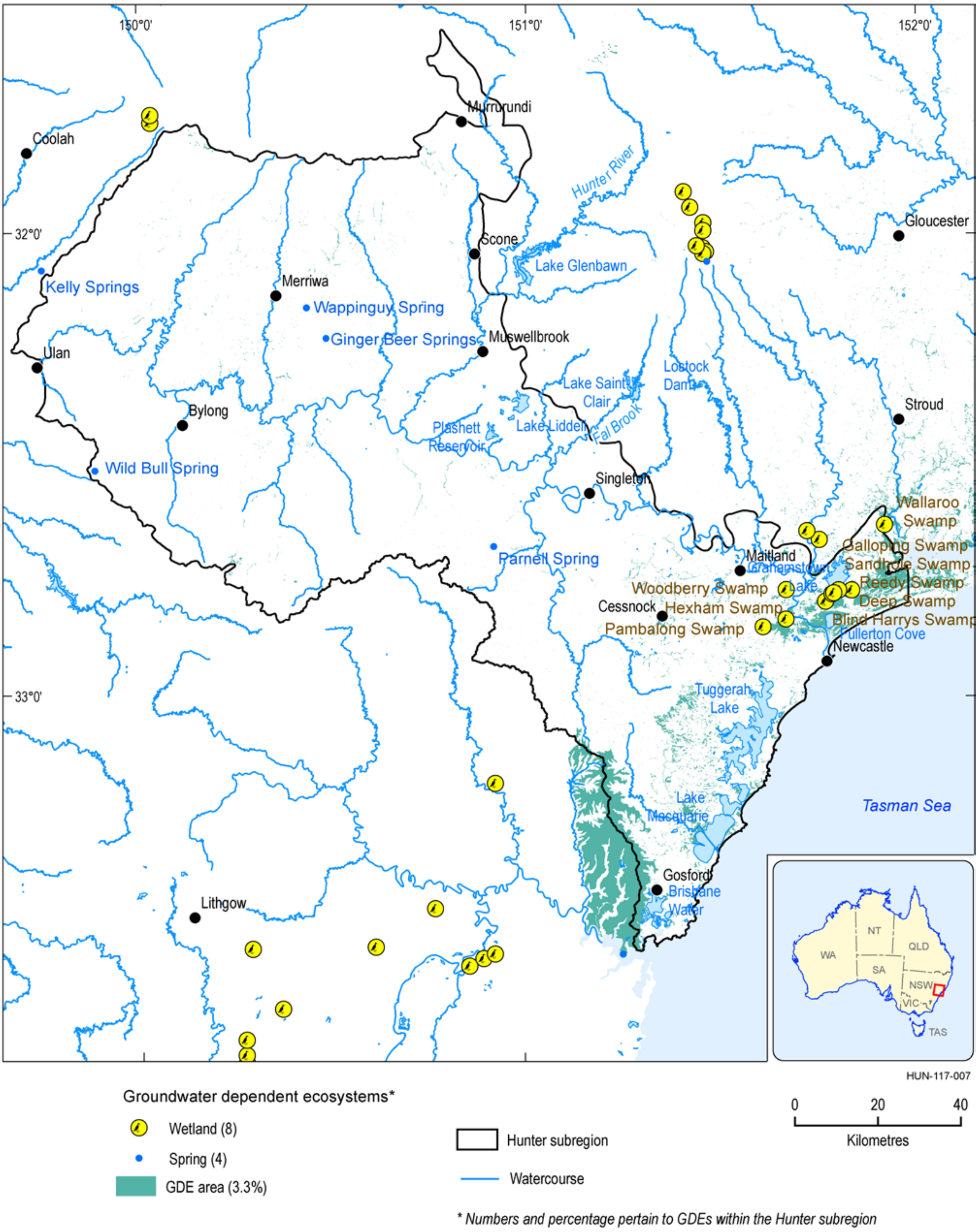

Figure 11 Wetlands and groundwater-dependent ecosystems of the Hunter subregion

Data: Serov et al. (2012), NSW Office of Water (Dataset 5)

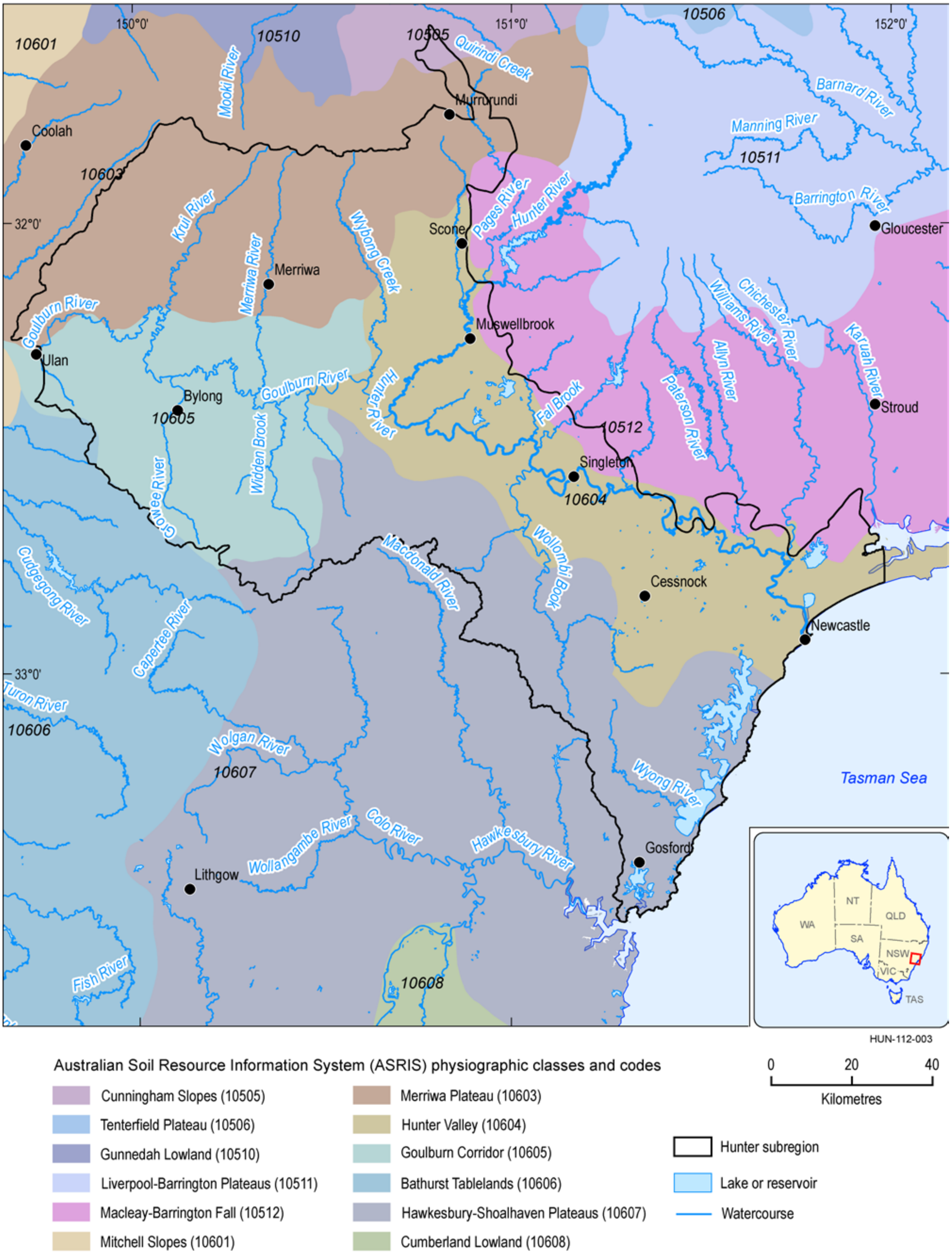

Figure 12 Australian Soil Resource Information System (ASRIS) physiographic classes and codes in the Hunter subregion

Data: ASRIS (Dataset 6)

Table 6 Description of the Australian Soil Resource Information System physiographic classes in the Hunter subregion, shown in Figure 12

Code	Class name	Class description	Area (km^2)
10512	Macleay-Barrington Fall	Plateau flank dissected into narrow strike ridges and valleys	561
10603	Merriwa Plateau	Rolling basalt upland with sandstone cliffs	3973
10606	Bathurst Tablelands	Granitic and basaltic tablelands and minor lowlands; includes the Canobolas dissected volcanic pile	45
10604	Hunter Valley	Undulating to low hilly country on weak rocks, with alluvial and sandy littoral plains	4946
10505	Cunningham Slopes	Ridges and valleys in metamorphic rocks	54
10605	Goulburn Corridor	Broad valley floors on weaker rocks, overlooked by irregular dissected plateaus	3485
10607	Hawkesbury-Shoalhaven Plateaus	Deeply dissected sandstone plateaus	3980

Data: ASRIS (Dataset 6)

There are seven main soils found in the Hunter subregion – Tenosols (30.0%), Kurosols (27.3%), Ferrosols (13.1%), Sodosols (8.4%), Vertosols (8.3%), Rudosols (5.9%) and Dermosols (4.0 %) – together covering 97% of the subregion (Figure 13). Their characteristics are briefly introduced below, ordered by descending area.

Tenosols in the vicinity of the Hunter subregion are alluvial soils flanking rivers, so quite recently deposited. This means that they are young, weakly developed soils that have poorly developed (tenic) B horizons (Isbell, 2002). Given the location along rivers, these soils are likely to be dominated by clayey or silty textures, likely with pockets of sand or gravel present, and are probably deep.

Kurosols are located in mid- and lower slope positions. They have a clear, sharp, or abrupt textural boundary between coarser textured A horizons (e.g. sands or loams) and finer textured (i.e. clayey) B horizons (Isbell, 2002). The other distinguishing feature of these soils is that the upper 0.2 m of the B horizon is strongly acid (pH <5.5).

Ferrosols are located on upland landscape areas, and on crests, ridges or hill flanks. They are typically deeply red in colour reflecting a high concentration of free iron, and lack a strong contrast in texture between the topsoil and subsoil. Their structure is generally very good and if sufficiently deep, they are ideal for agriculture with appropriate erosion management.

Sodosols are generally located in lower hillsides or in perched upper slope locations. They are generally associated with salinity (e.g. at seeps or where drainage is poor), and salts can be of local origin (connate) or windblown. These soils have a strong contrast in textures between the topsoils and subsoil, with very clayey, poorly structured clay subsoil, and can be a challenge to manage for agriculture due to structural issues (caused by excessive sodium ions) and salinity.

Vertosols are generally uniform structured clay profiles which exhibit vertic properties (i.e. a subsoil with a field texture of 35% or more clay that experiences significant shrinking and swelling, resulting from drying and wetting), including surface cracks (often very deep and wide), self-mulching surface horizons and gilgai surface features (i.e. the land surface is irregular with alternating mounds and depressions due to clay horizons shrinking and swelling with alternate drying and wetting cycles). These soils are often found in alluvial landscapes where depositional energy is low or in situ on weathered, clay rich, flat lying, sedimentary rocks. The vertic properties arise from the shrink swell nature of the 2:1 layer clay minerals present and their response to wetting and drying.

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 subregion are likely to be found.

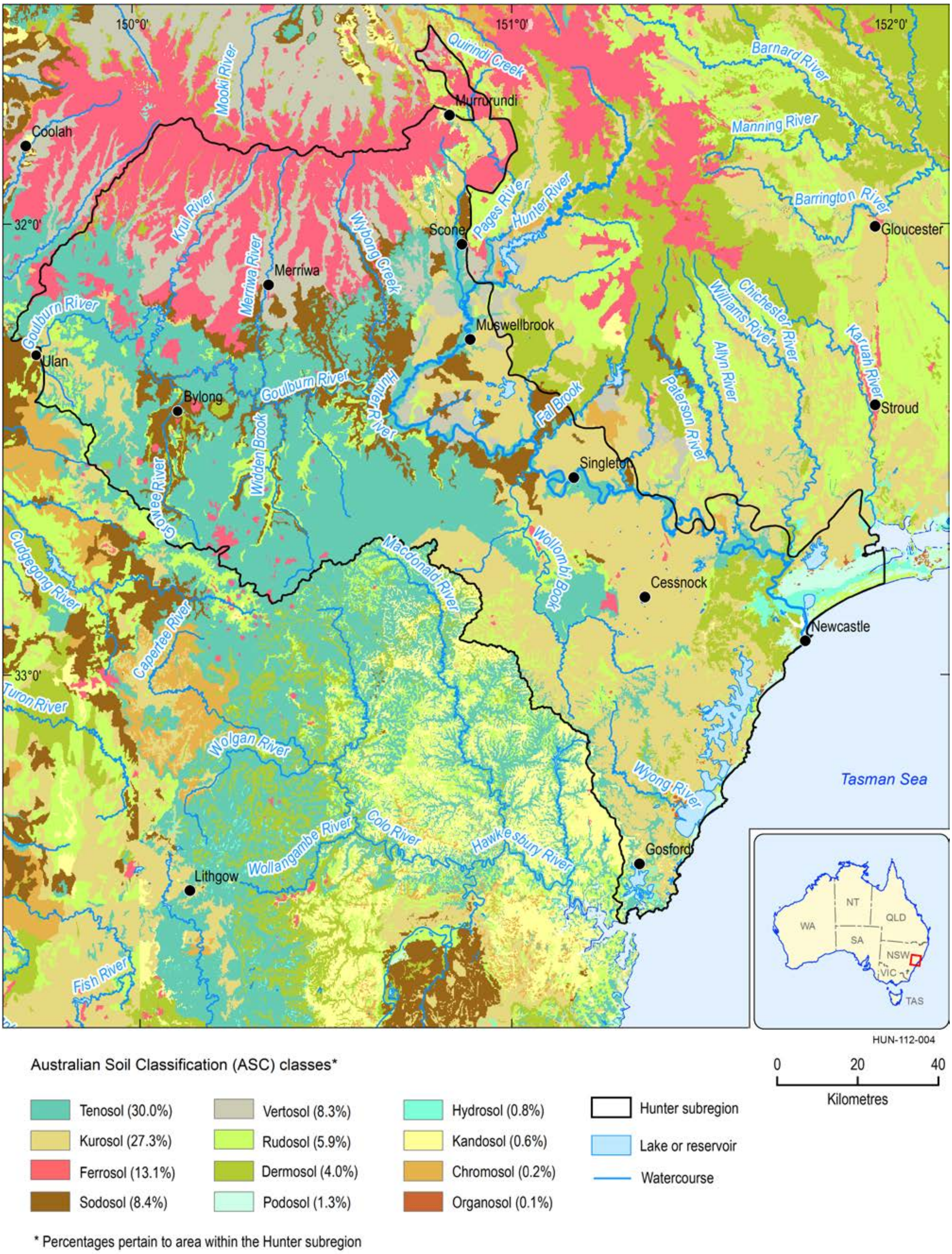

Figure 13 Australian Soil Classification (ASC) classes in the Hunter subregion

Data: CSIRO (Dataset 7)

Figure 14 shows that prior to European settlement and its associated land clearing, the dominant overstorey vegetation in the Hunter subregion was: (i) canopy coverage in the range of 10 to 70%,

(ii) eucalypt dominated and (iii) primarily of the tree or shrub growth-form (Carnahan (1976); Australian Survey and Land Information Group (AUSLIG) (1990)). Cool temperate rainforest dominated by species of Nothofagus were, and are still, present in the vicinity of the subregion (around the Barrington Tops; Figure 14).

Since European settlement there has been some vegetation clearing and the current major vegetation types are shown in Figure 15. Approximately one-half of the subregion contains remnant stands of native forests and woodlands, much of which are located in relatively rugged terrain associated with the southern part of the Hunter subregion, primarily associated with the heavily dissected Triassic capping Hawkesbury Sandstone. The Hunter subregion contains a number of Interim Biogeographic Regionalisation for Australia (IBRA) bioregions and subregions (SEWPaC, 2012b). The main IBRA bioregions within the Hunter subregion are the Sydney Basin bioregion (77% of the Hunter subregion; see the previous section) and the Brigalow Belt South bioregion (20% of the Hunter subregion; see the previous section). The remaining 3% of the Hunter subregion is covered by the NSW North Coast and Nandewar IBRA bioregions.

The Sydney Basin IBRA bioregion is one of the most species-diverse in Australia owing to great variation in geology, topography and climates (NSW National Parks and Wildlife Service, 2003). Over 38% of this IBRA bioregion is in conservation-oriented tenures, primarily national parks and conservation reserves. Over 15% is composed of six wilderness areas. The Greater Blue Mountains World Heritage Area, which occupies over 28% of the Sydney Basin IBRA bioregion, also contains the highly significant Wollemi National Park, protecting threatened species, many of which are locally endemic. Discovered in September 1994, the Wollemi pine (*Wollemia nobilis*) occurs only in a remote canyon in the park. Plant communities within the Sydney Basin IBRA bioregion include: (i) estuarine mangroves, salt marshes and reed swamps, (ii) coastal dune communities of eucalypt, banksia, tea-tree, she-oak, wattle or applebark, (iii) rainforest communities in gullies and canyons, (iv) coastal forest of Sydney bluegum, forest and open woodlands dominated by eucalypts and applebarks and (vi) river oaks and river red gums along streams. The Sydney Basin IBRA bioregion also contains nine significant wetlands. Further details of the vegetation of the Sydney Basin IBRA bioregion at the IBRA subregion level are provided in Section 1.1.7.

The part of the Brigalow Belt South IBRA bioregion within the Hunter subregion is almost entirely within the Liverpool Plain subregion of the Brigalow Belt South IBRA bioregion (NSW National Parks and Wildlife Service, 2003). Within the Liverpool Plains IBRA subregion, the threatened plant community of diverse grasslands with box trees and wilga occurs on black earths, whereas texture contrast hillslope soils are characterised by white box and white cypress pine with rough-barked apple, hill red gum, and occasional belah and mulga.

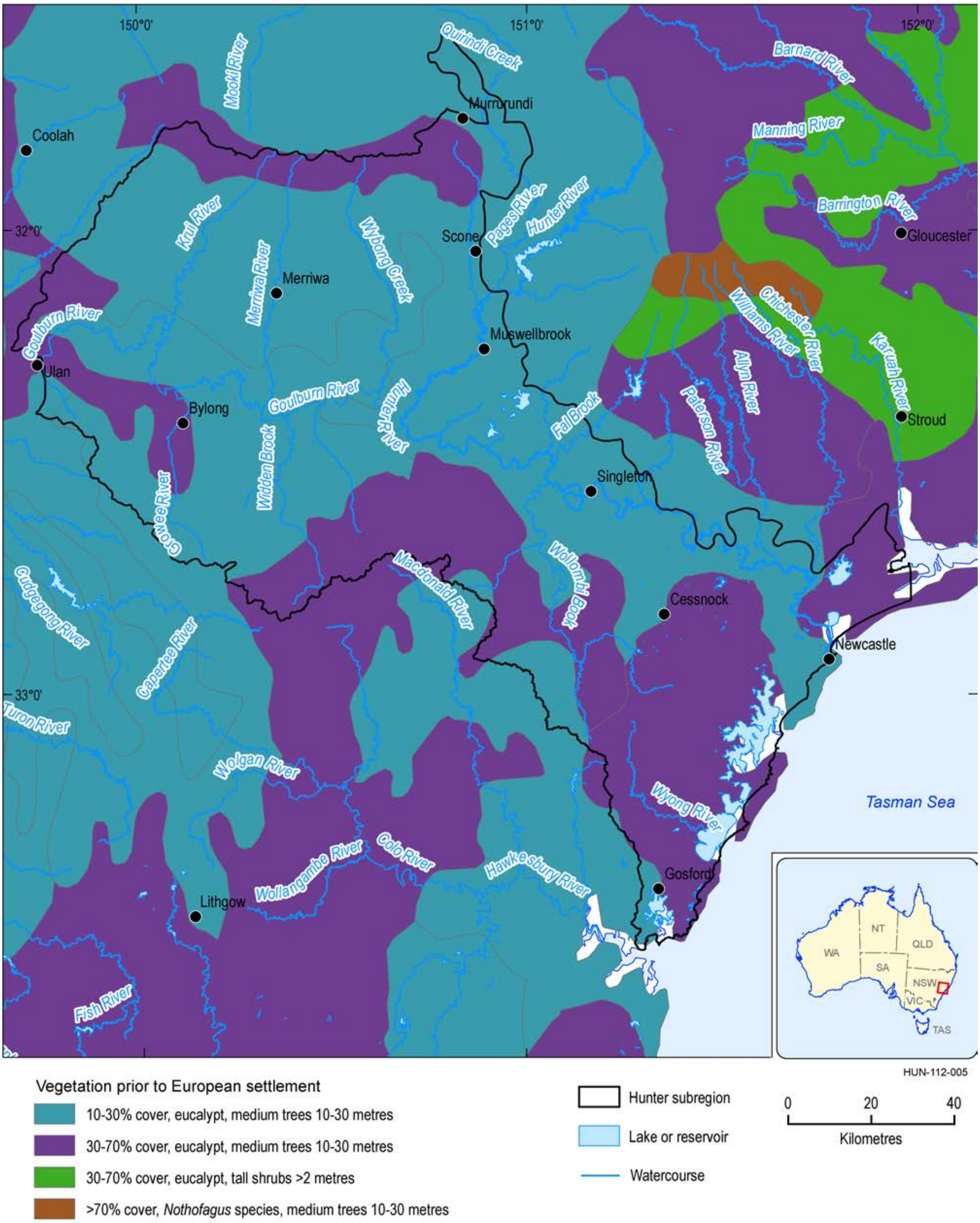

Figure 14 Vegetation prior to European settlement in the Hunter subregion

Data: Department of Environment (Datatset 8), AUSLIG (1990)

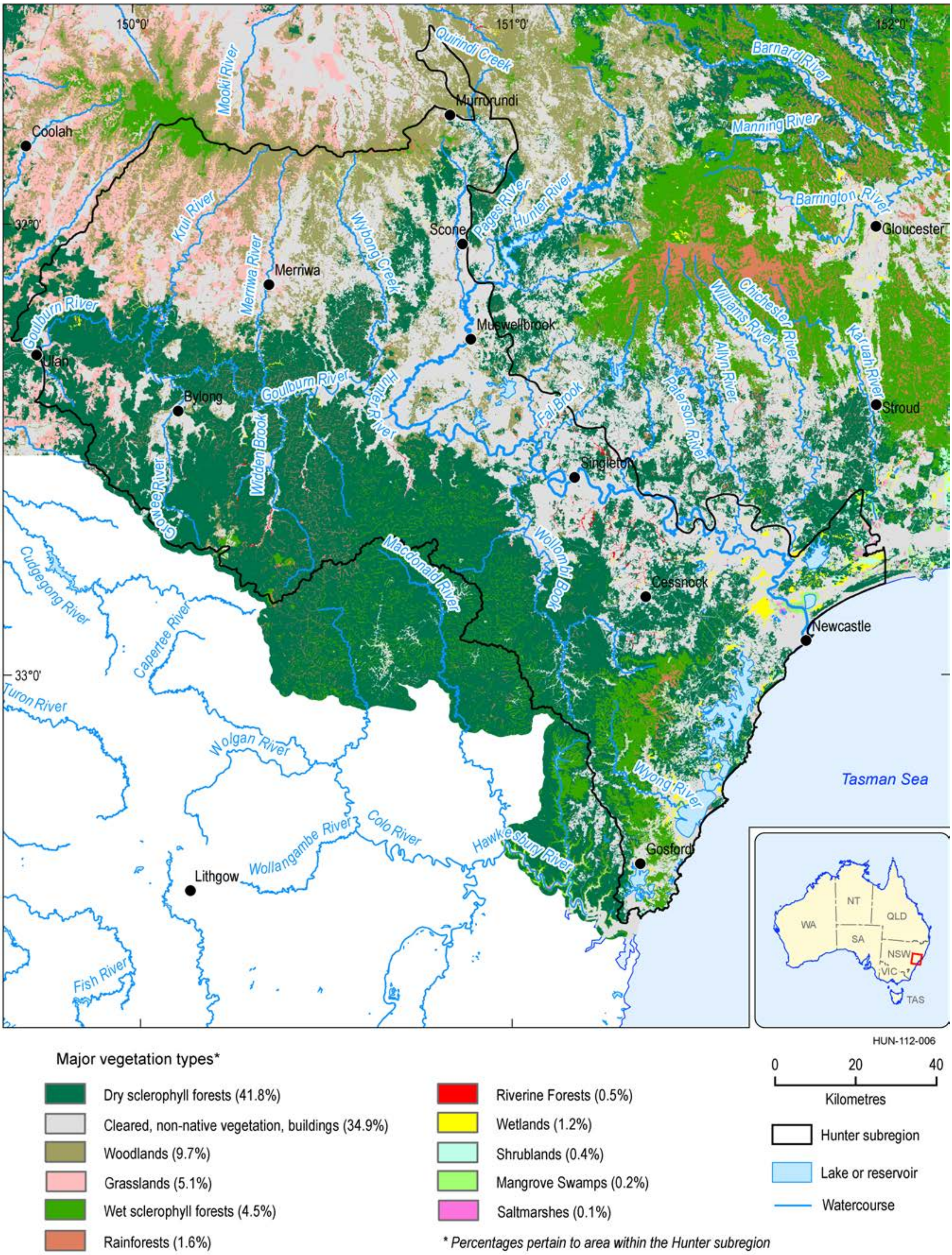

Figure 15 Current major vegetation types in the Hunter subregion

Data are not available for the entire map frame area, these are represented by white
Data: NSW Office of Environment and Heritage (Dataset 9)

Land cover is best observed from satellite imagery, which provides the opportunity to understand dynamics, calculate long-term averages and to determine the relative contributions from persistent and recurrent vegetation types (Donohue et al., 2009). Figure 16 shows that the total vegetation cover, derived from the MODIS satellite instrument for 2000 to 2012, for most of the Hunter subregion varies from 50 to 100%, with some areas having low total vegetation cover being associated with open-cut mining and urban areas. Much of the vegetation cover is persistent, in that it is ‘green’ for most of the year, and is associated with the remnant stands of native forests previously discussed. Figure 16 shows that only a relatively small proportion of the vegetation has a strong annual signal that defines recurrent (e.g. cropping) vegetation, where land cover varies from bare soil (i.e. zero % vegetation cover) to exceeding approximately 50% vegetation cover over a three to four month period (Figure 16). Within the Hunter subregion this pulse of recurrent vegetation is associated with cropping systems located in the western part of the subregion. The mean monthly dynamics of the recurrent component, illustrating strong ‘spring’ growth from July to October, are provided in Figure 17.

Vegetation height can be derived from satellite measurements/data, specifically lidar (light detection and ranging) (Simard et al., 2011) and, using this data source, Figure 18 shows that the persistent vegetation encountered over much of the Hunter subregion is tall (i.e. ~20 to 40 m high in the 1 km resolution grids calculated using data captured in 2005). While almost 40% of the land use in the subregion is grazing (Figure 20), there are isolated remnant mature trees (providing shade for livestock) in paddocks. These trees are causing some cells in pastures to have higher than expected mean cell heights.

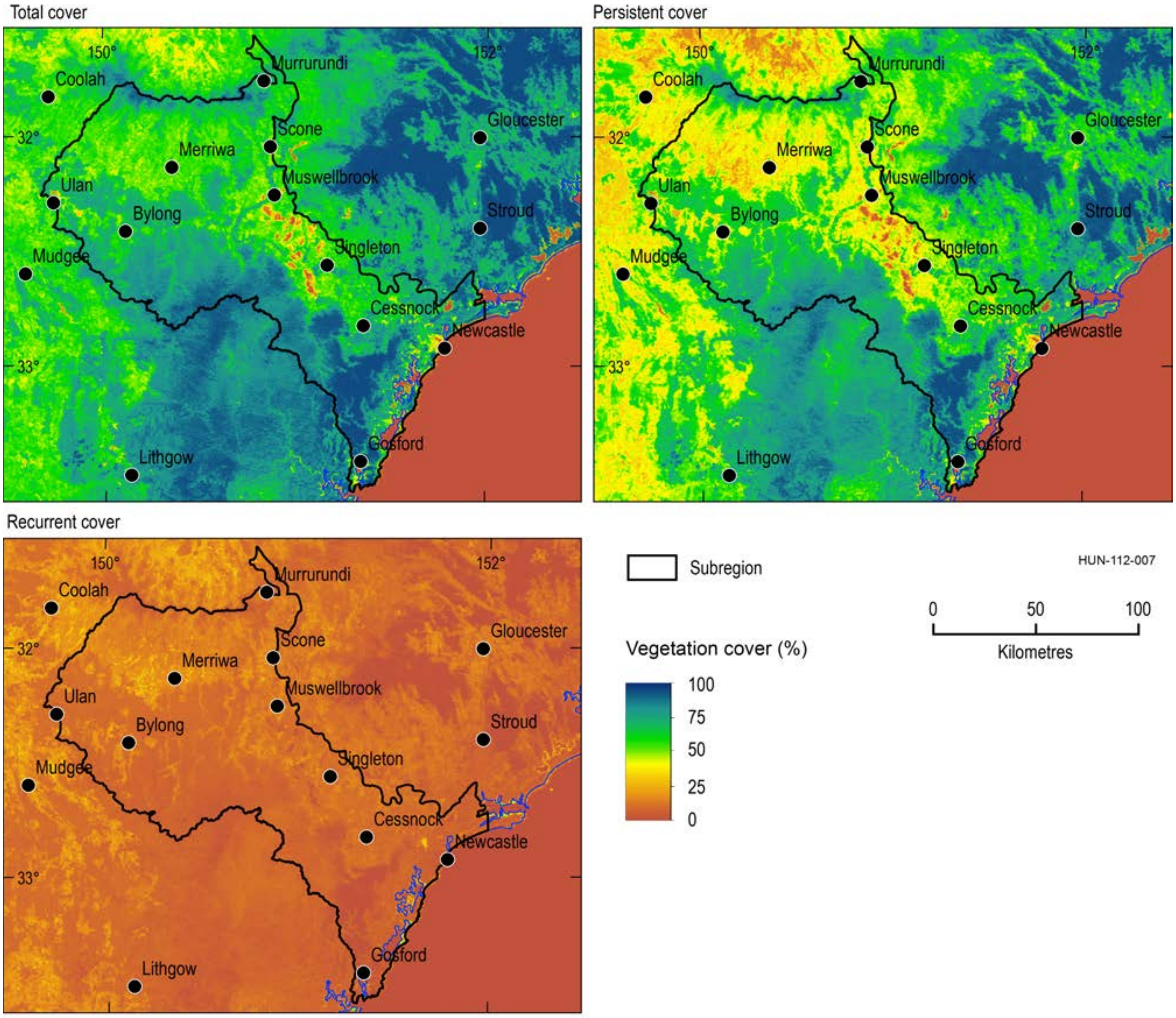

Figure 16 Vegetation cover in the Hunter subregion

Long-term mean values from 2000 to 2012 derived from the MODIS satellite sensor (Paget and King, 2008) with a 250 m grid cell resolution are shown. Total cover is temporally decomposed to provide persistent and recurrent estimates using the method of Donohue et al. (2009).
Data: CSIRO (Dataset 10)

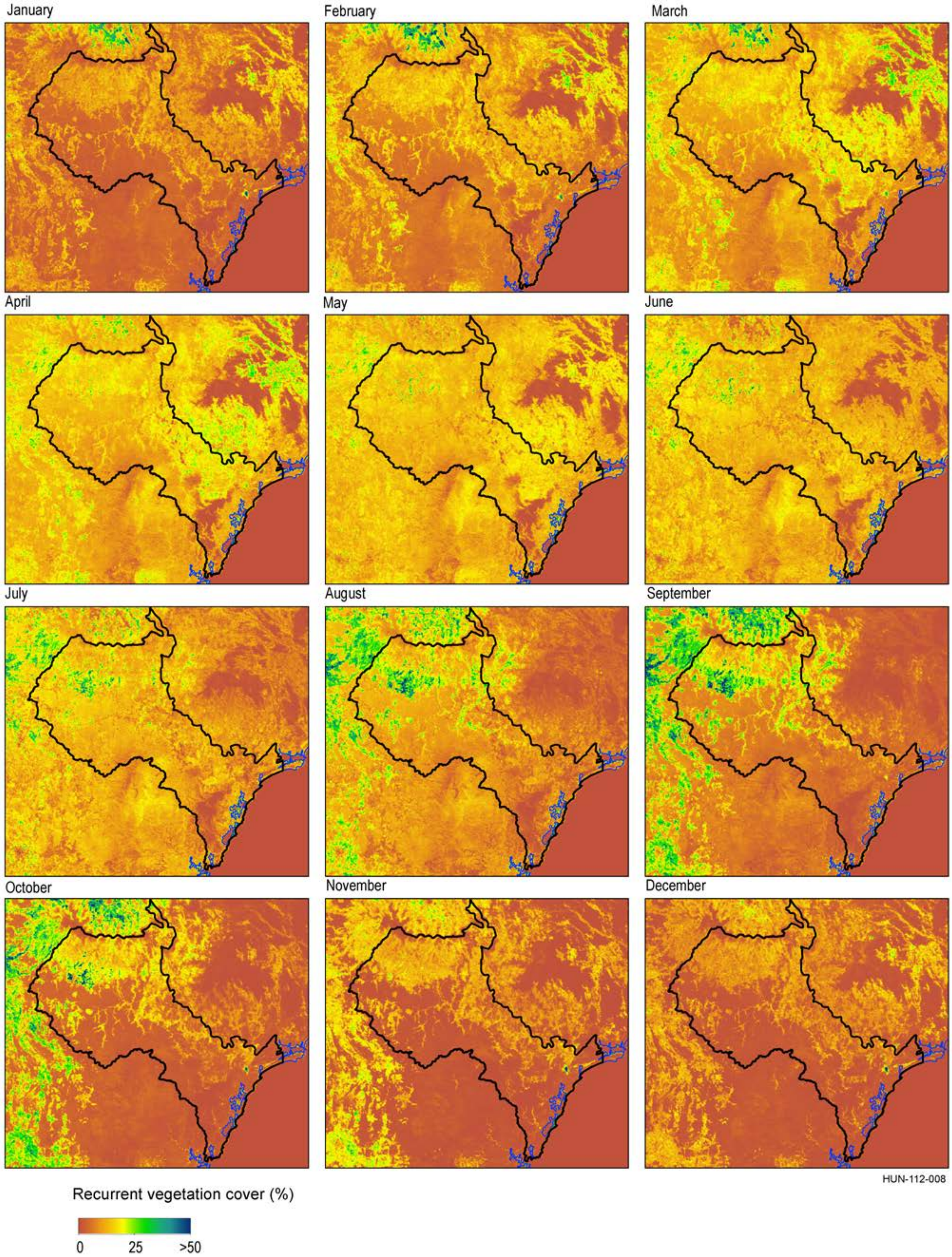

Figure 17 Monthly recurrent land cover in the Hunter subregion

Long-term monthly mean values from 2000 to 2012 derived from the MODIS satellite sensor (Paget and King, 2008) with a 250 m grid cell resolution are shown. Total cover is temporally decomposed to provide persistent and recurrent estimates using the method of Donohue et al. (2009).
Data: CSIRO (Dataset 10)

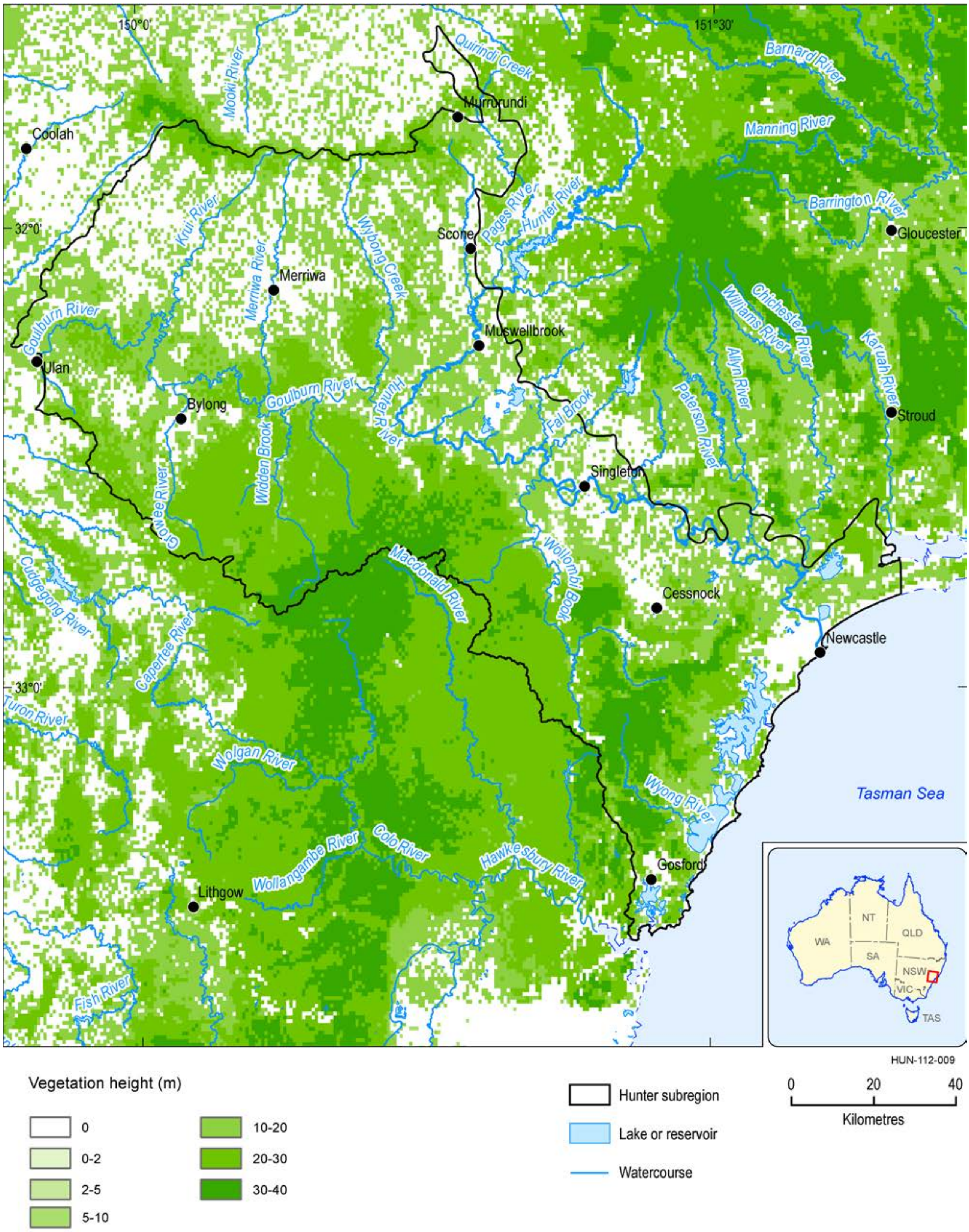

Figure 18 Vegetation height of the Hunter subregion

Data: CSIRO (Dataset 11)

1.1.2.2 *Human geography*

The human population in the Hunter subregion is mainly concentrated in the city of Newcastle, the Central Coast region (covering Gosford and other coastal towns), and the towns of Maitland and Cessnock (Figure 19). Intersecting the 2011 Australian Bureau of Statistics (ABS) Urban Centre and Locality (UCL) data with the Hunter subregion boundary indicates that there were 12 UCLs with populations greater than 5000 people in 2011. In total it is estimated that about 837,844 people live in the subregion. This value is estimated by intersecting the subregion boundary with the 2011 Australian Census mesh blocks boundaries and population counts, so is approximate only.

Table 7 Major population centres (>5000 people) in the Hunter subregion

Ranking	Name	Population
1	Newcastle	308,308
2	Central Coast	297,713
3	Maitland	67,132
4	Cessnock	20,013
5	Morisset – Cooranbong	16,918
6	Singleton	13,961
7	Raymond Terrace	13,217
8	Kurri Kurri – Weston	13,057
9	Muswellbrook	11,042
10	Medowie	8,342
11	Summerland Point – Gwandalan	5,401
12	Scone	5,079

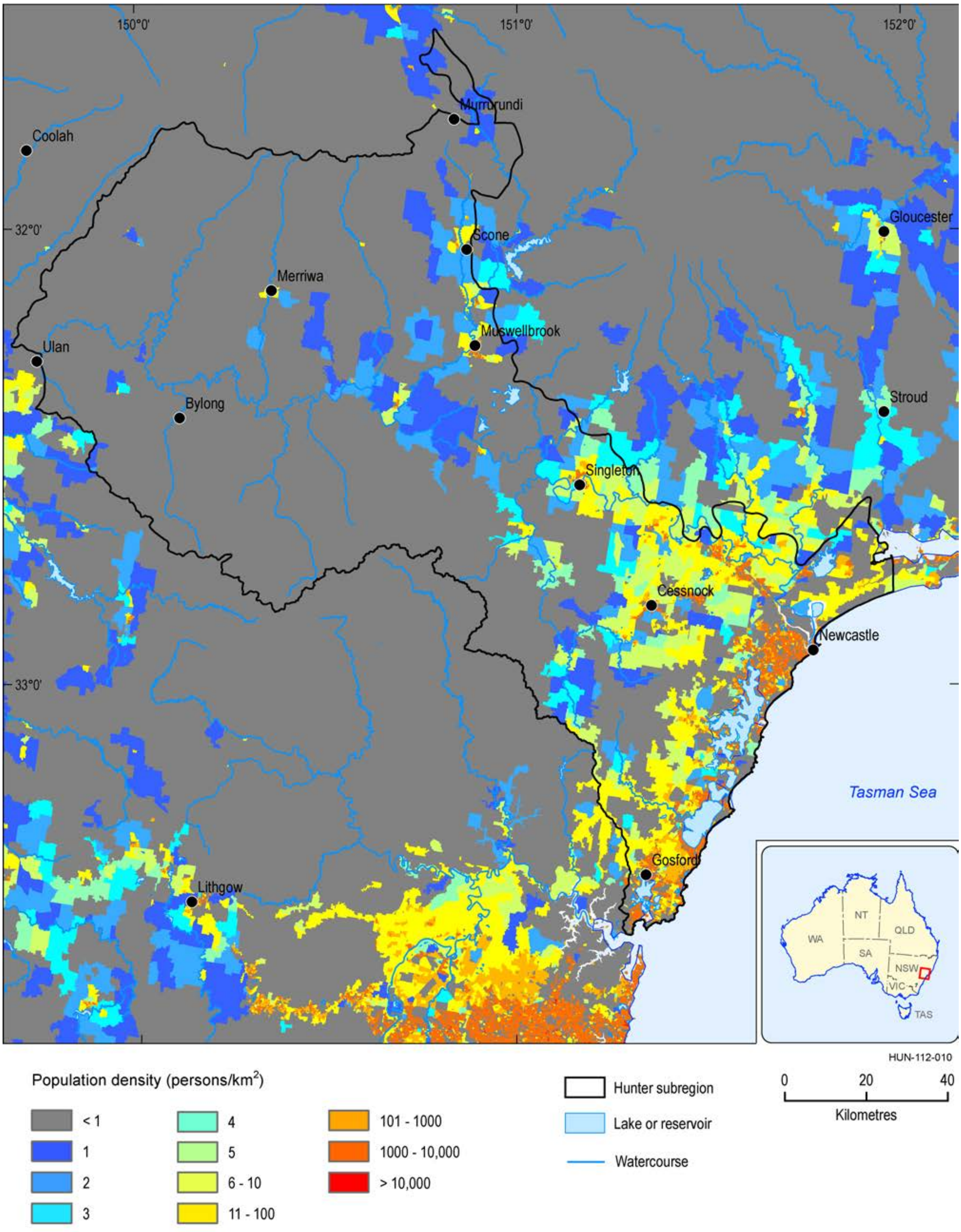

Figure 19 Human population density in the Hunter subregion

Data: ABS (Dataset 12)

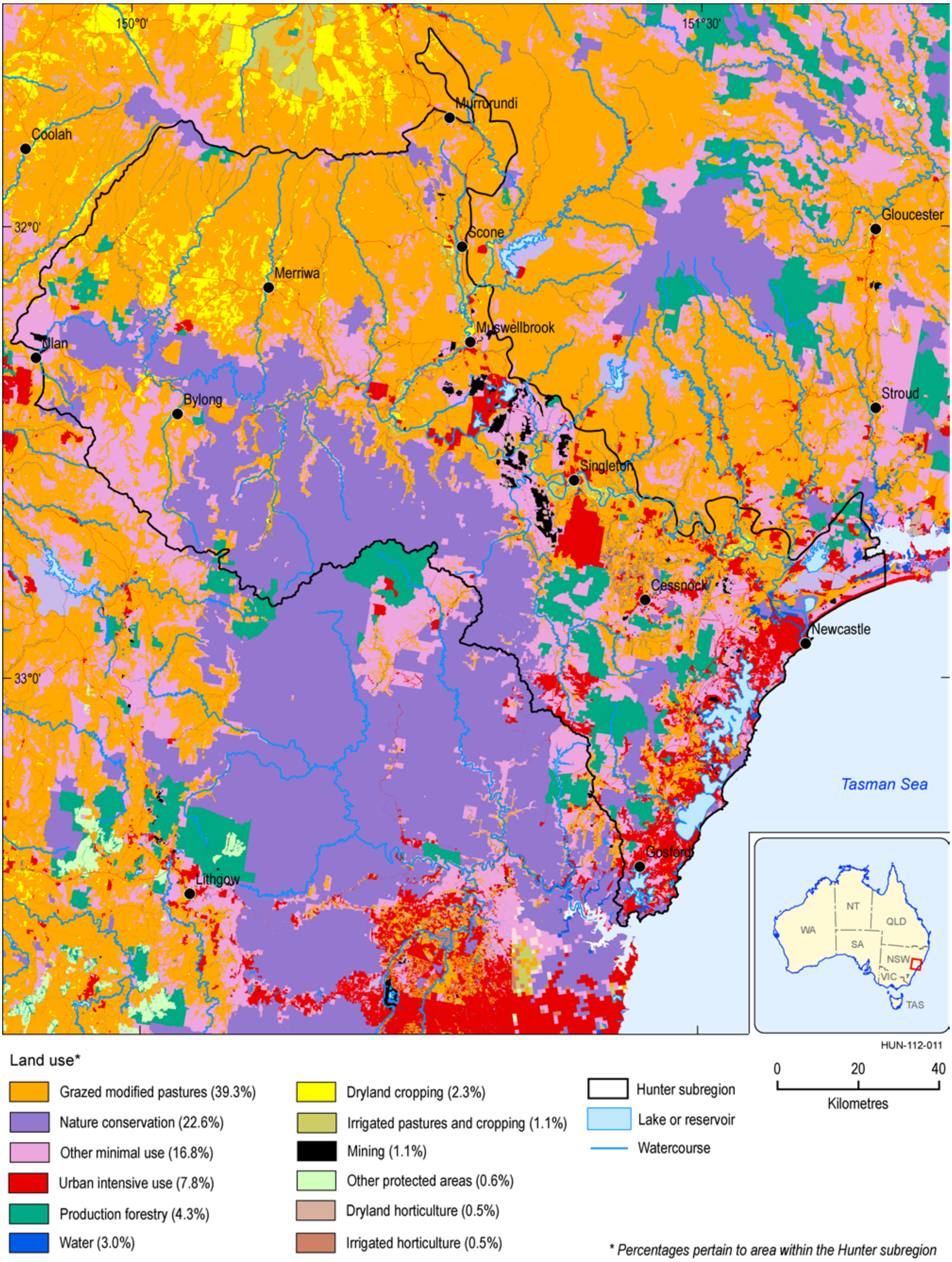

Figure 20 Land use in the Hunter subregion

Data: ABARES (Dataset 13)

The largest single current land use in the Hunter subregion is grazed modified pastures (i.e. ~40% of the subregion, Figure 20), with approximately another 40% of the subregion being classified as ‘nature conservation’ or ‘other minimal uses’ (Figure 20). Almost half of the remaining 20% of the subregion is urban (i.e. 7.8% of the total subregion), mining is 1.1% of the area (mainly focused in the Muswellbrook to Singleton area), and primary production other than grazed modified pastures (forestry and various agricultural activities, both irrigated and dryland) covers 8.7% of the subregion, with water bodies occupying 3% of the subregion area (Figure 20).

Figure 21 shows that there are several major dams on rivers in the Hunter subregion, including Glenbawn Dam (on the Hunter River), Liddell Dam (on Antiene Creek, among others), Glennies Creek Dam (on Fal Brook) and Grahamstown Dam (connected to the Williams River via surface canals). There are other dams within the Hunter subregion and numerous farm dams are located throughout the subregion. The Hunter River is regulated downstream from Glenbawn Dam to where it discharges to the Tasman Sea near Newcastle (Figure 21). Additionally, Fal Brook, a tributary of the Hunter River joining upstream of Singleton, is regulated downstream from Glennies Creek Dam (Figure 21).

Water use in the Hunter subregion is primarily for urban centres (both domestic and industry use), agricultural production (i.e. grazing, viticulture and other crop irrigation), and cooling of the Bayswater, Liddell, and Redbank coal-fired power stations (Figure 21) that provide a substantial component of electrical energy requirements in NSW. Other coal-fired power stations, including Eraring, Vales Point and Munmorah, are cooled primarily with salt water and do not require a water licence from NSW Office of Water (Dave Hoey, NSW Office of Water, pers. comm. 27 Oct 2014). Over the past five years the Munmorah power station has been decommissioned in a staged approach. Two of the four turbines were maintained on standby, but not used in production since August 2010, and the power station was disconnected from the grid in May 2014. Water is used in the coal mines that are located in the Hunter subregion, and to address the balance between water availability and salinity of the Hunter River the Hunter River Salinity Trading Scheme (HRSTS) was established in 1995; further details about the HRSTS are provided in the following Section 1.1.5. In some farms adjacent to the river network, water may be derived from any mixture of local surface runoff, bore water (i.e. groundwater) and extracted river water.

The NSW Government introduced coal seam gas (CSG) exclusion zones in October 2013 for existing residential zones in all local government areas in NSW (NSW Government, 2015). In January 2014, ‘future residential growth areas’, ‘additional rural village land’ (seven villages), and the equine and viticulture critical industry cluster (CIC) areas in the Upper Hunter were added to the CSG exclusion area. The exclusion zones ban new CSG activity inside, and also within a two kilometre buffer around, residential zones, future residential areas and additional rural village land. There is no buffer area around critical industry clusters. Additionally, information was released in January 2014, identifying the areas of ‘biophysical strategic agricultural land’ – land of high quality soil and water resources capable of supporting high levels of agricultural production – across NSW, which it deemed necessary to support the state’s $12 billion/year agricultural industry (NSW Government, 2014). The CSG exclusion zones for the Hunter subregion are shown in Figure 22, covering a total of 31.2% of the subregion. The CSG exclusion areas do not affect the existing arrangements for non-CSG types of mining and petroleum activity. In addition to the exclusion zones, within NSW mining and petroleum production are generally prohibited in land uses such as conservation zones (national park and other reserves) and in some land zoned for environmental protection. The exclusion zones relates to both the land surface and all geological strata below, this means no gas can be extracted using horizontal wells below the exclusion zones.

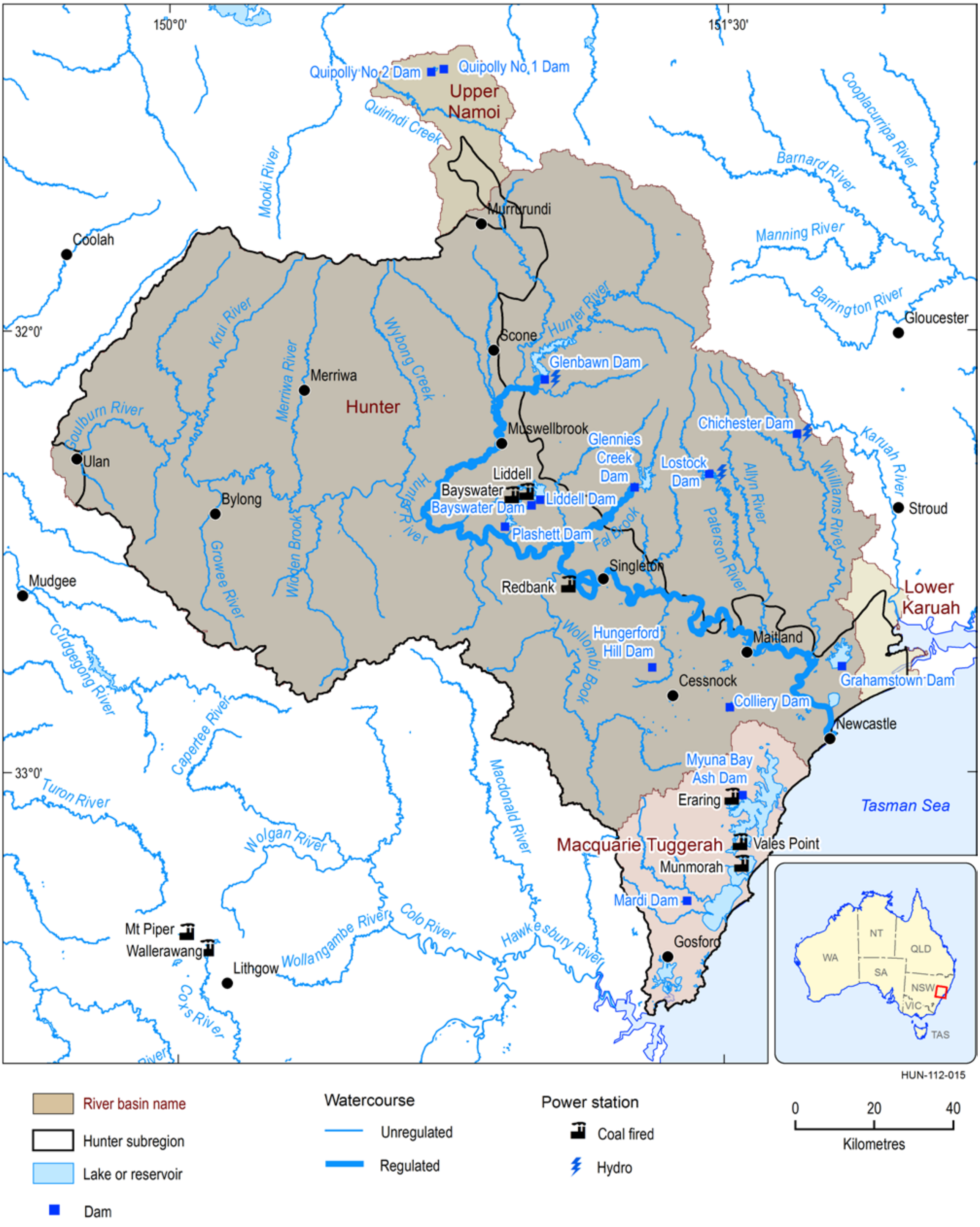

Figure 21 Dams and river regulation in the Hunter subregion

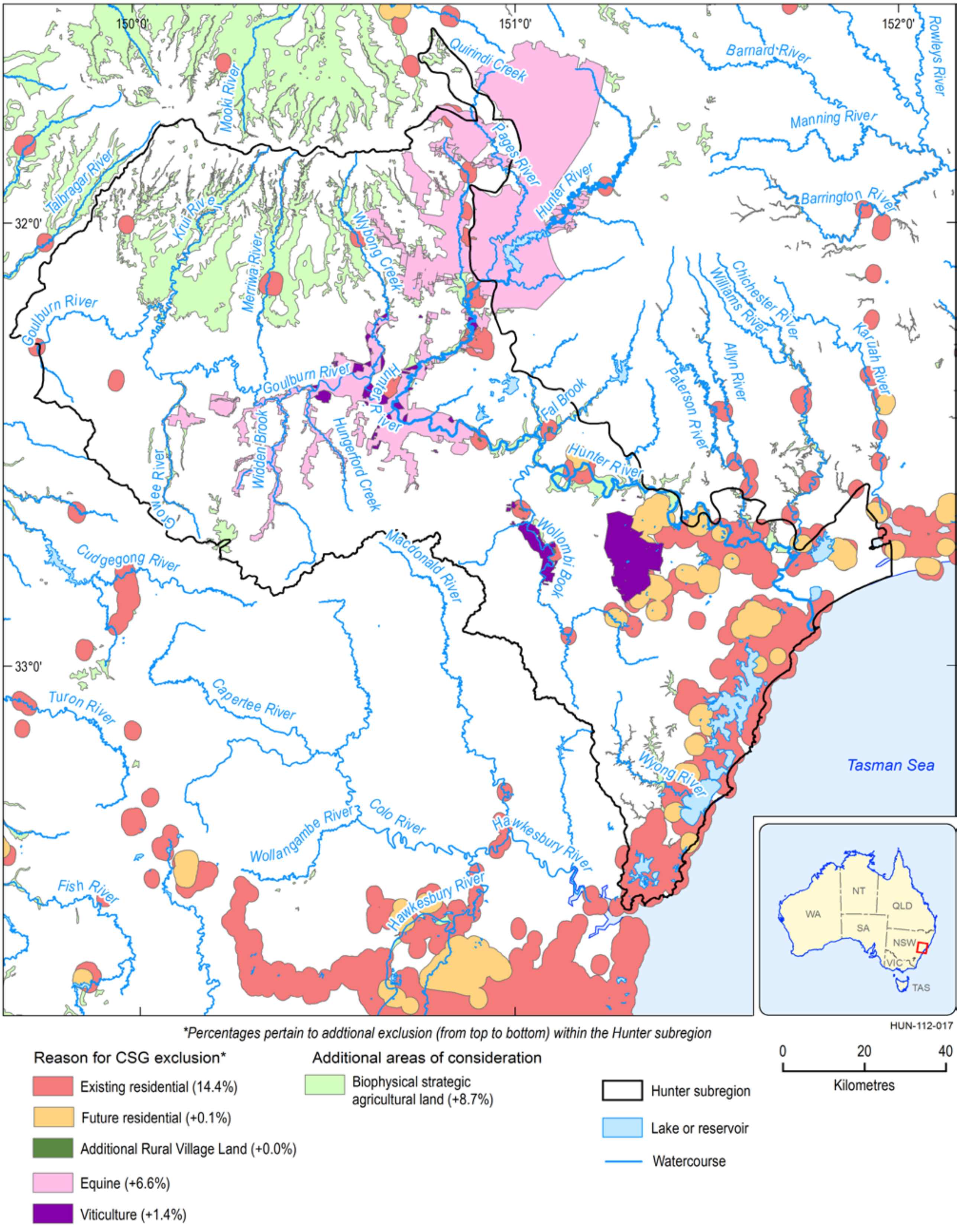

Figure 22 Coal seam gas exclusion zones in the Hunter subregion

As the coal seam gas (CSG) exclusion zones are overlapping the additional area to those above is indicated by a '+' sign. The biophysical strategic agricultural land is not part of the CSG exclusion zone and is considered in a separate NSW Government process.
Data: Department of Planning and Infrastructure (Dataset 14)

In this section, national Australia-wide grids of daily precipitation (P; available from 1900 onwards) generated by the Bureau of Meteorology (Jones et al., 2009) are used; they are 0.05 degree (or ~5 km) grid cell resolution. The Penman formulation is used to calculate daily potential evapotranspiration (PET; a measure of the atmosphere's 'drying power'), which is calculated per Donohue et al. (2010a), with meteorological data, other than daily mean wind speed (McVicar et al., 2008), being provided by the Bureau of Meteorology (Jones et al., 2009). The PET data also have 0.05 degree (or ~5 km) grid cell resolution. The daily PET data (1982 onwards, due to use of satellite based albedo (the colour of the land surface, defining how much sunlight is reflected) in the radiation calculations) and daily mean wind speed data (1975 onwards, when the Bureau of Meteorology network of anemometers become suitable for national assessment) are generated, and made freely available, by CSIRO Land and Water.

The climate is sub-tropical in the eastern part of the subregion, bordering on temperate in the western part of the subregion. The long-term (i.e. 1900 to 2012) mean P in the subregion is approximately 779 mm/year (Figure 23). Like much of Australia there is considerable inter-annual variability, with some years receiving high P (e.g. 1950 received 1490 mm/year) and consecutive years of lower than mean P (e.g. 1979 to 1983) that indicate drought conditions (Figure 23). This analysis shows temporal variability of a key hydrological variable: precipitation. Climate also exhibits spatial variability and Figure 24(a) shows the 1982 to 2012 annual mean P varies spatially over the subregion. In the broader vicinity of the subregion this ranges from 600 to 1440 mm/year; the higher P values are associated with higher elevations (Figure 8). In the subregion over the last 30 years (i.e. 1982 to 2012) the annual mean P is 793 mm/year, with the maximum and minimum being 1400 and 598 mm/year, respectively. PET in the broader vicinity of the subregion varies from 1250 to 1950 mm/year, and, as expected, the spatial pattern is complementary to P. Areas receiving high amounts of P are usually cooler and cloudier, so the PET values are lower in these parts of the landscape. Within the subregion the 1982 to 2012 annual mean PET is 1728 mm/year, and with the maximum and minimum being 1908 and 1462 mm/year, respectively.

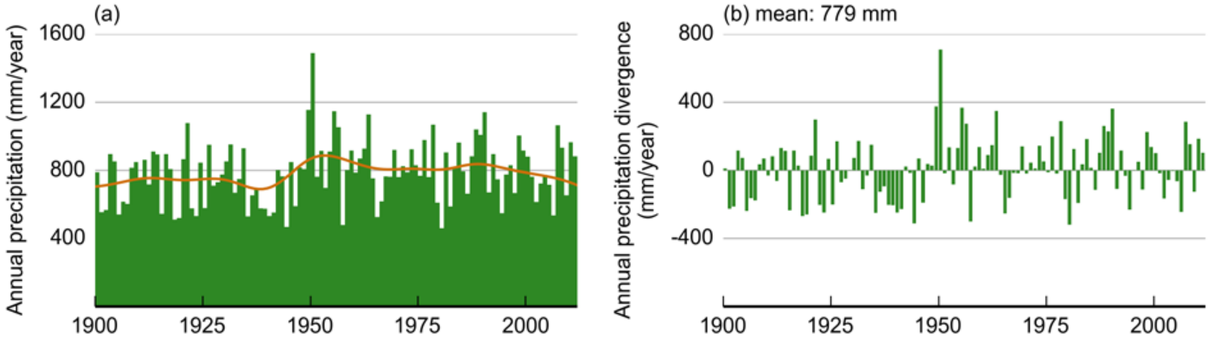

Figure 23 Temporal characteristics of annual precipitation for the Hunter subregion

(a) shows subregion-averaged annual precipitation with smoothed rolling average (orange line) and (b) annual precipitation divergence from the long-term (1900 to 2012) mean.
Data: Jones et al. (2009)

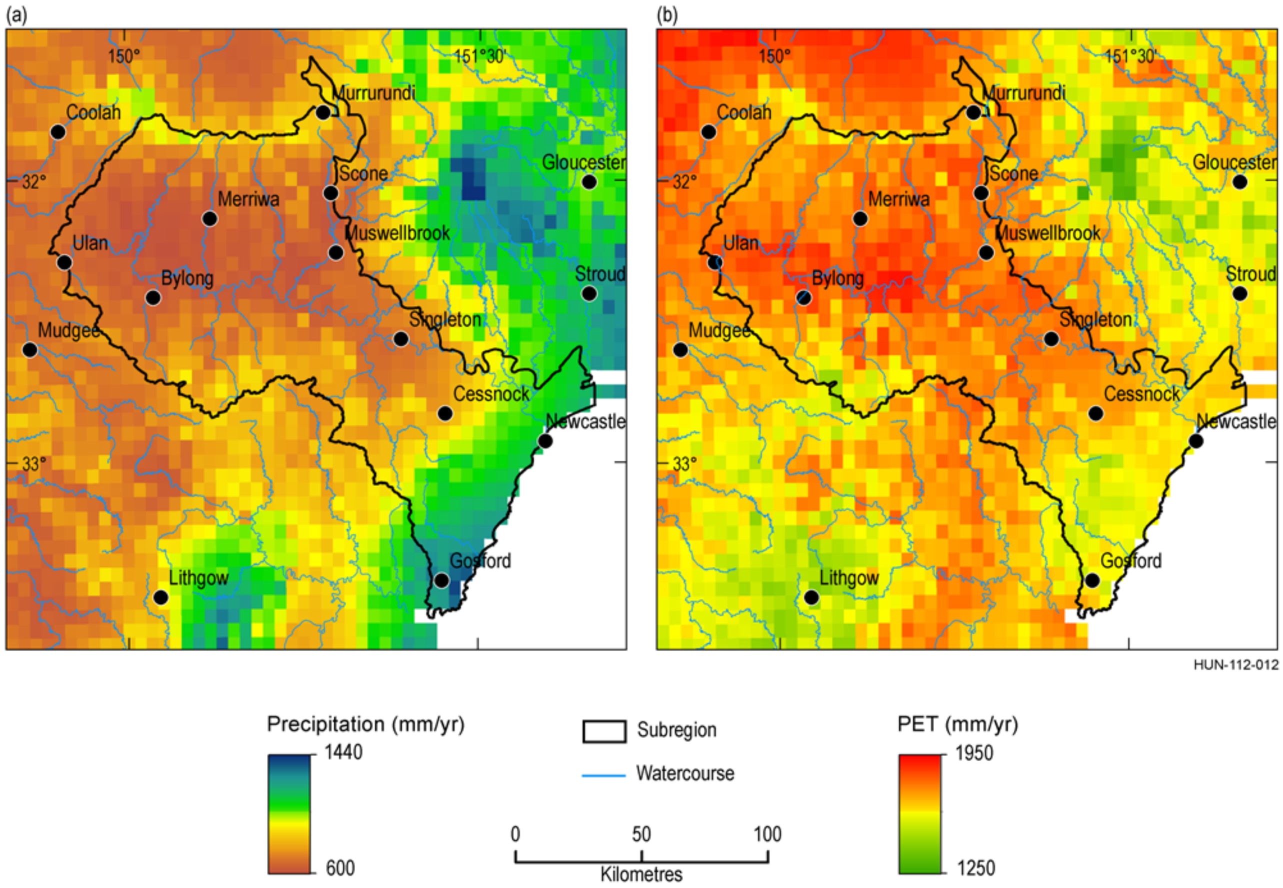

Figure 24 Spatial variation of 1982 to 2012 (a) annual mean P and (b) annual mean PET for the Hunter subregion

Data: (i) P from Jones et al. (2009), (ii) PET from Donohue et al. (2010a)

Using subregion-specific averages, within a year there is a slight seasonal cycle in P (Figure 25). On average, the rainy season extends from November to March, with the winter months (i.e. June to August, inclusive) being the relative drier part of the year. When monthly P is compared to monthly PET we see that P has a smaller magnitude to PET with PET being greater than P for most (not all) months. Given soil water storage dynamics, the Hunter subregion can be considered as ‘equitant’ (i.e. straddling the water-limit and energy-limit) throughout the year (McVicar et al., 2012b). This suggests that actual evaporation (AET) in the Hunter subregion is slightly water-limited (defined when the PET/P ratio is greater than 1.0, as opposed to being energy-limited; when PET/P is less than 1.0). Given the high amounts of P (relative for Australian conditions) there will be high levels of AET and associated vegetation growth (see Figure 16 and Figure 17).

Figure 26 shows mean monthly conditions over the past 30 years (i.e. 1982 to 2012), and below this there is temporal variability for P, PET and the climate factors (primarily air temperature, vapour pressure deficit, net radiation and wind speed) that govern PET. As expected, monthly P experiences greater variability when compared to other climate factors (Figure 26).

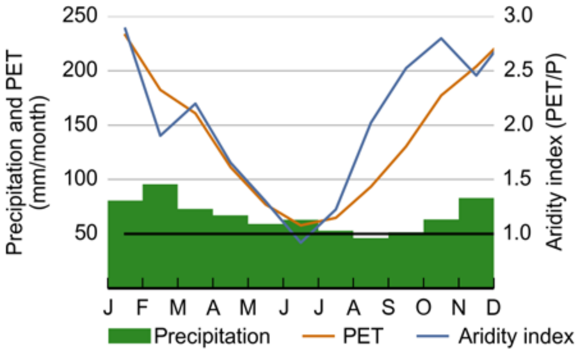

Figure 25 Mean monthly precipitation (P), potential evapotranspiration (PET) and aridity index for the Hunter subregion

Data: (i) P from Jones et al. (2009), (ii) PET from Donohue et al. (2010a)

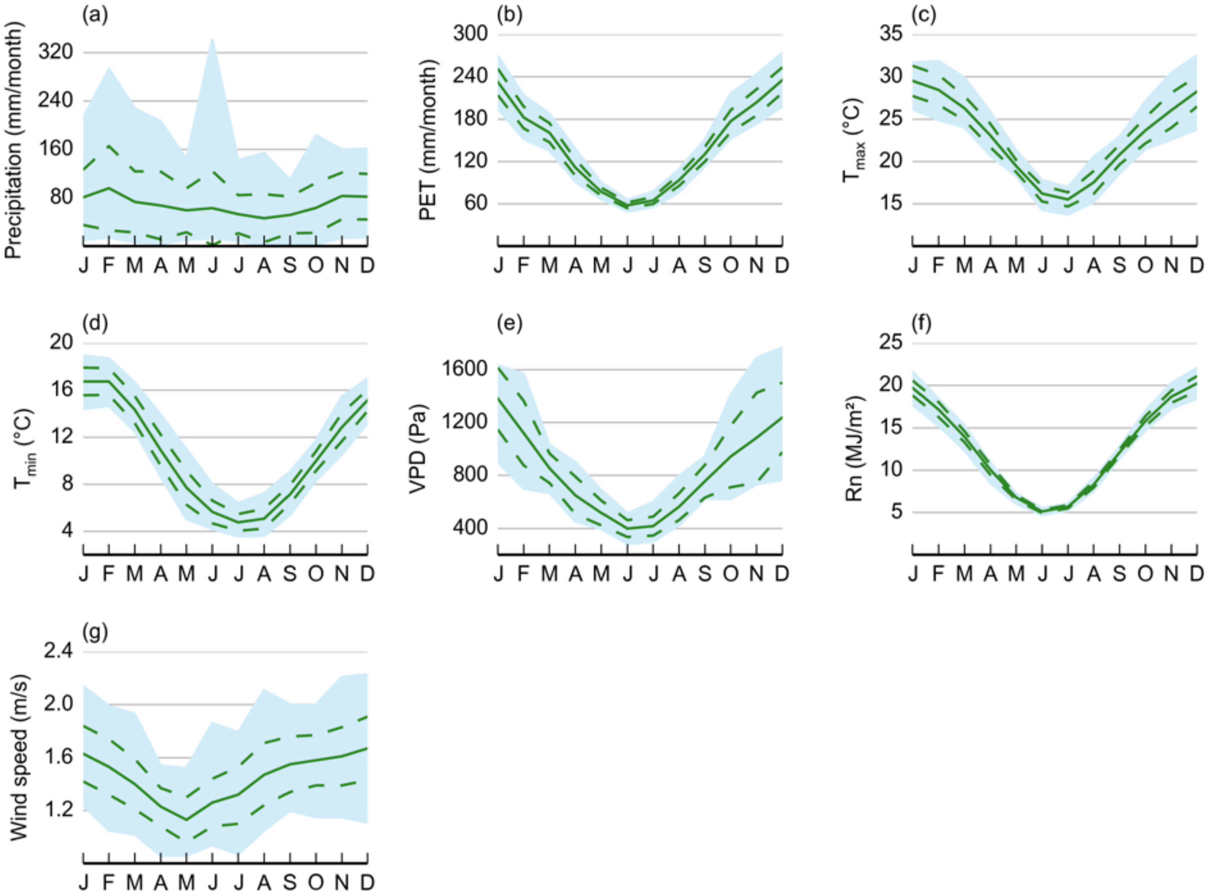

Figure 26 Monthly mean values of precipitation, potential evapotranspiration and other climate factors for the Hunter subregion

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 Hunter subregion. 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: (i) P, Tmax, and Tmin are from Jones et al. (2009), (ii) PET, VPD and Rn are from Donohue et al. (2010a), and (iii) wind speed is from McVicar et al. (2008)

Monthly trends of P, PET and all variables driving PET are shown in Figure 27. The monthly trends for precipitation 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 amounts of wind speed (in all months) and declining amounts of net radiation and vapour pressure deficit (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., 2010b; Donohue et al., 2011; McVicar et al., 2012a).

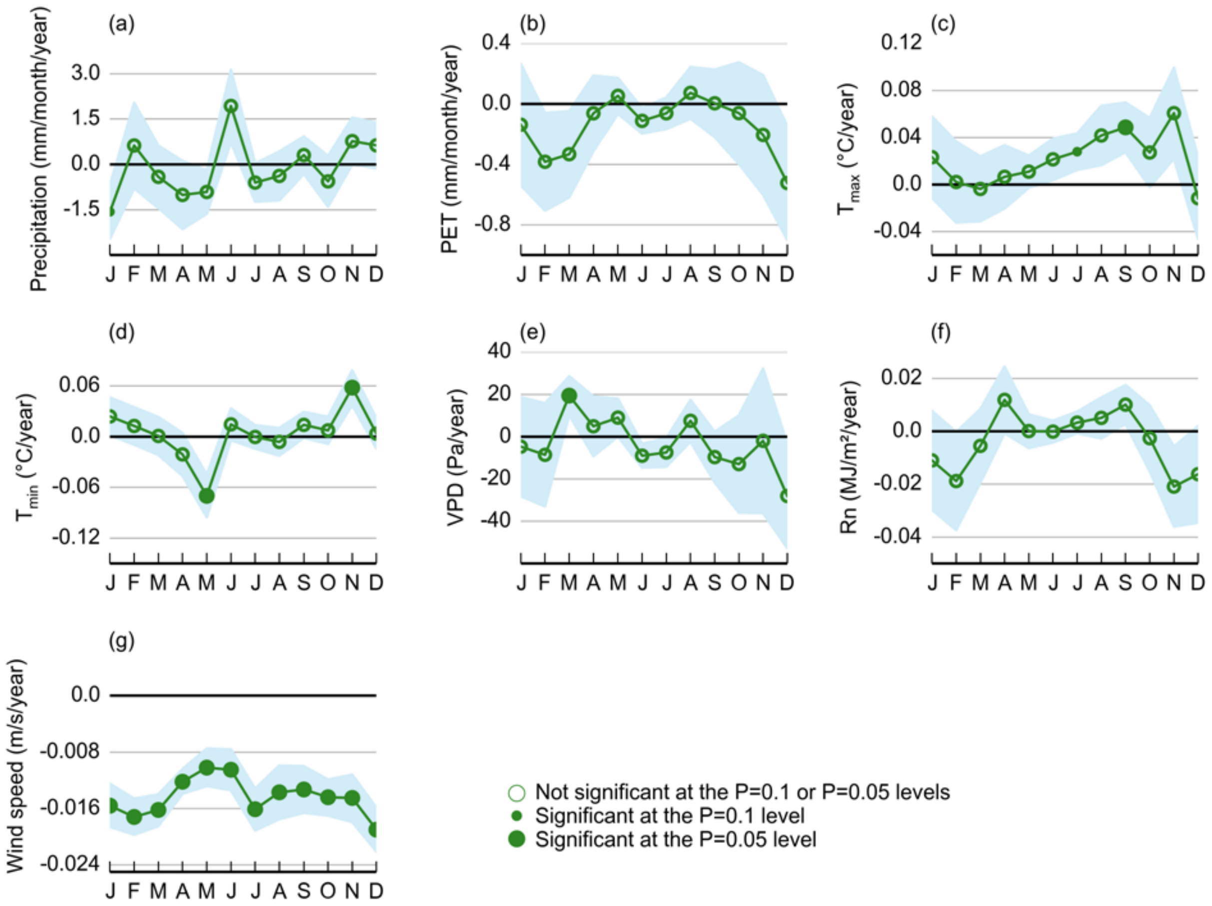

Figure 27 Annual trends by month of precipitation, potential evapotranspiration and other climate factors for the Hunter subregion

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 Hunter subregion. 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: (i) precipitation, Tmax, and Tmin are from Jones et al. (2009), (ii) PET, VPD and Rn are from Donohue et al. (2010a), and (iii) wind speed is from McVicar et al. (2008)

While future climate projections produced by global climate models (GCMs) are not in agreement (Lim and Roderick, 2009; Sun et al., 2011), one approach is to use their outputs and assess what future projections of rainfall and runoff will be. Using 15 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 to provide future daily climate projections of P and PET that can be used in a rainfall-runoff model. Compared to the global mean temperature in 1990, the IPCC A1B scenario indicates a global temperature that is 1 °C higher in 2030 and 2 °C higher in 2070. This scenario is based upon: (i) very rapid economic growth, (ii) with global populations peaking mid-century and declining thereafter, and (iii) the rapid introduction of new and more efficient technologies with a balance across all energy sources (IPCC, 2007). 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 for the 15 GCMs and reported changes for large catchments such as the Hunter River and Macquarie-Tuggerah Lakes catchments, which comprise much of the Hunter subregion (see Figure 10). Table 8 shows that for both catchments just over half of the GCMs selected suggest there will be 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 –9%, –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 –17%, –4% and 7%, respectively (Table 8).

Table 8 Summary of projected impacts of climate change on rainfall for the broad vicinity of the Hunter subregion

			1 °C of global warming			2 °C of global warming		
Basin	Historical precipitation (mm/year)	Number (out of 15) of global climate models projecting a decrease in future precipitation	Dry extreme	Median	Wet Extreme	Dry extreme	Median	Wet Extreme
Hunter River	770	8	–9%	–2%	4%	–17%	–4%	7%
Macquarie-Tuggerah Lakes	1137	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). Table 9 shows that the Post et al. (2012) modelling results suggest for a 1 °C rise in temperatures (associated with 2030) there is approximately a –22%, –6% and 7% change in Q projected for the dry extreme, median and wet extreme, respectively. For a 2 °C rise in temperatures (associated with 2070), these values are approximately –40%, –10% and 14%, respectively (Table 9). As noted previously the Hunter basin is ‘equitant’ and so estimates of both P and PET are important for future projections of Q (McVicar et al., 2012b). Given this, use of Morton’s wet environment areal formulation of PET, which does not include wind speed in its formulation, means that the impact of declining rates of observed wind speed which are offsetting increasing air temperature enhancement of PET (Donohue et al., 2010a; McVicar et al., 2012a; McVicar et al., 2012b) are not included in the resultant Q calculations. Hence the values presented in Table 9 are approximate projections only, as key process understanding is not encapsulated in the modelling.

Table 9 Summary of projected impacts of climate change on runoff for the broad vicinity of the Hunter subregion

			1 °C of global warming			2 °C of global warming		
Basin	**Historical precipitation (mm/year)**	**Number (out of 15) of global climate models projecting a decrease in future precipitation**	**Dry extreme**	**Median**	**Wet Extreme**	**Dry extreme**	**Median**	**Wet Extreme**
Hunter River	92	11	−22%	−6%	7%	−40%	−10%	15%
Macquarie-Tuggerah Lakes	271	11	−22%	−6%	6%	−41%	−10%	13%

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

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1.1.3 Geology

Summary

The Hunter subregion is within the geological Sydney Basin and the minor Werrie Basin, which in turn form part of the Permian-Triassic Sydney-Gunnedah-Bowen Basin (SGBB) that developed as a contiguous geological complex. The Sydney Basin is structurally constrained to the west by the Lachlan Fold Belt, to the north-east by the New England Fold Belt, and to the east and south where the basin extends to the edge of the continental shelf. A basement high, the Mount Coricudgy Anticline, forms the basis of a structural boundary between the Sydney and Gunnedah basins. However, sedimentary rocks typical of the northern Sydney Basin occur north of the Mount Coricudgy Anticline, implying connectivity between the basins. The Werrie Basin stratigraphy is closely associated with the Sydney and Gunnedah basins.

Coal measure sedimentation in the Sydney Basin began in the early Permian and was terminated towards the end of the Permian by major uplift and basin tilting. Permian fluvial, coastal plain and marine sediments were deposited on Paleozoic basement, after which rapid subsidence led to deposition of coal-bearing sequences in the late Permian. The Hunter subregion straddles three of the five coalfields that make up the Sydney Basin: mainly the Hunter and Newcastle coalfields and part of the Western Coalfield. The Hunter and Newcastle coalfields each host three coal measure sequences: the Greta Coal Measures, the Wittingham Coal Measures (in the Hunter with its equivalent in the Newcastle Coalfield, the Tomago Coal Measures), and the Newcastle Coal Measures. The main coal of economic interest in the Western Coalfield is the Illawarra Coal Measures.

The Greta Coal Measures in the Sydney Basin form a wedge-like sequence ranging from 60 to 90 m thick. The Homeville Coal Member of the Greta Coal Measures is up to 8 m thick and outcrops at Kurri Kurri. The coals were formed as a result of peat accumulation behind advancing barrier islands. The informally named Greta seam of the Greta Coal Measures, however, is sulfur-rich, indicating that it was deposited in a marine environment. The Foybrook Formation, which is part of the Wittingham Coal Measures, contains coal seams interbedded with sandstone, siltstone, claystone and tuff, formed by a river-dominated delta system. The coals are particularly well developed in the Muswellbrook area but are characterised by erratic splitting, which is also true of other coals in the Wittingham Coal Measures. The Jerrys Plains Subgroup is the upper part of the Wittingham Coal Measures that developed as part of a river-dominated sedimentary sequence and consists of multiple coal seams laid down in back-barrier coal swamp and delta plain environments. Coals formed in the upper delta plain are thicker and laterally continuous. In the Newcastle Coalfield the coals (such as those of the Tomago Coal Measures) formed in terrestrial, lower delta plain and brackish marine environments. The Newcastle Coal Measures were deposited under fluvial (river) conditions and are subject to splitting and erosion caused by rapid channel migration of the river system.

The Illawarra Coal Measures are divided into four subgroups in the Western Coalfield which is within the Hunter subregion: the Nile Subgroup that consists of prodelta to lower delta-plain sediments; the Cullen Bullen Subgroup that hosts the Marrangaroo Formation, the Lithgow Coal, the Blackmans Flat Formation and the Lidsdale Coal, that were deposited in fluvial and deltaic environments; the Charbon Subgroup that consists of several formations, coals and oil shales; and, the Wallerawang Subgroup that typically consists of sediments likely to have been deposited in alluvial, point-bar, levee and floodplain environments. Deposition of the Charbon Subgroup occurred in a delta system (such as Long Swamp Formation) and overbank swamps (such as Irondale Coal), in addition to distributary mouth bar-crevasse splays (Angus Place Sandstone) and lower delta plains (State Creek Mine Formation). Some of the coals are economic whereas others are thin, discontinuous and uneconomic. A marine interval is represented by the Baal Bone Formation, which is 10 to 50 m thick and represents possibly a lower delta-front environment and a back-barrier swamp environment, such as the Moolarben Coal Member. The Werrie Basin contains coal that correlates with the Greta Coal Measures in the Hunter Coalfield.

1.1.3.1 Geological structural framework

The Sydney Basin forms part of the composite Permian-Triassic age Sydney-Gunnedah-Bowen Basin (SGBB) system, which extends for approximately 1700 km from southern NSW to central Queensland, as illustrated in Figure 28. The Sydney-Gunnedah part of the basin (also referred to as the Sydney-Gunnedah Basin) is up to approximately 600 km long and approximately 200 km wide and extends offshore to the edge of the continental shelf (Tadros, 1995, p. 163).

The SGBB system evolved as a large, elongate geological complex, from the Late Carboniferous to the Middle Triassic (approximately 310 to 230 million years ago (Ma)). The series of contiguous basins formed along part of the ancient Gondwana continental margin and has a complex, multiphase history including early rifting in a back-arc environment, and thermal subsidence evolving into a retro-arc foreland basin (Bann et al., 2004, p. 181). The prolonged, subsiding basin environment was therefore suitable for coal accumulation. A three-dimensional geological model of the SGBB produced by Danis (2012, p. 26) shows an outline of the basement structure, providing knowledge on the depth to basement, depth to basal volcanics and thickness of the sedimentary rock sequence.

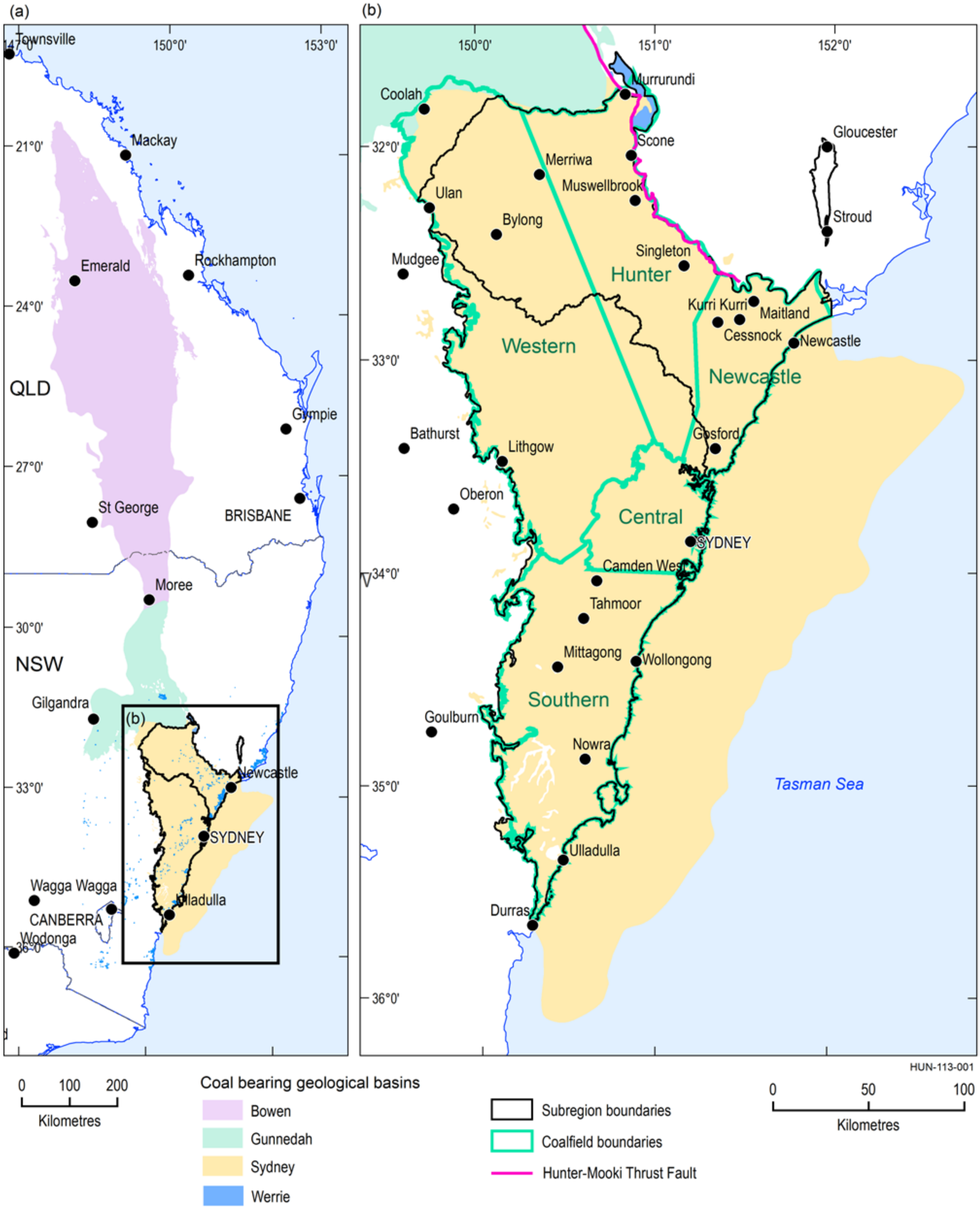

Figure 28 Location of the Sydney Basin showing the main coalfields of the basin

Data: DTIRIS (Dataset 1), Geoscience Australia (Dataset 2), DTIRIS (Dataset 3)

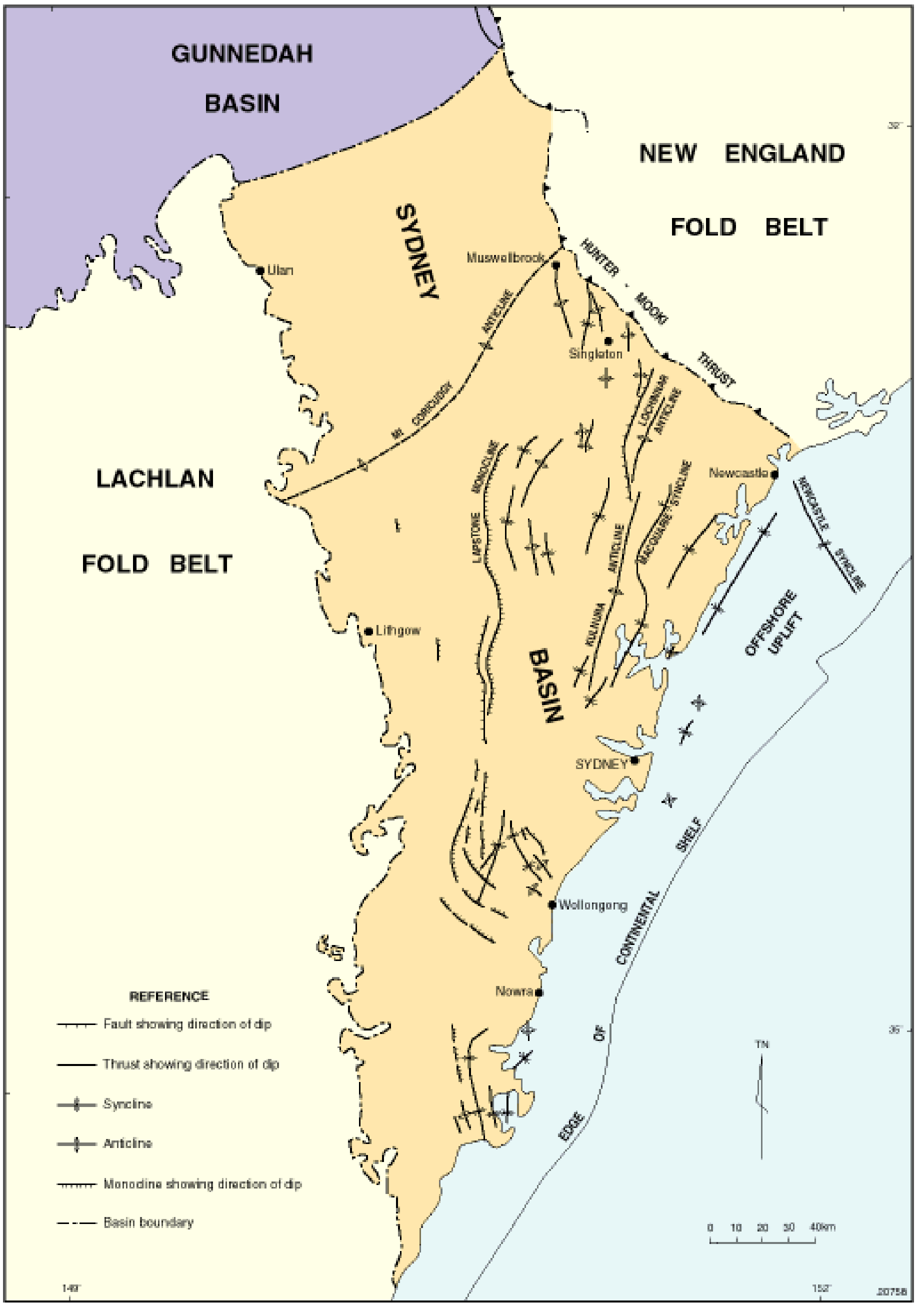

Figure 29 Structural elements of the Sydney Basin

Source: Stewart and Alder (1995)

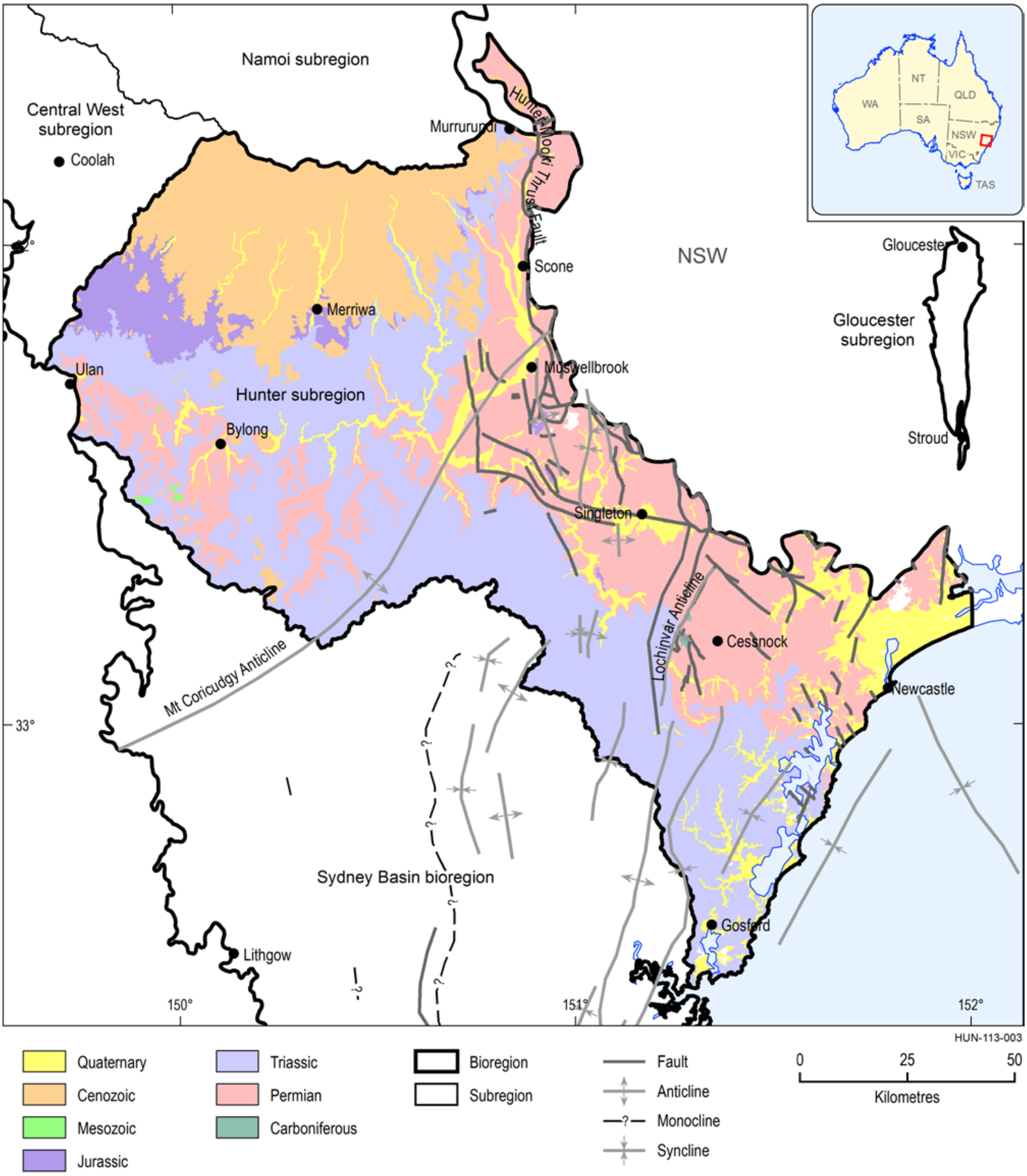

Figure 30 Surface geological map of the Hunter subregion

Data: Stewart JR and Adler JD (1995), Geoscience Australia (Dataset 4)

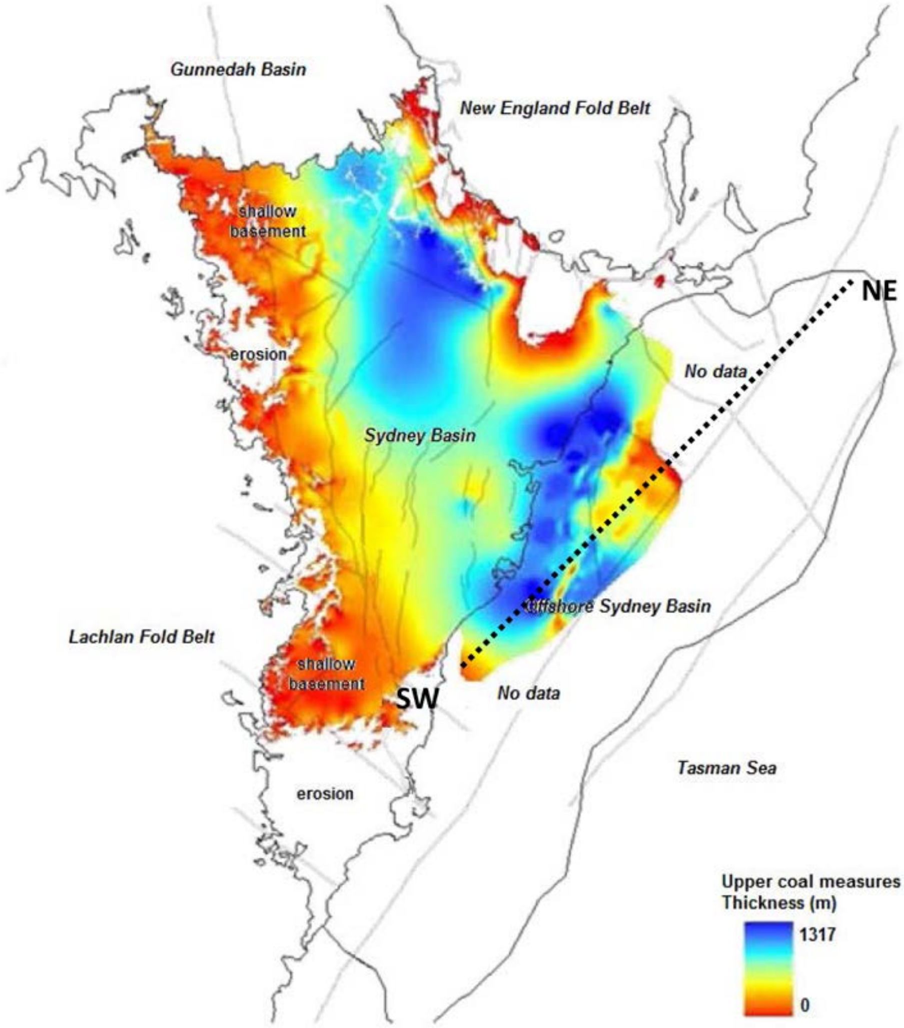

Figure 31 Thickness contour map of the upper coal measures of the Sydney Basin (modified from Blevin et al., 2007)

Dotted line shows the approximate transect for the cross-section in Figure 32

The main structural boundaries of the Sydney Basin include the Hunter-Mooki Thrust Fault System in the north-east, and an erosional or depositional boundary in the west where the Permian-Triassic sedimentary rocks on-lap the Lachlan Fold Belt (Figure 28 and Figure 29). The Mount Coricudgy Anticline is believed to divide the Sydney Basin from the Gunnedah Basin to the north where the basement shallows (Danis et al., 2011, p. 536; Bembrick et al., 1980, p. 2). In the south-east, the Sydney Basin extends to the edge of the continental shelf (Tadros, 1995, p. 163).

The sedimentary pile in the Sydney Basin is asymmetrical. The thickest accumulations are along the east-dipping Hunter-Mooki Thrust Fault System (Figure 29) suggesting that subsidence was greatest along that fault. The sequence thins to the west.

Coal measure sedimentation in the Sydney Basin began in the early Permian and was terminated towards the end of the Permian by major uplift and basin tilting (Scheibner, 1999, p. 27). The earliest Permian units were deposited in fluvial, coastal plain and marine environments on older Paleozoic basement rocks. This deposition was followed by rapid subsidence in the middle Permian, providing more space for sediment accumulation, with the main period of coal deposition occurring in the late Permian (Tadros, 1995, p. 166). The Sydney Basin contains generally flat-lying, Permian-Triassic sequences and ranges from 2 to 4 km in depth (Veevers, 1984; O'Neill and Danis, 2013, p. 19).

Within the Hunter subregion rocks of Triassic age outcrop across most of the surface in the south, whereas rocks of Permian age outcrop along the Hunter-Mooki Thrust Fault in the east, as shown in Figure 30. In the north Cenozoic-aged basalts cover most of the surface (Figure 30). These intrusions are discussed in the hydrogeology section of the context statement. Figure 31 shows the distribution of the upper coal measures within the basin, which is thickest in the northern and south-eastern regions. The structure, major rock units and coal measure sequences in the basin are shown in the cross-section in Figure 32.

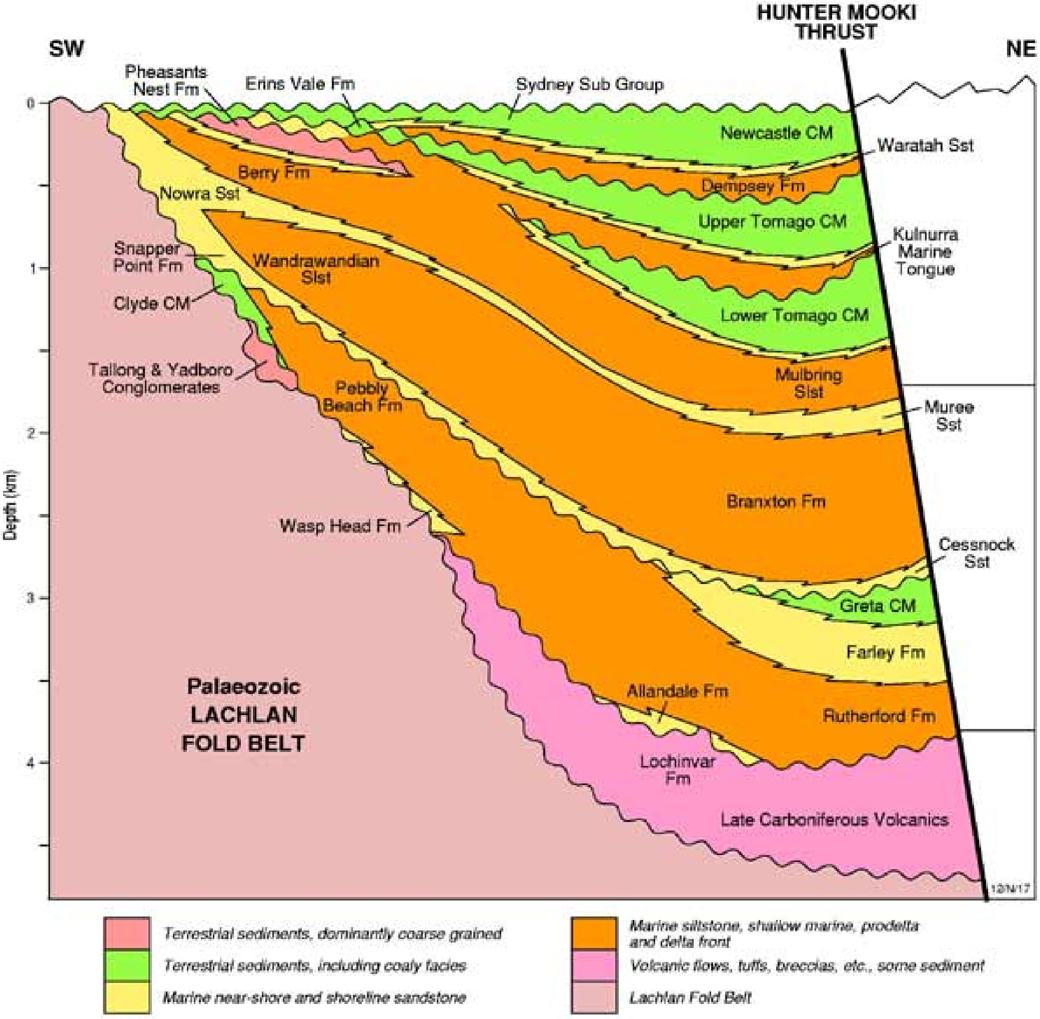

Figure 32 A south-west–north-east cross-section through the Sydney Basin showing the major rock units and coal measure sequences

Source: Geoscience Australia (2014)
The likely location of section line is shown in Figure 31

The Sydney Basin has five coalfields: the Hunter, Newcastle, Western and Southern coalfields, which are currently mined, and the Central Coalfield which is not mined (Figure 28). Each is based on structural and geographic boundaries. The stratigraphic horizons across the western, southern and central regions can be well correlated, with the bulk of the coal deposits hosted within the Illawarra Coal Measures, as shown in the generalised stratigraphic column in Figure 33.

Stratigraphic horizons in the north and north-eastern regions can be well correlated, where coal deposits are generally hosted within the three coal measure sequences. Younger sedimentary units of Jurassic and Cenozoic age also occur in the Hunter subregion but are not shown in Figure 33 and are not the focus of this geology section because they do not contain significant economic coal resources. These Jurassic and Cenozoic units may contain groundwater resources, and thus are mentioned in places throughout Section 1.1.4.

The Werrie Basin is located on the eastern side of the Hunter-Mooki Fault System on New England Fold Belt basement adjacent to the eastern side of the Gunnedah Basin and the north-western side of the Sydney Basin. It is a north–north-west trending synclinal structure in the south-western part of the New England Fold Belt. The Werrie Basin lies within the buffer zone of the Sydney and Gunnedah basins and contains a terrestrial coal-bearing unit that correlates with the Maules Creek Formation in the Gunnedah Basin and the Greta Coal Measures in the Hunter Coalfield of the Sydney Basin. The Hunter-Mooki Fault System terminates the basin at each end (Resources and Conservation Assessment Council, 2002, p. 65). There is currently no official geographic information system (GIS) shapefile available for the Werrie Basin (S Lewis, Geoscience Australia, 2014, pers. comm.). A digitised file of the basin extent has thus been prepared specifically for this assessment. Due to its relatively small size, the Werrie Basin is not currently included in the Australian Geological Provinces Database (Geoscience Australia, 2013). As this feature is so small and ill defined, in some geological circles it is termed the Werrie Syncline. Definition of the Hunter subregion used a spatially disconnected part of the Gunnedah Basin (Geoscience Australia, 2009) with a boundary that closely resembles other more detailed definitions of the Werrie Basin (Carey, 1934; DMR, 2002).

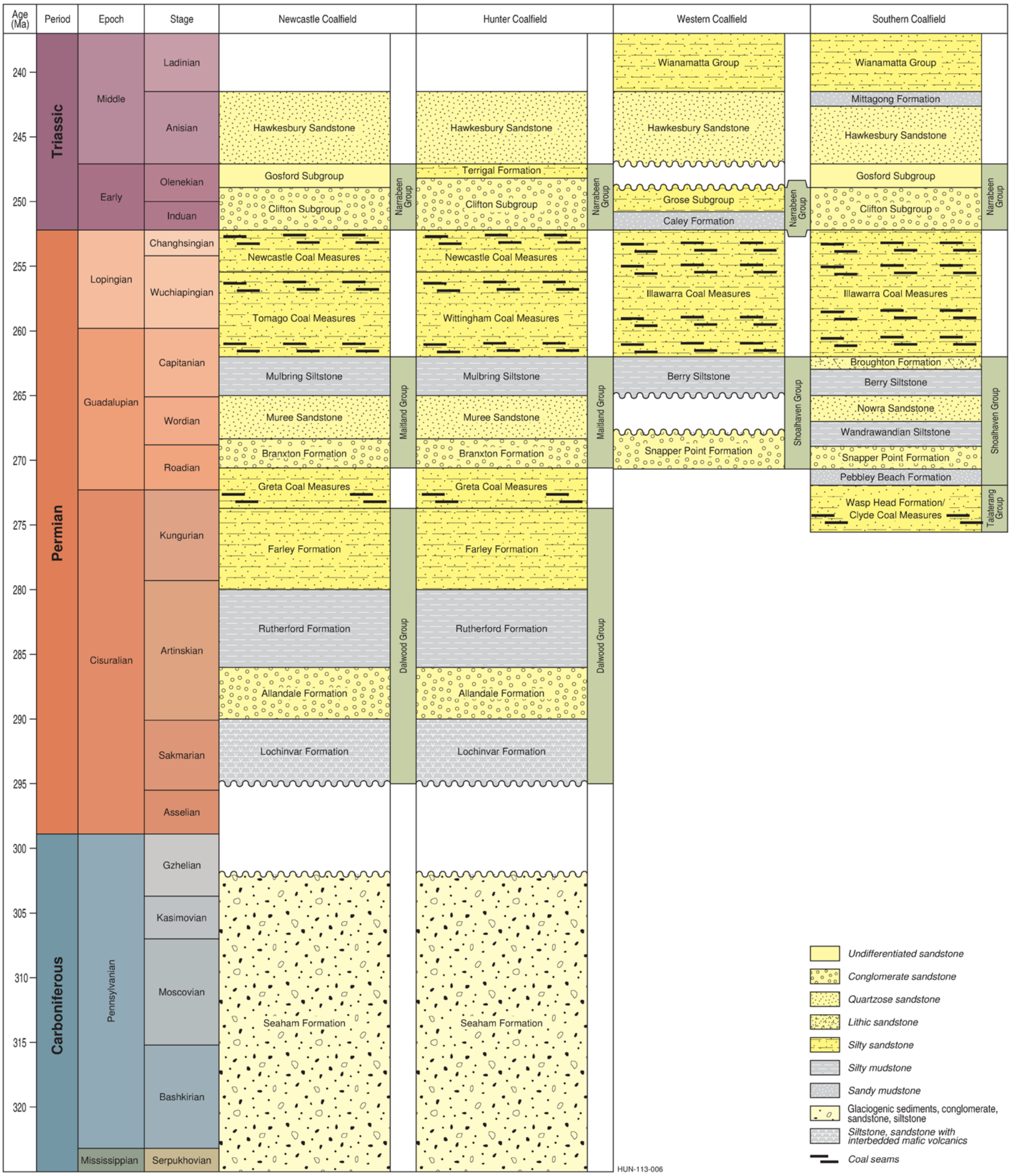

Figure 33 Generalised stratigraphic column of the Permian and Triassic units in the main coalfields of the Sydney Basin (Younger Jurassic and Cenozoic units that occur in the Hunter subregion are not shown here as they do not contain economic coal resources)

Source: Geoscience Australia (2014)

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

1.1.3.2 Stratigraphy and rock type

The Hunter subregion includes parts of the Hunter, Newcastle and Western coalfields, and the stratigraphy and rock types of these areas are discussed in this section. More detailed information on the Southern Coalfield of the Sydney Basin can be found in the Sydney bioregion context statement report. The Central Coalfield is not discussed further as it is not a prospective area and it is currently unlikely that it would be developed in future. This section is not focused on discussing in detail all of the stratigraphic units known from the three coalfield areas. The focus here is on providing a suitable overview of the main coal-bearing stratigraphic units and some of the key non-coal bearing units. More information about the coal and coal seam gas resources, mines and proposed developments can be found in the Hunter subregion product 1.2.

1.1.3.2.1 Hunter Coalfield

In the north-east of the Sydney Basin the Hunter Coalfield hosts the Newcastle, Wittingham and Greta coal measures. The main stratigraphic units for the coalfield are shown in Figure 33. According to Glen and Beckett (1989, p. 592), most of the sediments were sourced nearby from the uplifted New England Fold Belt. Sedimentation in the coal basins is characterised by four major episodes of deltaic to fluvial deposition, separated by three marine transgressive events.

Greta Coal Measures

The middle Permian Greta Coal Measures (Figure 33) were deposited by fluvial and deltaic sediment systems that prograded into the basin, and are exposed in the northern part of the coalfield near Muswellbrook, and in the south along the western limb of the Lochinvar Anticline. In the Muswellbrook area the Greta Coal Measures (comprising sandstone, siltstone, claystone, chert and coal) are characterised by crevasse-splay, marsh or lacustrine, and coal swamp deposits (Sniffin and Beckett, 1995, p. 177). The Greta Coal Measures are stratigraphically subdivided into several constituent formations. The Rowan Formation, which contains bright coal seams, igneous intrusions and fine-grained sedimentary rocks with some clastic sand bodies (Boyd and Leckie, 2000, p. 261), overlies the basal Skeletar Formation, which consists of colluvial/alluvial mudstone, sandstone and conglomerate. Around the Lochinvar Anticline the coal measures overlie the marine sedimentary rocks of the Rutherford and Farley formations, and have characteristic fine-grained conglomerate with associated sandstone, siltstone, mudstone and shale. The massive, fine-grained Neath Sandstone rests on the formations mentioned above and is overlain by the Kurri Kurri Conglomerate, which hosts the Lower and Upper Homeville Coal Members. Overlying that are the Kitchener and Paxton formations, which are also coal-bearing (Van Heeswijck, 2001, p. 420). Underground it is separated from the overlying Greta seam (Greta seam is an informal name according to the Australian Stratigraphic Units Database) mainly by conglomerate up to 30 m thick (Hutton, 2009, p. 48). The Greta seam in the Cessnock area is up to approximately 11 m thick. The coals are thicker in the Muswellbrook area, where the seams are associated with the Muswellbrook Anticline. In the south near the Lochinvar Anticline, the deepest coals, the Lower and Upper Homeville seams are low ash yielding coals with high volatile matter. Seam continuity is commonly disrupted by faulting and some seams are affected by igneous intrusions (Basden, 1969, p. 325).

Maitland Group

The Branxton Formation of the Maitland Group (Figure 33) was formed under transgressive marine conditions, followed by a significant marine regression depositing conglomeratic fan-delta and interbedded sandstone and siltstone forming the Muree Sandstone. Large amounts of silt and clay were then deposited in a deep marine shelf environment to form the Mulbring Siltstone (Sniffin and Beckett, 1995, p. 185).

Wittingham Coal Measures

The sandstone-dominated Saltwater Creek Formation represents a transition from a marine delta front to river-dominated lower delta plain deposits on which the overlying Vane Subgroup of the Wittingham Coal Measures rests. The Foybrook Formation of the Vane Subgroup contains coal seams interbedded with sandstone, siltstone, claystone and tuff layers, and was formed by a river-dominated delta system with sediments derived from two main source areas (Sniffin and Beckett, 1995, p. 180). A marine incursion followed deposition of the Foybrook Formation resulting in deposition of the sandstone-rich Bulga Formation and the Archerfield Sandstone; the latter comprises beach/barrier beach-lagoon deposits. Near Muswellbrook the Bulga Formation-Archerfield Sandstone sequence seems to form a single unit, whereas the Bulga Formation is absent towards the south (Sniffin and Beckett, 1995, p. 186). The coals of the Foybrook Formation are well developed in the Muswellbrook area but are characterised by erratic splitting. Many of the coal seams of the Wittingham Coal Measures are characterised by multiple splitting. Individual coal seams tend to be thin and of inferior quality, and have fewer igneous intrusions than the seams in the Greta Coal Measures (Sniffin and Beckett, 1995, p. 181).

The Jerrys Plains Subgroup developed as a river-dominated sequence from major source areas outside of the coalfield. The Bayswater Coal Member is the lowest coal seam in this sequence, and was formed by progradation of a back-barrier coal swamp. Deposition of alternating interdistributary bay laminites and upwards coarsening crevasse-splay sandstones occurred in a lower delta plain environment, with the thin and banded Broonie Coal Member and Vaux Coal Member forming part of this sequence. Upper delta plain conditions then resulted in thicker and laterally continuous seams such as the Piercefield Coal Member and Mount Arthur Coal Member, after which lower delta plain conditions were re-established with the deposition of the Glen Munro through to the Whybrow Coal Member. Deposition of the Jerrys Plains Subgroup ended with a marine transgression, forming the base of the Denman Formation (Sniffin and Beckett, 1995, p. 181–182). Most of the coal mined in the Hunter Coalfield is sourced from the Jerrys Plains Subgroup.

Newcastle Coal Measures

The siltstone-sandstone laminites of the Denman Formation and the coarse arenites of the Watts Sandstone represent a depositional transgressive-regressive event between the Wittingham Coal Measures and the Newcastle Coal Measures. Rapid change to lower delta plain conditions following the progradation of the Watts Sandstone is the unit in direct underlying contact with the Newcastle Coal Measures. The Newcastle Coal Measures were deposited under fluvial conditions with rapid channel migration. Seam splitting and erosion are common (Sniffin and Beckett, 1995, p. 189).

Structural elements of the Hunter Coalfield

The major structures in the Hunter Coalfield include the Lochinvar, Muswellbrook, Camberwell and Sedgefield Anticlines, the Belford and Loder Domes, and the Bayswater and Rixs Creek Synclines. These are the major synsedimentary structures which formed during the Permian and affected the distribution of most sedimentary sequences in the coalfield, as well as thickness and architecture of the sequences (Sniffin and Beckett, 1995, p. 178). The major fault systems, namely the Hunter-Mooki Thrust Fault in the east, and the Mount Ogilvie Fault in the west, can be seen in Figure 34. The Hunter River Cross Fault in the south is not shown in Figure 34 as insufficient information on the trace of the fault was available during map preparation.

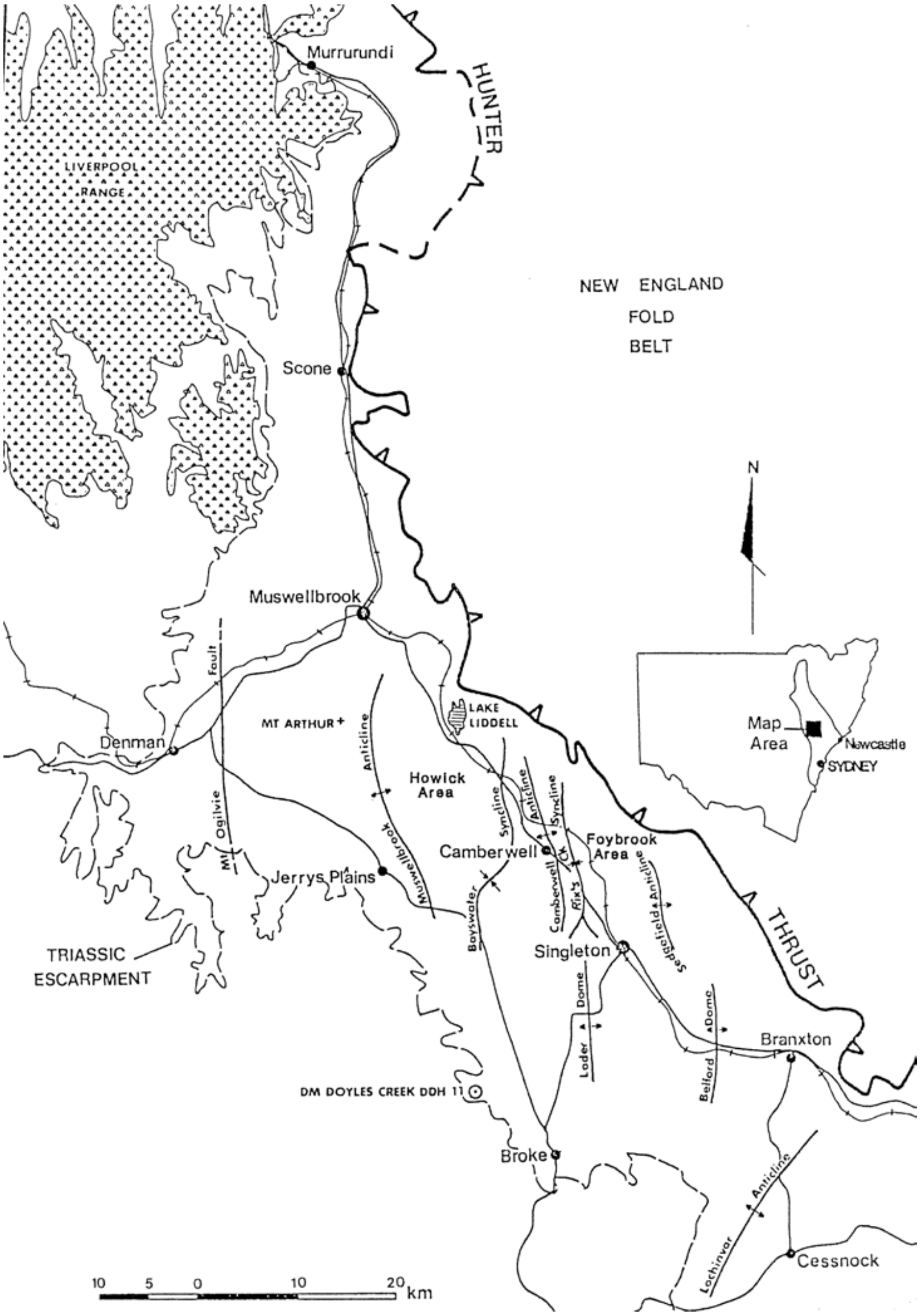

Figure 34 Structural elements of the Hunter Coalfield (Hunter Thrust shown here is the same as Hunter-Mooki Thrust Fault)

Source: Sniffin and Beckett (1995)

1.1.3.2.2 Newcastle Coalfield

Dalwood Group

The Dalwood Group comprises a mixed assemblage of marine sedimentary rocks and volcanic rocks, with the basal section consisting of shale, siltstone, and lithic sandstone alternating with basalt, volcanic breccia and tuff. The rest of the sequence consists of conglomerate, lithic and feldspathic sandstone, siltstone and shale, with minor limestone, marl and coal (Agnew et al., 1995, p. 197).

Greta Coal Measures

In the Newcastle Coalfield the Greta Coal Measures occurs as a stratigraphic wedge commonly 60 to 75 m thick (Agnew et al., 1995, p. 197), with a maximum known thickness of 90 m (McClung et al., 1980, p. 61). It comprises mainly sandstone and conglomerate with minor siltstone, shale and coal (Agnew et al., 1995, p. 197). The unit thins towards the south (McClung et al., 1980, p. 61). The Greta Coal Measures are confined in outcrop to the Lochinvar Anticline (McClung et al., 1980, p. 61). The massive and even-grained Neath Sandstone is the lowest unit in the coal measure sequence, on which the Lower and Upper Homeville Coal Members were formed as a result of peat accumulation behind advancing barrier islands. These seams coalesce and thin south of Kurri Kurri and are contained within the Kurri Kurri Conglomerate (Agnew et al., 1995, p. 203). The sulfur-rich Greta seam within the Kitchener Formation was deposited in front of a marine transgression and is split towards the east by the Kearsley Lens. The marine transgression was interrupted by coarse clastic sedimentation and deposition of the channel sands of the Paxton Formation, which hosts the Pelton Coal Member (Agnew et al., 1995, p. 204). Tuffaceous layers are fairly rare in the Greta Coal Measures (Agnew et al., 1995, p. 203). Unlike the Greta Coal Measures in the Hunter Coalfield, igneous dykes and sills are common in the Greta Coal Measures of the Newcastle Coalfield (Agnew et al., 1995, p. 204).

Maitland Group

The 1200 m thick sequence of marine sedimentary rocks of the Maitland Group is divided into three main formations: the Branxton Formation, the Muree Sandstone and the Mulbring Siltstone (Agnew et al., 1995, p. 197). The basal units consist of sandstone and sandy siltstone (Agnew et al., 1995, p. 199). The Branxton Formation, deposited during a steady marine transgression, contains mainly sandstone and conglomerate at the base and silty sandstone and siltstone are more common at the top (McClung, et al., 1980, p. 61). The Muree Sandstone consists of thick conglomerate adjacent to the Hunter-Mooki Thrust Fault, and sandstone and interbedded sandstone-siltstone facies further south (McClung, et al., 1980, p. 63). The Mulbring Siltstone approximately 330 m thick comprises mainly dark siltstone with minor claystone and sandstone (Agnew et al., 1995, p. 199) deposited under shallow marine conditions.

Tomago Coal Measures

The equivalent of the Wittingham Coal Measures in the Hunter Coalfield, the Tomago Coal Measures, thickens to the east, ranging from approximately 600 m near Maitland to greater than 1200 m in the Williamtown area (Agnew et al., 1995, p. 199). During deposition of the coal measures, marine to brackish environments prevailed (Diessel, 1980, p. 104). The coal measures contain one formation and two subgroups: the Wallis Creek Formation, Four Mile Creek and Hexham subgroups. The approximately 300 m thick Wallis Creek Formation is a cyclical sequence of terrestrial coal formation and brackish marine phases of bioturbated siltstone, fine-grained sandstone, mudstone and laminated shale. The main coal seams include the Morpeth and Rathluba Formations (Agnew et al., 1995, p. 204). The Four Mile Creek Subgroup has a higher coal to interseam sediment ratio compared to the other subgroups and shows no evidence of marine influence. It is approximately 160 m thick and the major economic horizons include the Donaldson seam and Big Ben Coal Member (Agnew et al., 1995, p. 204). The 140 m thick Hexham Subgroup is dominated by brackish to marine mudstone and laminite of the Dempsey Formation and the marine influence is reflected in sulfur values of the lower coals, such as the Buttai Coal. The uppermost section of the Hexham Subgroup is indicative of a lower delta plain setting and a return to terrestrial conditions of the Newcastle Coal Measures (Agnew et al., 1995, p. 204). The Tomago Coal Measures contain abundant thin but persistent tuffaceous claystone horizons (Agnew et al., 1995, p. 203).

Newcastle Coal Measures

The dominantly fluvial sequence of the Newcastle Coal Measures has a maximum known thickness of approximately 450 m, and consists of conglomerate, sandstone, siltstone, tuff and numerous coal seams (Agnew et al., 1995, p. 199). The coal measures were deposited in a high-energy terrestrial setting, resulting in significant amounts of coarse-grained sediments (Diessel, 1980, p. 104). Directly underlying the base of the Newcastle Coal Measures is the medium-grained, well sorted Waratah Sandstone which contains low- to high-angle cross bedding. On these sands the Borehole coal seam (informal name) developed in swamps covering back-barrier lakes and lagoons. Organic-rich mud, laminated shale and siltstone and sandstone form the base of the overlying interval of the Yard and Victoria Tunnel seams (informal names), an interval dominated by swamps and river deposits. Meandering river depositional conditions then changed to become braided channels. Following deposition of the Victoria Tunnel and Australasian seams (informal names), depositional conditions evolved from a braided channel to a higher energy piedmont-alluvial fan environment, culminating in the deposition of a conglomerate within the Adamstown Formation.

The coals within the interval between the Australasian and Fassifern seams (informal names) split and coalesce over short distances, and the interval is characterised by large volumes of tuffaceous material (Agnew et al., 1995, p. 205). Among the sedimentary formations in the Newcastle Coalfield, the Newcastle Coal Measures contain the greatest volume of pyroclastic rocks, with tuffaceous claystones of variable thickness and lateral extent occurring throughout the sequence (Agnew et al., 1995, p. 203). The clastic sediments of the upper Newcastle Coal Measures were deposited in well-defined channels by high-energy braided rivers. The Fassifern seam is the thickest and most widespread coal seam in the upper Newcastle Coal Measures. The lower part of the Fassifern seam is up to 8 m thick, and contains several mudstone and tuffaceous claystone bands in its basal section. The upper Fassifern seam is separated from the lower Fassifern seam by the lower phase of a conglomerate in the Boolaroo Formation, and the upper Fassifern seam is also separated from the Awaba Tuff by a conglomerate in the Boolaroo Formation.

The Awaba Tuff, which ranges from 1 to 27 m, is the most widespread unit in the Newcastle Coal Measures (Agnew et al., 1995, p. 206). Above the Awaba Tuff the Great Northern seam is associated with several phases of a major alluvial channel system deposited contemporaneously with the seam. At the top of the Newcastle Coal Measures the Wallarah seam is present over all but the north-western portion of the coalfield, where it is known as the Vales Point seam (Agnew et al., 1995, p. 208).

Structural elements of the Newcastle Coalfield

The Hunter-Mooki Thrust Fault forms the north-western boundary of the coalfield (Agnew et al., 1995, p. 208). Various fold structures influence the outcrop pattern, thickness variation and distributions of the Tomago and Newcastle Coal Measures in the Newcastle Coalfield (Diessel, 1980, p. 111). Major fold structures include the south-plunging Lake Macquarie Syncline in the centre of the coalfield. The Lochinvar Anticline is present in the west, as shown in Figure 35. Minor fold structures include the Delta Syncline at the Hunter River mouth and the Shepherds Hill Anticline (Diessel, 1980, p. 113). North-trending faults disrupt the Permian and Carboniferous units in the coalfield, some with displacements of greater than 60 m. Faults with less significant displacement occur throughout the coalfield, including normal, reverse, strike-slip and bedding plane faults. Igneous dykes are common (Agnew et al., 1995, p. 209).

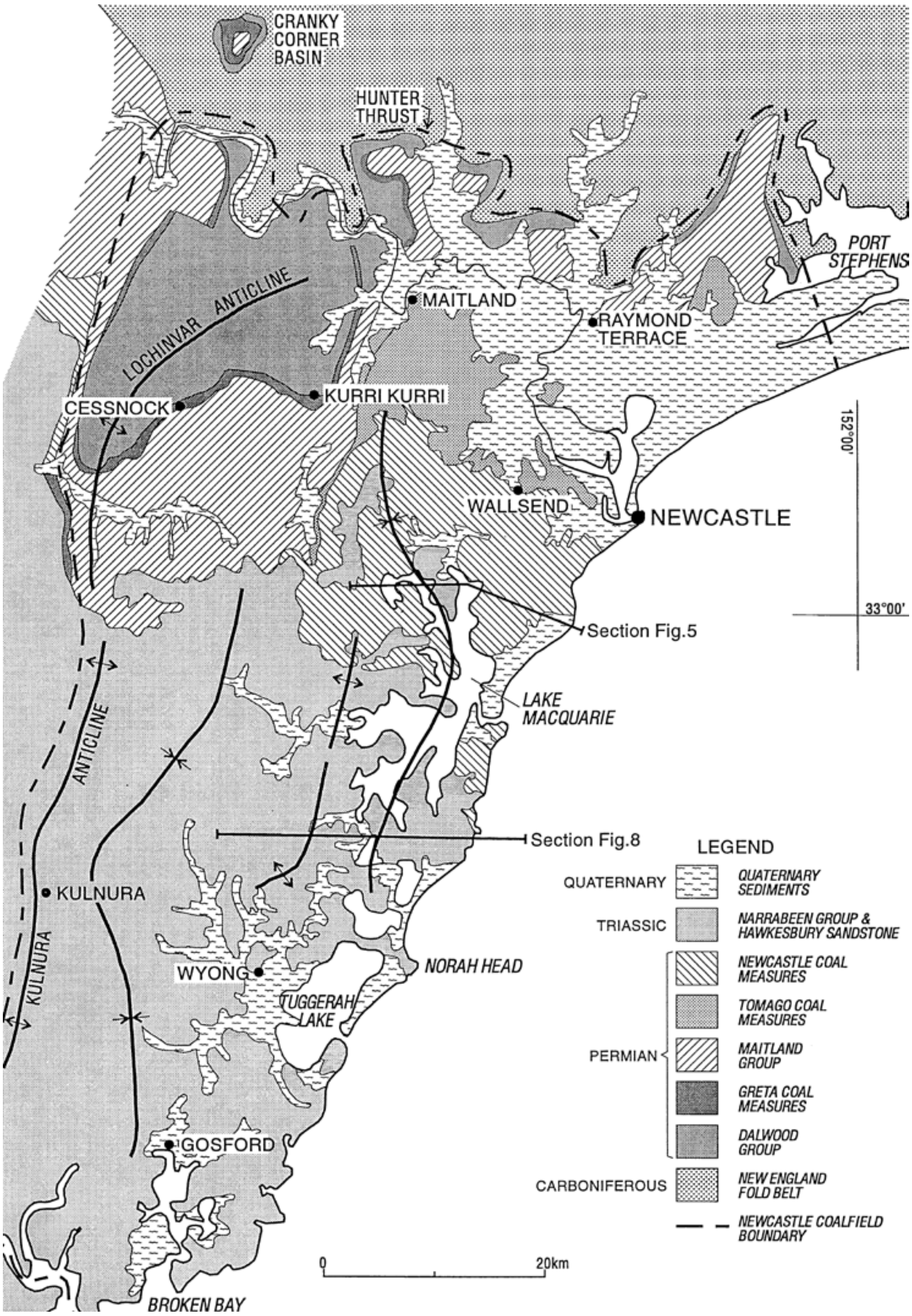

Figure 35 Structural elements of the Newcastle Coalfield

Source: Agnew et al. (1995)

1.1.3.2.3 Western Coalfield

Talaterang Group

In the Western Coalfield the Talaterang Group forms the basal part of the Sydney Basin succession and the rocks are relatively undeformed (Tye et al., 1996, p. 58). It is overlain by the Shoalhaven Group and includes the Clyde Coal Measures and the Wasp Head Formation (Tye et al., 1996, p. 58). Hutton (2009, p. 43) stated that there was little possibility of economic seams being found in the Clyde Coal Measures of the Western Coalfield as the seams are discontinuous and thin.

Shoalhaven Group

The relatively undeformed rocks of the Shoalhaven Group disconformably overlie the Talaterang Group, and are largely interpreted as being of marine shelf to coastal plain origin (Tye et al., 1996 p. 58, 63). The Shoalhaven Group is of early Permian age and includes the Yarrunga Coal Measures. Hutton (2009, p. 43) stated that there was little possibility of economic seams in the Yarrunga Coal Measures, since, similar to the Clyde Coal Measures, the seams of the Yarrunga Coal Measures are discontinuous and thin. In the Western Coalfield the Shoalhaven Group unconformably overlies basement metamorphic rocks of Silurian and Devonian age and Carboniferous granite (Yoo et al., 2001, p. 9). It consists of the Snapper Point Formation, an approximately 90 m thick medium-grained sandstone, and the Berry Siltstone, a predominantly grey micaceous sandy siltstone which can be up to 210 m thick (Yoo et al., 2001, p. 10).

Illawarra Coal Measures

The Illawarra Coal Measures dip gently to the east in the south and to the north-east in the north of the coalfield (Yoo et al., 1995, p. 231). In the Western Coalfield the sequence is divided into four subgroups: the Nile, Cullen Bullen, Charbon and Wallerawang subgroups.

The Mount Marsden Claystone is the lowermost formation of the Nile Subgroup, and consists mainly of sandstone and claystone (Yoo et al., 1995, p. 234). It is overlain by the quartz-lithic Coorongooba Creek Sandstone, which grades into the Gundangaroo Formation at the top. The latter is an interbedded quartz-lithic sandstone and carbonaceous siltstone with some coal beds (Yoo et al., 1995, p. 234, 239). The three formations of the subgroup, which were deposited under prodelta to lower delta plain conditions, are not consistently recognisable throughout the coalfield (Yoo et al., 2001, p. 15).

The main lithological units of the Cullen Bullen Subgroup are the Marrangaroo Conglomerate, the Lithgow Coal, the Blackmans Flat Conglomerate and the Lidsdale Coal (Yoo et al., 2001, p. 15). The Marrangaroo Conglomerate is an upwards fining pebbly sandstone or conglomerate which grades into a medium-to-fine-grained sandstone, between 2 and 24 m thick. Sediments of the Marrangaroo Conglomerate were incorporated into a fluvial environment which prograded into fan deltas. Extensive swamps in the interlobe areas of these deltas provided a suitable environment for the deposition of the dull coal and interbedded carbonaceous claystones of the Lithgow Coal (Yoo et al., 1995, p. 239). The Lithgow Coal overlies the Marrangaroo Conglomerate, and is the major economic coal unit in the Lithgow, Rylstone and Bylong areas, ranging in thickness from less than 1 to 9 m (Yoo et al., 1995, p. 236; Yoo et al., 2001, p. 21). It is overlain by the coarse-grained, commonly pebble-bearing, quartzose sandstone of the Blackmans Flat Conglomerate, which was deposited in an alluvial plain. The latter is up to 20 m thick in the south of the coalfield, and ranges from approximately 3 to 11 m at Bylong, and from 2 to 5 m in the Ulan area (Yoo et al., 2001, p. 24). The Lidsdale Coal consists of predominantly dull coal with minor bright coal layers, thin claystone, carbonaceous and tuffaceous claystone and siltstone, and ranges in thickness from less than 1 to 5 m. In the north of the coalfield the Lidsdale Coal is persistent in the Ulan area, where it makes up the lower section of the Ulan Coal. The Ulan Coal has a total thickness of approximately 14 m in the Ulan area (Yoo et al., 1995, p. 238–240; Yoo et al., 2001, p. 26).

In ascending stratigraphic order the Charbon Subgroup includes the Long Swamp Formation, Irondale Coal, Newnes Formation, Glen Davis Formation, Baal Bone Formation (Denman Formation equivalent), Angus Place Sandstone (Watts Sandstone equivalent) and State Mine Creek Formation. The Long Swamp Formation consists of claystone and siltstone, which are commonly bioturbated, tuff, sandstone, and thin discontinuous coal layers, formed within delta systems prograding from the north-east. The mean thickness of the formation in the west of the coalfield is 30 m and increases to 60 m in the area east of Rylstone and 100 m south-west of Mount Coricudgy (Yoo et al., 1995, p. 238; Yoo et al., 2001, p. 28).

The dull and bright coal with stone bands of the Irondale Coal is relatively thin (1.3 to 1.5 m) but persistent and formed in an overbank swamp environment. In the Ulan-Bylong area the uppermost ply of the Ulan Seam is correlated with the Irondale Coal (Yoo et al., 1995, p. 238–240; Yoo et al., 2001, p. 29).

The Newnes and Glen Davis formations were deposited as overbank and swamp deposits (Yoo et al., 1995, p. 240). The Newnes Formation is between 8 and 14.5 m thick between Lithgow and Ulan, and approximately 4 m near Bylong. It generally consists of a fine- to medium-grained, lithic sandstone, and interbedded siltstone and claystone west of the Wollar Hingeline, and an upward-fining lithic sandstone east of the Wollar Hingeline (Yoo et al., 1995, p. 238; Yoo et al., 2001, p. 29).

The coal, carbonaceous claystone, claystone, siltstone and sandstone of the Glen Davis Formation have a total mean thickness of approximately 8.1 m and generally range between 17 and 26 m thick in the north of the coalfield. The Glen Davis Formation contains two thin, uneconomic coal seams, the upper of which is the Bungaba Coal Member, which consists of dull coal (with minor bright coal) and numerous carbonaceous and tuffaceous claystone layers. At Newnes and Glen Davis the formation hosts oil shales. The thick quartzose sandstone of the Cockabutta Creek Sandstone Member is also hosted within the Glen Davis Formation and ranges in thickness from 2.5 to 9.8 m.

The Glen Davis Formation is overlain by the Baal Bone Formation east of the Ulan Hingeline and by the Moolarben Coal Member of the State Mine Creek Formation west of the Ulan Hingeline (Yoo et al., 1995, p. 238; Yoo et al., 2001, p. 35–37). The marine interval represented by the Baal Bone Formation is 24 m thick in the Lithgow area and as far north as Rylstone and Bylong. It is 10 m thick near Ulan and thickens in an easterly direction from 20 m at Bylong to 50 m at Denman. The rocks consist of dark grey claystone, laminated claystone and fine-grained sandstone with common bioturbation, into fine-grained, which grades into lithic sandstone of possible lower delta-front environment (Yoo et al., 1995, p. 238; Yoo et al., 2001, p. 40).

The coarsening-up lithic sandstone of the Angus Place Sandstone, a distributary mouth bar-crevasse splay facies, is white, coarser grained, cross-bedded and with calcareous cement and ranges in thickness from 5 m to a maximum of 15.5 m (Yoo et al., 1995, p. 239; Yoo et al., 2001, p. 41).

The lower delta plain facies of the State Mine Creek Formation consist of claystone, mudstone, siltstone, and minor sandstone, and three coal seams are generally present: the Moolarben and Turill Coal Members, and the ‘Lennox seam’ or ‘Goulburn seam’ (informal names), which is only locally developed in the Ulan area. The formation ranges in thickness from 5 to 10 m along the western margin and thickens towards the east. The Moolarben Coal Member, deposited in a back-barrier swamp, consists predominantly of dull coal with some bright coal layers at its base. Similarly the Turill Coal Member consists of dull coal with bright layers and numerous thin carbonaceous claystone layers in the lower half (Yoo et al., 1995, p. 239; Yoo et al., 2001, p. 41–43).

The Wallerawang Subgroup consists of the Gap Sandstone and the overlying Farmers Creek Formation; generally reaching a total thickness of approximately 27 m with a maximum recorded thickness 59 m (Yoo et al., 2001, p. 43). The fluvial channel Gap Sandstone is an off-white upward-fining medium-to-coarse-grained quartz-lithic to lithic sandstone, with a consistent thickness ranging from 3 to 5 m across most of the coalfield and locally thicker (11 m) in the Wilpinjong area (Yoo et al., 2001, p. 43). The Farmers Creek Formation hosts the Middle River Coal Member at the base, the Woodford Coal Member in the middle and the Katoomba Coal Member at the top (Yoo et al., 1995, p. 239). It consists of claystone, carbonaceous claystone, siliceous claystone, siltstone, sandstone and coal and oil shale (Yoo et al., 2001, p. 43). The formation consists of alluvial, point-bar, levee and floodplain sequences with floodplain swamps (Yoo et al., 1995, p. 240).

Narrabeen Group and Digby Formation

The quartz-lithic sandstones of the Narrabeen Group form near-continuous and mesa-like plateaux, which are characteristic morphological features in the Western Coalfield. The sequence can be up to 656 m and moderately thins westwards (Yoo et al., 2001, p. 52). In the north of the coalfield equivalents of the Narrabeen Group were referred to as the Wollar Sandstone, although this formation has lithological composition and lithofacies characteristics similar to the Digby Formation of the Gunnedah Basin. The four different rock types recognised in the northern part of the coalfield include conglomerate, quartz-lithic sandstone, quartzose sandstone siltstone and sandstone (Yoo et al., 2001, p. 52).

Hawkesbury Sandstone

The Hawkesbury Sandstone has a thickness of approximately 244 m in the Kurrajong Heights area and thins westwards to 52 m at Mount Tomah and 55 m at Mount Banks. It is massive, quartzose sandstone with numerous quartz conglomerate layers and sporadic shale lenses (Yoo et al., 2001, p. 53).

Napperby Formation and Wianamatta Group

The approximately 35 m thick Napperby Formation is recognised in the northern part of the Western Coalfield, and consists of an upwards coarsening lacustrine sequence, with finely laminated dark grey claystone at the base, finely layered siltstone and sandstone laminite in the middle, and lithic sandstone at the top (Yoo et al., 2001, p. 53). The Wianamatta Group is represented in the Western Coalfield by the Ashfield Shale. Rocks of the Napperby Formation in the northern part of the coalfield have similar characteristics to those of the Wianamatta Group (Yoo et al., 2001, p. 53).The Ashfield Shale consists of a lower sequence of dark grey to black, sideritic claystone-siltstone and grades upwards into a fine sandstone-siltstone laminite (Herbert, 1980, p. 262), which is preserved under basalt on the eastern side of Mount Tomah and at Mount Irvine (Yoo et al., 2001, p. 54).

Jurassic and Cretaceous units

In the northern part of the Western Coalfield, Lower to Middle Jurassic fluvial and lacustrine sedimentary rocks fluvial and lacustrine sedimentary rocks of the Purlawaugh Formation unconformably overlie the Triassic rocks of the Napperby Formation. The Purlawaugh Formation consists mainly of quartz-lithic sandstone, siltstone and sideritic ironstone lenses with minor layers of kaolinitic claystone, and is disconformably overlain by the medium-to-coarse-grained Pilliga Sandstone (Yoo et al., 2001, p. 54). North-east of Coolah approximately 90 m of fine-to medium-grained lithic sandstone, with mudstone, claystone, thin limestone and thin coal beds of the Bungil Formation overlie the Pilliga Sandstone (Yoo et al., 2001, p. 55). The thin coal beds of the Bungil Formation are not of economic interest.

Structural elements of the Western Coalfield

The northern part of the Western Coalfield is on the Gunnedah Basin’s Wollar Shelf in the west and the Murrurundi Trough in the east. The southern part of the Western Coalfield occupies the Sydney Basin’s Blue Mountains Shelf in the west and the Macdonald Trough in the east. Areas of the coalfield on the Wollar and Blue Mountains shelves are separated from the Murrurundi Trough and the Macdonald Trough by the Mount Tomah Monocline (Yoo et al., 2001, p. 57). Along with the Lapstone Structural Complex, a north-trending monocline and fault system within the Macdonald Trough, the Mount Tomah Monocline is the most significant structural feature of the Western Coalfield, as shown in Figure 36. The Mount Coricudgy Anticline is a major basement growth-feature with present elevation of approximately 2000 m above the floor of the Macdonald Trough (Yoo et al., 2001, p. 57). Structural hingelines in the coalfield include the Ulan, Wollar and Bylong hingelines (Yoo et al., 2001, p. 59 (Figure 9). One of the few major faults in the north-western part of the coalfield is the Kurrajong Fault, an east-dipping, high-angle reverse fault system. Several other faults are recorded in the western margin of the coalfield, particularly where intersected by mine workings (Yoo et al., 2001, p. 60).

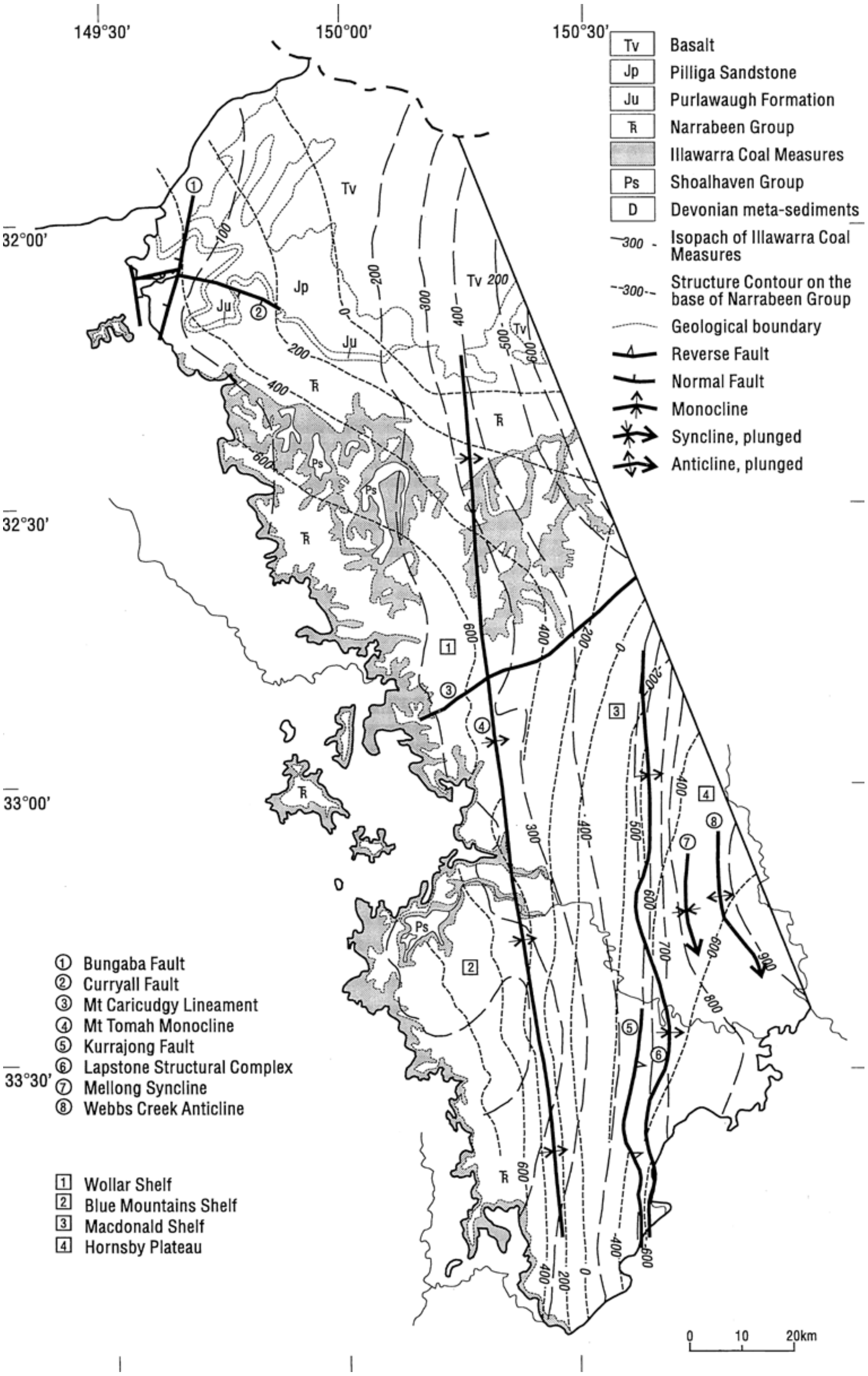

Figure 36 Structural elements of the Western Coalfield

Source: Yoo et al. (1995)

1.1.3.3 Basin history

As described previously (Section 1.1.3.1), the Sydney Basin is part of the Sydney-Gunnedah-Bowen Basin (SGBB) complex. The dominant tectonic feature of eastern Australia, the Tasman Fold Belt, is composed of five fold belts of which three are either wholly or partly in NSW: the Kanmantoo, Lachlan and New England fold belts (Scheibner, 1999, p. 18). Of these, the Lachlan Fold Belt and the New England Fold Belt are separated by the SGBB (Figure 28).

The Sydney-Gunnedah Basin is bound by older Paleozoic, mainly metamorphic and granitic rocks of the Lachlan Fold Belt, to the south and west, and the New England Fold Belt to the north-east. A series of tectonic events led to the formation of the basin complex and the comprehensive reconstruction of its tectonic development in NSW is discussed by various authors including Johnson (1989), Scheibner (1999), Veevers (2000) and Woodfull et al. (2004).

The structure of the SGBB complex was influenced primarily by events during the Middle Devonian to early Carboniferous, which gave rise to the Kanmantoo and Lachlan fold belts. By the end of the Kanimblan Orogeny (early Carboniferous) the fold belts had emerged as new cratons. Post-orogenic magmatism related to a subduction-associated volcanic arc (where deep, lithospheric material subducts and recycles large amounts of oceanic crust) was present in the New England Fold Belt region. Plate interaction ended in the New England region during the late Carboniferous and the rocks were subjected to strong contraction. During the contraction the fore-arc basin complexes were thrust over the volcanic arc. This orogenic pile-up of the early New England Fold Belt over the edge of the Lachlan Fold Belt caused foreland loading and lithospheric flexure, and the down-bowed area became the future depositional site for the SGBB (Scheibner, 1999, p. 26).

During the late Carboniferous to early Permian, a continental rift formed in the down-bowed region, which later developed into a transitional tectonic foreland basin, the SGBB. During the middle Permian, orogenic contraction and further rise of the New England region during the Hunter Orogeny caused renewed foreland loading of the down-bowed region. Coal measure sedimentation began in the early Permian with detritus supplied from the eastern orogenic belt. Compressional movements were accommodated by the Hunter-Mooki Thrust Fault System (Tadros, 1995, p. 166).

Compression intensified towards the end of the Permian, causing major uplift and basin tilting, and coal measure sedimentation was terminated. The New England Fold Belt experienced widespread post-orogenic magmatic activity from the middle Permian to the early Triassic. Tectonism during the Middle Triassic Bowen Orogeny was mainly confined to folding and thrusting, which deformed the rocks of the SGBB and the New England Fold Belt (Scheibner, 1999, p. 27).

Deposition of sediments and coal measures in these basins continued into the early Cretaceous. During this time, mantle upwelling started under the continent that was, at the time, part of Gondwana, with related intraplate igneous activity. The Australian continent rifted and broke away from the rest of Gondwana. The rifting progressed anticlockwise southwards during the early Cretaceous between Australia and India, and later eastwards between Australia and Antarctica (Scheibner, 1999, p. 28). The continent underwent further rifting during the Jurassic and a marine incursion occurred during the early Cretaceous. The Eastern Highlands became elevated during the late Cretaceous and this continued into the Cenozoic as a result of intraplate igneous activity (Scheibner, 1999, p. 28).

The Sydney Basin sequence was affected by three major phases of igneous activity dating from the late Palaeozoic to the middle to late Cenozoic (Thomas and Hill, 2003, p. 1). Volcanic activity commenced in the New England Fold Belt during the middle Permian to Triassic, peaking during the late Permian, which is consistent with the range of dates (247.7 to 271.4 Ma) for tuff layers associated with the Permian coals of the Hunter Coalfield (Metcalfe et al., 2012, p. 1). Along with volcanic and volcaniclastic rocks commonly being interlayered with the sedimentary strata, this indicates that volcanic activity occurred in the period contemporaneous with sedimentation, with volcanism contributing large quantities of volcanogenic material to the sedimentary sequence.

A second period of igneous activity was related to mantle upwelling at the beginning of the breakup of Gondwana during the Jurassic and Cretaceous (Scheibner, 1999, p. 29), and the possibility of late intraplate volcanism during the last approximately 10 Ma has also been investigated by Sutherland (1992). A comprehensive review of the Cenozoic volcanism in Australia was conducted by Vasconcelos et al. (2008), which confirmed these findings.

1.1.3.4 Basin connectivity

As the Sydney Basin developed in conjunction with other basins to the north, some connectivity would be expected to the north, with the Gunnedah Basin, which in turn is connected to the more northern Bowen Basin. However, shallow basement at the Mount Coricudgy Anticline is believed to divide the Sydney and Gunnedah basins, and may form a structural boundary (Danis et al., 2011, p. 536; Bembrick et al., 1980, p. 2). Nevertheless, rocks typical of the northern Sydney Basin are present north of the anticline (NSW DTI, n.d.) suggesting that some connection remains. Additionally, Danis et al. (2011, p. 541) stated that sedimentary thickness is around 1.5 km over the Mount Coricudgy Anticline and the Western Coalfields, near the boundary with the Gunnedah Basin, reinforcing that significant sedimentary connection may exist, albeit less thick than elsewhere in the Sydney-Gunnedah Basin (O’Neill and Danis 2013, p. 19). The Sydney Basin is otherwise laterally constrained; to the west it is bounded by the older basement rocks of the Lachlan Fold Belt, to the north-east by the New England Fold Belt and to the east and south where the basin extends to the edge of the continental shelf.

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1.1.4 Hydrogeology and groundwater quality

Summary

The hydrogeological systems in the Hunter subregion are associated with Permian-Triassic fractured rock aquifers, alluvial aquifers along major rivers and creeks, and a coastal sand aquifer in the coastal zone of the region. The Hunter Valley represents a regional groundwater discharge zone and a dividing streamline for groundwater flow. Similar to surface water, the main regional groundwater fluxes south from Hunter-Mooki thrust fault, which forms the northern boundary of the Sydney Basin, largely following the subregion’s topography from upland towards the river channels with overall discharge to the ocean.

The Hunter Valley Alluvium aquifer is an important groundwater management unit (GMU). It is fully allocated with total licensed abstraction of 80.4 GL/year. The Kingdon Ponds and Dart Brook alluvial aquifers, located in the north-west of the subregion, are the major components of this groundwater management unit. The Tomago sands are an important water resource for the Newcastle area, being one of three main water sources. The Tomago sands groundwater resource is an important drought contingency but surface water catchments dominate potable water supplies during normal times.

The Hunter subregion is spatially dominated by fractured rock aquifers, including those in the Liverpool Range Volcanics, Jurassic, Narrabeen and Permian sedimentary (mainly sandstone) group. However groundwater yields from these aquifers are generally low.

The Permian units are associated with a series of coal measures and intervening marine sequences. The saline water associated with this geological unit is thought to have a controlling influence on the overall water quality of the Hunter River (Kellett et al., 1989). The weathered profile, or regolith that is up to 100 m thick, can act as an unconfined aquifer which feeds into local springs after high rainfall, though most are depleted during extended dry and drought periods. Enhanced permeability of these formations is associated with faults and fractures, particularly in the hinge areas and limbs of anticlines.

The coal seams exhibit many joints and cleats and are the main aquifers within the Permian units. Groundwater in the regolith and deeper coal measures can be isolated due to the presence of less permeable interburden formations, unless vertical faulting provides a connecting pathway to deeper strata.

Groundwater diffuse recharge from Permian material is estimated at less than 2% of annual rainfall, with high values associated with areas of the enhanced regolith permeability. Alluvial aquifers also receive recharge from the natural river flow and particularly during flooding; this is supplemented by leakage or environmental water releases from water supply dams. Groundwater discharge forms river baseflow throughout the subregion, which is more persistent in the main Hunter alluvial systems than in the elevated areas. There is potential for groundwater within the Hunter subregion to interact with groundwater systems to the south (Sydney Basin) or to the west (Gunnedah Basin), mainly within deeper strata, but the volumetric fluxes between these basins are likely to be minimal.

1.1.4.1 Groundwater systems

1.1.4.1.1 Hydrogeological characteristics of geological formations in the Hunter subregion

Hydrogeological investigations in the Hunter subregion have been undertaken for decades with earlier publications available to the project dating back to 1958 (Williamson, 1958), with some references from the early 1890s. These studies indicate that the hydrogeological systems in the subregion are largely influenced by bedrock origin and tectonic activities during the post-Carboniferous period (David et al., 2004; De Silva, 1998; WRC, 1986). These systems can be broadly grouped in three hydrogeological units: alluvial aquifers along major rivers and creek lines, coastal aquifers in the coastal area, and Triassic-Permian fractured rock aquifers of the Hunter subregion. These aquifer types are spatially variable and mostly localised.

Alluvial aquifers

The extent of alluvial deposits (Quaternary deposits) in the subregion is shown in Figure 37. They are commonly formed as sequences of clays, silts, sands and gravels (NSW Department of Planning, 2005), but are rarely uniform and in some areas have low permeability. Highly permeable coarse alluvial materials are frequently found in the base of the alluvial deposits (basal deposits). The deposits become finer towards the upper layers. Higher clay content in alluvial deposits, and hence lower permeability, is found in alluvium along the Goulburn River and its tributaries. This originates in the Liverpool Plains, and is said to be a by-product of the basalt weathering (McMahon, 1964; Williamson, 1958) (Figure 37). Further downstream where the rivers drain into clastic formations, the alluvial material is coarser.

The Hunter Valley Alluvium aquifer forms a groundwater management unit (GMU) with major importance for agriculture (DPI, 2005; 2013). The Kingdon Ponds and Dart Brook alluvial aquifers, located in the north-west of the subregion (Figure 37), are the major components of this GMU. Other important groundwater resources are found in the Page River, Wybong and Hunter River alluvial aquifers. The Page River alluvial aquifer is also associated with the most significant environmental values. Alluvial deposits developed along other creeks in the subregion are commonly thin and are not considered such important aquifers.

Hydraulic conductivity of the alluvial deposits is in the range of 10 m/day to 239 m/day (Williamson, 1958). Aquifer thickness in saturated zones of alluvium ranges from 3 to 17 m (Australian Groundwater Consultants Pty Ltd, 1984), and increases downstream. The watertable is shallow and within the first metres of the area is close to the river. The water levels are responsive to high rainfall and flooding events. During the drought between 2001 and 2004 the water levels in the Kingdon Ponds alluvial aquifer dropped by 5 m, which also led to an increase in salinity by 43% (NSW Department of Planning, 2005).

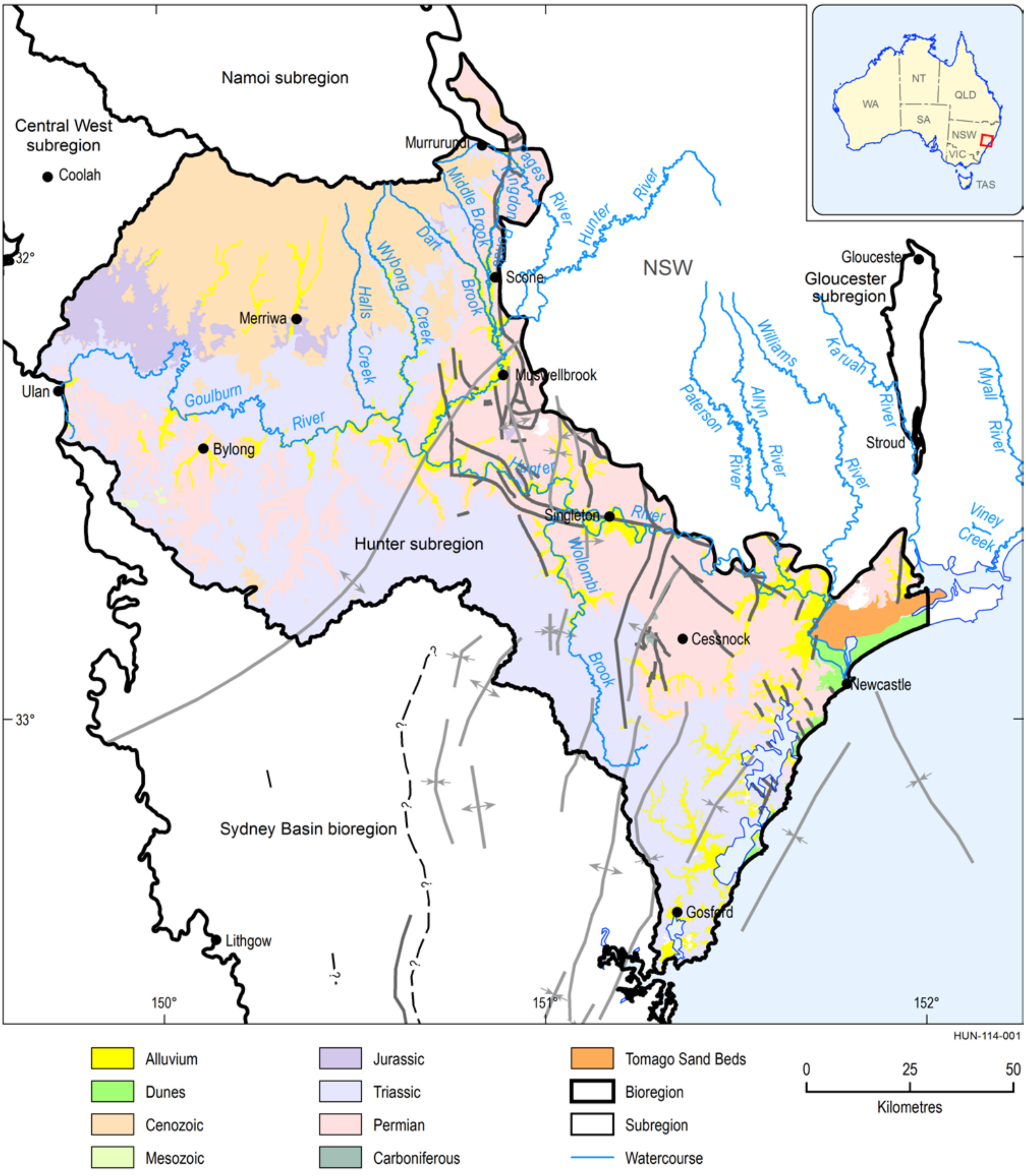

Figure 37 Surface geology map showing Quaternary deposits (Hunter Valley alluvial aquifers and Tomago sands aquifer) as well as fractured rock formations, which may also form local aquifers

Data: Stewart and Adler (1995), Geoscience Australia (Dataset 1), Bureau of Meteorology, Climate and Water Division (Dataset 2)

Coastal sand aquifer

The Tomago Tomaree Stockton Coastal Sands groundwater is used for urban water supply by the Hunter Water Corporation (NSW Government, 2010), providing the potable water supply to the Newcastle area, and is particularly important during droughts (Woolley et al., 1995). However, during normal times, surface water catchments dominate potable water supplies to the Newcastle area. The Tomago sands extend 35 km from the Hunter River in the east to Port Stephens in the east and cover an area of 183 km^2. Dunal and/or coastal (of aeolian origin) sands of medium grain size form a highly permeable unconfined aquifer and rainfall rapidly infiltrates through the unsaturated zone to recharge the saturated zone. This formation receives the highest diffuse recharge rate in the region. However the rapid infiltration makes this aquifer susceptible to contamination and so to ensure the protection of the quality of the water resource the majority of the aquifer is protected as a water reserve (Crosbie, 2003).

Transmissivity was estimated between 400 m/day to more than 600 m/day (Crosbie, 2003) with a specific yield of about 0.2. The groundwater level is very responsive to rainfall events, with groundwater level rises over a metre observed on an event basis (Crosbie, 2003).

A significant proportion of the area at Tomago has been listed as a high priority groundwater-dependent ecosystem (DIPNR, 2003).

This aquifer contains mineral sands and has been investigated for its mineral deposits as well as being a source of water (Coffey and Sinclair Knight Mertz, 1996; SML, 1971).

Fractured rock aquifers

There is a series of aquifers hosted by fractured rock formations, including the Liverpool Range Volcanics, Jurassic, Narrabeen and Permian group. The Sydney Basin is dominated by porous rocks that are fractured, and pumping yield from these rocks is generally low.

Liverpool Range Volcanics

The north-west area of the Hunter subregion is formed by Cenozoic formation associated with alkaline mafic to ultramafic flows (basalt, dolerite), polymictic conglomerate and quartzose sandstone. This formation thickness varies from 800 m (Barnes et al., 2002) to less than 100 m in Wybong Creek catchment (Kellett et al., 1989).

The basalt terrain can be quite productive in terms of groundwater (De Silva, 1998). The highest yields occur where a combination of cavities are interconnected with joints, fractures and faults (NSW Department of Planning, 2005). Other aquifers associated with the basalt can form due to weathering and erosion on the surface of the lava sheet prior to subsequent lava flows. The water quality associated with basaltic terrain is generally good with low salinity. However, in some locations the water may exhibit hardness due to calcium and magnesium carbonates or may be slightly acidic and contain iron. Bore yields in the Cenozoic aquifer are typically 432 m^3/day (NSW Department of Planning, 2005).

Terrestrial deposits of Jurassic and Triassic period (Narrabeen Group)

In some publications (De Silva, 1998), the water-bearing strata in terrestrial units of the Carboniferous period and Triassic period (Narrabeen group) are characterised as porous aquifers, implying that hydraulic properties in units of these groups are associated with primary porosity. These water-bearing units can be separated into an individual group as groundwater here has certain specific properties compared to other bedrock aquifers (referred to as fractured rock).

The Jurassic formation, mainly represented by Pilliga Sandstone, is only present in the north-west of the subregion and consists of medium to very coarse grained sandstone and conglomerate. Only limited information on hydrogeological characteristics is available, mainly associated with data generated for the Ulan Mine Complex. Here Jurassic Pilliga Sandstone, overlays the Narrabeen Group. Both units, along with the underlining Permian coal measures, form an aquifer. Compared with other units, the hydraulic conductivity of the Jurassic rock is lower but also more variable. Within the mining area the Jurassic sandstones and siltstones are also mostly unsaturated.

The Narrabeen Group covers a large area in the south and south-west of the Hunter subregion. This formation is comprised of conglomerates, sandstones and shales deposited in fluviatile, fluviatile-deltaic and lacustrine environments with overall thickness ranging from 90 to 700 m (Moffitt, 2000). The Narrabeen Group forms a locally significant aquifer and springs, particularly in the Blue Mountains area.

The Narrabeen Group forms a sub-horizontal sedimentary sequence of aquifers and aquitards. Generally the sandstone units act as aquifers and the claystone units act as aquitards. Permeable zones of these units are occasionally associated with coarser grained materials containing relatively higher pore space. However, secondary porosity features, such as bedding plane partings and the network of joints, are the predominant flow pathways. It is generally accepted that hydraulic conductivity is an order of magnitude greater in the horizontal direction (Ward and Kelly, 2013, p. 42, Table 5.1). However, some vertical fluxes through the fracture network are possible locally (McNally and Evans, 2007). Bores yields are generally in the range of 17 to 216 m^3/day (NSW Department of Planning, 2005). On average hydraulic conductivity of sandstone aquifers is 0.01 m/day with effective porosity of 0.02 (Kellett et al., 1989). Changes in hydraulic conductivity of these units with depth are characterised by a logarithmic decrease in conductivity with linear decrease in depth, reaching less than 10^{-4} m/day at 400 m below ground (see Ward and Kelly, 2013, p. 22, Figure 3.5).

Groundwater discharge from the sandstone units of the Narrabeen Group contributes to baseflow in the streams and to supporting groundwater-dependent ecosystems.

Permian Group

The Permian units are largely associated with a series of coal measures. They are commonly subdivided into the upper and lower coal measures and the intervening marine sequence. The saline water associated with this geological unit is thought to have a controlling influence on the overall water quality of the Hunter River (Kellett et al., 1989). The fine-grained, consolidated nature of these rocks is reflected in low primary porosity, with most groundwater flow associated with secondary faults, fractures and joints. The coal seams exhibit many joints and cleats and are the main aquifers within these rocks.

Parts of the overlying weathered zone or regolith act as an intergranular aquifer storage. These zones may feed into springs following periods of high rainfall but most are depleted during extended dry and drought periods. Watertables in the regolith can be isolated from deeper coal measures through the presence of massive and relatively impermeable conglomerates that overlie the coal seams. This isolation is however likely to be interrupted at locations where vertical faulting provides a connecting pathway to deeper strata (Mackie Environmental Research, 2006).

The most transmissive fractured rock aquifers are likely to be those with the most and youngest open tension fractures, where the likelihood of lining and filling with mineral precipitates is lower. Such areas were identified by Kellett et al. (1989) (in addition to the face of the escarpment of Triassic rocks):

- the Permian rocks of the Hunter River valley floor as intersecting sets of closely spaced cleats perpendicular to bedding in coal seams
- fractures associated with the youngest, low angle joints and bedding plane separation in the Permian rocks of the valley
- the hinge areas and limbs of anticlines (e.g. Muswellbrook anticline) where two sets of primary tension fractures (parallel and perpendicular to the fold axes) were formed; the further lateral extension of fractured zone were associated with later uplift of domal structures (see map in Section 1.1.1.3).

The hydraulic properties in these areas could be an order of magnitude greater than in other regolith within the subregion.

A reduction in the hydraulic conductivity of the coal seam aquifers with depth is observed in many coal mines. Australian Groundwater Consultants Pty Ltd (1984) developed an equation based on the interpretation of depth-dependent hydraulic conductivities of 17 coal seams in the Upper Hunter Valley as:

$$k = k_0 * e^{(-cz)} \tag{1}$$

where k is the hydraulic conductivity (m/day), k_0 is the reference hydraulic conductivity of 5 m/day, c is the slope of the trend line (0.046 for Hunter Valley coal seams) and z is depth below ground (m).

Aquifers in the porous rocks within the Permian sandstones, shales and coal measures strata are hydraulically connected with the alluvial aquifers. It is acknowledged that hydraulic connectivity between the near-surface regolith aquifers and groundwater in the coal measures is not well characterised (Ward and Kelly, 2013). However groundwater exchange in the deeper strata is not significant. The groundwater ages of 22,000 to 33,000 years reported by McLean et al. (2010) for the Blakefield seam 323 m below ground level are consistent with the millennial rates of fluid movement expected in porous rock at these depths.

Depth to groundwater is greater in the elevated part of the landscape and becomes shallower in proximity to streamlines. As such, the groundwater flow directions in shallow hydrogeological systems, regolith and alluvial aquifers, largely follow similar pathways as surface water following topographic features in the subregion.

1.1.4.1.2 Structural elements and their hydrogeological characteristics

In addition to the effect of folding on the hydraulic properties of Permian units, there is evidence that faults play an important role in the hydraulic connectivity of fractured rock and alluvial aquifers at some locations. Increased alluvial aquifer salinity was associated with the Mount Ogilvie Fault area (Kellett et al., 1989). At the same time, the Hunter Thrust Fault is considered to be an impermeable boundary between the New England Fold Belt, in the north-east, and the Sydney Basin.

1.1.4.1.3 Groundwater use

The NSW Office of Water is responsible for the development and review of water sharing plans (WSP) which govern the extraction of water from surface and groundwater sources in NSW. All WSPs are a regulation of the NSW *Water Management Act 2000* and have a term of ten years from the date of commencement, after which time they must be extended or replaced[1].

Alluvial and non alluvial aquifers are present in the Hunter subregion 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 extraction limits in WSPs are based on the entitlement when the plan commenced. Where a WSP is in place, entitlement for general purposes can only be purchased on the market. Identified specific purposes can apply if provided for by the relevant WSP or under the NSW *Water Management (General) Regulation 2011*. In areas where a WSP has not commenced, access licences may still be applied for under the NSW *Water Act 1912*.

Alluvial aquifers identified in the Hunter subregion are considered to be highly connected to surface water, and are generally managed conjunctively with the surface water source they are associated with. Most of the alluvial groundwater in the Hunter subregion is managed under the NSW *Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources 2009* for the Hunter Unregulated and Alluvial Water Sources. This WSP may be amended in the future to include floodplain alluvium which does not have a strong connection to surface waters.

The draft WSP for the North Coast Fractured and Porous Rock Groundwater Sources, which is currently under development with a view to commence in 2015, will manage groundwater extracted from the hard rock groundwater sources which fall within the Hunter subregion.

Table 10 gives an estimate of groundwater entitlement in these two WSP areas.

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[1] ‘Extension’ refers to the extension of plans for a further 10-year term without change; ‘replacement’ refers to replacement of the plan with a new plan where changes to the existing plan are proposed.

Table 10 Groundwater entitlements

The boundaries of the areas covered by these water sharing plans extend beyond the Hunter subregion.

Water sharing plan	Water source	Estimated groundwater share components (ML/y)
The NSW *Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources 2009*	Baerami Creek Water Source	2524
	Bow River Water Source	5
	Bylong River Water Source	7714
	Dartbrook Water Source[a]	28074
	Doyles Creek Water Source	293
	Glendon Brook Water Source[a]	60
	Glennies Water Source[a]	10
	Halls Creek Water Source	691
	Hunter Regulated River Alluvial Water Source	29046
	Jerrys Water Source[a]	1246
	Lower Goulburn River Water Source	3086
	Lower Wollombi Water Source	3702
	Luskintyre Water Source[a]	10
	Martindale Creek Water Source	1575
	Merriwa River Water Source	1901
	Munmurra River Water Source	19
	Muswellbrook Water Source[a]	1169
	Newcastle Water Source[a]	91
	Pages River Water Source[a]	7396
	Singleton Water Source	230
	Upper Goulburn River Water Source	102
	Upper Wollombi Brook Water Source	74
	Wallis Creek Water Source	5
	Widden Brook Water Source	1206
	Williams River Water Source[a]	66
	Wollar Creek Water Source	782
	Wybong Creek Water Source[b]	2236

Water sharing plan	Water source	Estimated groundwater share components (ML/y)
Draft of the NSW *Water Sharing Plan for the North Coast Fractured and Porous Rock Groundwater Sources* (under development – due in 2015)	Liverpool Ranges Basalt Coast Groundwater Source	4268
	Oxley Basin Coast Groundwater Source	1042
	Sydney Basin North Coast	76,465

[a]denotes that only a portion of the water source falls within the Hunter subregion.
[b]denotes that this water source is set to be merged in 2015 with the water sharing plan for the Hunter Unregulated and Alluvial Water Sources.

The key water sources for the NSW *Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources 2009* are the Hunter Regulated River Alluvial Water Source, the Dart Brook Water Source, the Pages River Water Source, the Bylong River Water Source and the Lower Wollombi Brook Water Source. The Kingdon Pond Alluvium is part of the Dart Brook Water Source.

While there is minimal coastal sand aquifers that fall within the Hunter subregion, a large portion of the Tomago and Stockton groundwater sources do fall within the Hunter subregion. Estimated groundwater share components in these groundwater sources are 26,090 and 1008 respectively, with most of the entitlement in the Tomago water source being for the purpose of town water supply.

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.

There are small portions of other WSP areas that fall within the Hunter subregion – however groundwater entitlement in these areas is relatively minor.

1.1.4.2 Groundwater quality

Geological conditions have the dominant control in salinity and chemical composition of groundwater in the Hunter subregion. The saline water associated with the Permian coal measures and the intervening marine sequence is thought to have a controlling influence on the overall water quality of the Hunter River (Kellett et al., 1989). Groundwater quality is generally brackish to saline (Mackie Environmental Research, 2006). Salinity within the hard rock aquifers associated with the Hunter coal seams is typically in the range 4000 to 12,000 µS/cm, but electrical conductivity (EC) has been recorded at over 26,000 µS/cm. The pH values range from 5.8 to 9.2 with a mean around 7.1 (NSW Department of Planning, 2005).

However, low salinity was recorded in water hosted by the coal seams within the Koogah Formation in the area of Bickman Coal Mines, which is the most northern mining location in the Hunter subregion (Aquatera, 2009). Here the mean total dissolved solid concentrations in the main coal seams were between 468 and 893 mg/L (see Aquatera, 2009, p. 2). Groundwater salinity decreased with depth of coal seam within the Koogah Formation in the area of Bickman Coal Mines.

Coal seams in the Hunter Valley also have high sulfur contents, particularly in the Greta Coal Measures mined in the Cessnock Coalfield, which may be a potential source of elevated water acidity.

Kellett et al. (1989) identified eight provinces in the Upper Hunter Valley, each with a unique hydrochemical signature. In addition to the southern New England Fold Belt (which is not included in the Hunter subregion), these include:

1. The province formed by fractured rocks of the Triassic Narrabeen Group in the south and west of the assessment area. The groundwater is of low to moderate salinity (mean total soluble salts (TSS) = 600 mg/L) and dominated by ions of sodium (Na^+), magnesium (Mg^{2+}), chlorine (Cl^-). Relatively low pH (around 6) may reflect high levels of iron (Mackie Environmental Research, 2006).
2. The four provinces with the Permian fractured rocks forming the Central Lowlands and foot slopes, including:
    a. The groundwater of the Newcastle Coal Measures which is moderately saline (mean TSS = 1070 mg/L), dominated by Na^+, Mg^{2+}, Cl^-, HCO_3^- (bicarbonate). The fundamental difference between the Newcastle Coal Measures and the underlying Permian rocks is that groundwater quality is not largely influenced by marine environment during deposition stage
    b. Groundwater in the Wittingham Coal Measures (west) within the Jerrys Plains Subgroup containing the Cenozoic intrusion (the WI1 province) is of moderate to high salinity (mean TSS = 2300 mg/L), dominated by Na^+, Cl^-, HCO_3^-. The lower average salinity in this province and different chemical composition to groundwater in the eastern part of the Wittingham Coal Measures are believed to be a consequence of both a longer period of flushing by meteoric water and prior thermal mobilisation of connate marine fluids peripheral to the Cenozoic intrusives
    c. Groundwater in the Wittingham Coal Measures (east and south-east) where intrusive units are absent (the WI2 province) is the most saline in the Hunter River valley (mean TSS = 5700 mg/L). Hydrochemical facies grade from Na^+, Cl^-, HCO_3^- in the WI1 province to Na^+, Cl^- in the WI2 province, and mean SO_4^{2-} concentration is over ten times higher in the WI2-type groundwater
    d. The GM province incorporates the largest proportion of marine sedimentary rocks in the Upper Hunter Valley, which consists of groundwater of the Maitland Group, Greta Coal Measures, and Dalwood Group. The chemistry of groundwater is dominated by Na^+, Cl^-, HCO_3^- and SO_4^{2-} and is highly saline (mean TSS = 4300 mg/L). The strong marine signature is perpetuated through the upper seams of the Greta Coal Measures because these beds were saturated by oceanic water while they were still actively growing peats.
3. Alluvial aquifers of the Hunter floodplains were divided into two provinces: alluvial aquifers upstream from the Hunter-Goulburn River confluence (HFP 1) and alluvial aquifers

> downstream from this confluence (HFP 2). This boundary reflects a distinct change in aquifer-built material (mean grain size and sorting) and as such aquifer provenance (HFP 1 – the coarse grained lithic sediments derived from the Carboniferous rocks; HFO 2 – the fine-grained dominantly sands eroded from the Triassic rocks). Though chemical composition of groundwater in these provinces is similar, groundwater salinity increases from mean TSS from 650 mg/L in the HFP 1 province to 840 mg/L in the HFP 2 province. This suggests intersection of the stream with groundwater from the Permian coal measures which is known to be saline.

Locally groundwater quality in the alluvial aquifers can be influenced by a number of factors. Kellett et al. (1989) also found that Cenozoic basalt contributed salt to the headwaters of the creeks in the Hunter. The pH of waters in the upper catchment is consistent with that of groundwater in contact with basalt and suggests that aluminosilicates may be weathering to produce dissolved silica and bicarbonate.

It was also observed that upward fluxes of groundwater from regolith aquifers to alluvial aquifers could lead to stratification of groundwater quality in the latter with high salinity levels at the base of the alluvial aquifers. As alluvial aquifers are intensively used, groundwater abstraction can enhance upward fluxes from underlying Permian units, particularly during drought periods, leading to groundwater quality deterioration. For example, during the drought of 2001 to 2004, when groundwater levels in alluvial aquifers dropped by 5 m, mean salinity in alluvial aquifers increased by 43% (NSW Department of Planning, 2005).

Mining operations in some locations led to the groundwater gradient reversing from alluvial to Permian aquifers (see Australasian Groundwater and Environmental Consultants Pty Ltd, 2013, p.37, Figure 14). This has led to a reduction in groundwater salinity in the alluvial aquifers (see Australasian Groundwater and Environmental Consultants Pty Ltd, 2013, p.38, Figure 15). As the changes in the groundwater gradient did not lead to any significant changes in groundwater levels, this is likely to be indicative of the compensating effect of alluvial aquifer recharge associated with river flow.

Mean values of groundwater salinity (electrical conductivity) observed by Beale et al. (2000) in 718 bores across all geologies of the Hunter subregion are shown in Table 11. The values indicate that groundwater salinity is elevated in the majority of the Hunter subregion. The exceptions are related to the alluvial aquifers in the west and the aquifers in the Narrabeen Group in the south-east of the subregion.

Table 11 Salinity of groundwater in various geological formations and provinces in the Hunter subregion

Geology	Group or province	Electrical conductivity (µS/cm)				Number of bores
		Minimum	Maximum	Mean	Stdev	
Quaternary	Central	355	5060	1377	835	250
	West	155	944	557	258	20
	South-east	542	6400	1614	1041	67
	All	155	6400	1375	886	337
Cenozoic	Main	170	2760	1142	474	43
	Outliers	5380	6290	5835	643	2
	All	170	6290	1350	1086	45
Triassic	West	126	11800	1772	1886	48
	South-east	199	1100	568	358	7
	All	126	11800	1619	1809	55
L. Permian	Central	380	25800	3649	3716	74
	South-east	169	5730	1542	1540	25
	West	226	7600	1579	1320	88
	All	169	25800	2393	2753	187
E. Permian	Central	630	9500	3387	2874	11
	South-east	373	9350	2280	2222	22
	All	373	9500	2649	2471	33
Carboniferous	South-east	777	11050	3431	2626	27
	West	260	3130	1055	544	34
	All	260	11050	1600	2137	61
Total no of bores						718

Source: Table 9 in Beale et al. (2000)

1.1.4.3 Groundwater flow

The main regional groundwater fluxes in the Hunter subregion largely follow topography, from the upland towards the river channels with overall discharge towards the ocean.

Groundwater recharge mechanisms include:

- recharge predominately from rainfall, the volume of which is commonly estimated as less than 2% of annual rainfall with higher values associated with the areas of regolith permeability (e.g. in the anticline zones) (Mackie Environmental Research, 2006). Watertables and pressures in the coal measures appear to be sustained by rainfall percolation into out-cropping strata at a generally low rate

- localised recharge to alluvial aquifers, mainly associated with natural river flow during rainfall events and particularly during flooding. This is also supplemented by leakage or environmental water releases from water supply dams (e.g. Glenbawn or Liddell dams)
- upward fluxes from fractured rock aquifers to alluvial aquifers, which can also lead to high salinity in rivers during baseflow periods.

Recharge to groundwater systems generally occurs in areas where the regolith is well developed or where alluvial deposits have accumulated. The largest portion of recharge to the main alluvial aquifer system is driven by rainfall in the upper catchments rather than local rainfall. Due to a lower permeability of the upper alluvial layers a large streamflow event or a series of events are required to cause significant recharge in the aquifer systems. The effect of a recharge mound can be observed 60 to 800 m from the stream. In areas where floodplains exist recharge is greater.

Groundwater discharge mechanisms include:

- upward fluxes from fractured rock aquifers to alluvial aquifers, particularly in areas where Permian fractured rock aquifers occur
- Permian groundwater discharge as springs and seepage to watercourses
- discharge from alluvial aquifers forms river baseflow throughout the subregion, which is more consistent in the main Hunter alluvial systems and less consistent in the elevated areas (NSW Department of Planning, 2005)
- groundwater abstraction for irrigation and other purposes, which is particularly significant during dry seasons or drought periods
- ultimately groundwater from the Hunter subregion is discharging to the ocean, which includes submarine discharge along the coast.

In the headwater regions (e.g. the Goulburn River catchment) baseflow ceases approximately 10 to 20% of the time. However even during such periods water remains in the creeks as disconnected pools which provide refuge and as such are critical habitat for aquatic species (NSW Department of Planning, 2005). To ensure environmental flow requirements are met, ‘Cease to Pump’ conditions exist in a number of regional water sharing plans, which define thresholds of minimal river flow (e.g. in the Wybong Creek this threshold is 0.5 ML/day).

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1.1.5 Surface water hydrology and water quality

Summary

The Hunter subregion contains rivers that flow into two major river basins: the Hunter river basin and the Macquarie Tuggerah basin. It also contains a small part of the Namoi river basin and a small part of the Karuah river basin. There are 23 dams within the Hunter subregion built for flood mitigation, hydro-electric power, irrigation, water supply and conservation. The major ones include Glenbawn Dam, Glennies Creek Dam, and Lostock Dam. Water quality (salinity) had been a considerable issue for the Hunter River. Since the introduction of the Hunter River Salinity Trading Scheme in 1995, the river salinity quality has improved considerably. The Hunter River has a long history of floods, the most notable being the February 1955 event. Wet and dry years for the river are strongly influenced by climate variability. High streamflow for the rivers within the subregion occurs in February, March and June; low streamflow occurs from September to December.

1.1.5.1 Surface water systems

Major surface water systems in the Hunter subregion are rivers, lakes, reservoirs, swamps, and surface water infrastructure such as dams (Figure 38). The Hunter River includes eight major tributaries: Moonan Brook, Stewarts Brook, Paterson River, Williams River, Pages Creek, Pages River, Goulburn River, and Wollombi Brook. The Macquarie Tuggerah catchment includes three major tributaries: Dora Creek, Wyong River and Ourimbah Creek. The Quirindi Creek flows through the northern part of the subregion. The lower Karuah River flows through the eastern part of the subregion.

1.1.5.1.1 Surface drainage networks

The biggest river in this subregion is the Hunter River, a major river in NSW, Australia. It rises in the Liverpool Range, and flows generally south and then east before flowing into Lake Glenbawn. It then flows south-west and then east-south-east before reaching its mouth on the Tasman Sea at Newcastle. The Hunter River is joined by ten tributaries upstream of Lake Glenbawn, and a further 31 tributaries downstream of the reservoir. Its eight main tributaries include the Moonan Brook, Stewarts Brook, Paterson River, Williams River, Pages River, Pages Creek, Goulburn River, and Wollombi Brook (Table 12).

The Hunter River splits into two main channels from east of Hexham, separated by the Ramsar-protected Kooragang Wetlands. The southern arm of the river also creates Hexham Island, while the northern creates Smiths Island and flows into Fullerton Cove. The two channels converge at Walsh Point, reaching confluence with Throsby Creek adjacent to the Newcastle central business district, before reaching the river mouth.

Figure 38 Surface drainage network and streamflow gauges within the Hunter subregion

The thick blue line shows regulated sections of the Hunter River, managed under the Hunter Regulated River Water Sharing Plan. The unregulated sections of the Hunter River above Glenbawn Dam are managed under the Hunter Unregulated Alluvial Water Sources Water Sharing Plan.
Data: Bureau of Meteorology (Dataset 1)

The Hunter River descends 1397 m over its 468 km course from the high upper reaches, through the Hunter Valley, and out to sea. The total Hunter river basin area is 21,437 km^2.

The Macquarie Tuggerah basin is located in the NSW Central Coast and Lake Macquarie area directly south of the Hunter basin (Figure 38). The Macquarie Tuggerah basin covers an area of 1836 km^2 and is bordered by a series of east flowing streams in the north, and the Sugarloaf Ranges to the north-west. The Hawkesbury River acts as a boundary to the south, while the Hunter Range separates this basin from the Mangrove Creek basin.

The Macquarie Tuggerah basin includes three major rivers, Dora Creek, Wyong River and Ourimbah Creek. Dora Creek runs south-east for 25 km to meet Lake Macquarie at the township of Dora Creek. The major tributaries of Dora Creek include Moran, Tobins, Jigadee, Blarney and Deep creeks. Wyong River runs south-east for 48 km to meet Tuggerah Lake at Tacoma. The Wyong River's major tributaries include Jilliby Jilliby and Cedar Brush creeks. Ourimbah Creek runs south-east for 31 km to meet Tuggerah Lake at Chittaway. Ourimbah Creek's major tributaries include Elliots, Bumbles, Toobys, and Bangalow creeks, which drain the southern-most corner of the subregion.

The Hunter subregion contains a part of the lower Karuah river basin. The Karuah River originates from the south-eastern slopes of the Gloucester Tops section of the Great Dividing Range, south-west of Gloucester, flows generally south-east and south, and discharges into Port Stephens near the township of Karuah. The total length of the Karuah River is about 100 km. It has two major tributaries within the Hunter subregion: Chilcotts Creek with a length of 6.8 km and Colly Creek with a length of 6.4 km.

The Hunter subregion also contains a small part of the upper Namoi river basin, through which Quirindi Creek – a tributary of the Mooki river basin – flows. Quirindi Creek originates from Crawney Mountain at an elevation of 723 m, and flows into the Mooki River at an elevation of 299 m, dropping around 424 m over its 87.4 km length. Major tributaries of Quirindi Creek include Quipolly Creek, Kangaroo Creek, Basin Creek, and Back Creek.

Table 12 Catchment area for the main rivers and their main tributaries within the Hunter subregion

Main rivers	Main tributaries	Direction[a]	Catchment area (km^2)
Hunter			21,437
	Moonan Brook	Left	185.37
	Stewarts Brook	Left	190.46
	Paterson River	Left	1188.4
	Williams River	Left	1383.5
	Pages Creek	Right	365.27
	Pages River	Right	1191.4
	Goulburn River	Right	7802.6
	Wollombi Brook	Right	1866.5
Macquarie Tuggerah			1835.8
	Dora Creek	Left	702.02
	Wyong River	Right	349.50
	Ourimbah Creek	Right	311.02

[a] Direction means the left or right side along the main rivers from upstream to downstream.

1.1.5.1.2 Surface water infrastructure

There are 23 dams within the Hunter subregion (Figure 38).The major dams in the Hunter river basin include Glenbawn Dam, Glennies Creek Dam, and Lostock Dam (NSW Government, 2014). The Glenbawn Dam is the largest, and is situated on the Hunter River about 14 km east of Scone, NSW. The purpose of the dam includes flood mitigation, hydro-electric power, irrigation, water supply and conservation. Its contribution reservoir is Lake Glenbawn. Construction of this dam commenced in 1947, and was completed in 1958. It was enlarged to triple its capacity in 1987. Its holding capacity is 750,000 ML, with a surface area of 2614 ha and a maximum depth of 85 m. The dam has an additional reserve capacity of 120,000 ML to hold floodwaters to reduce flooding in the river downstream. The Glennies Creek Dam on Glennies Creek is 39 km upstream from the junction with the Hunter River, and 25 km north of Singleton. It was commissioned because the Glenbawn Dam could no longer satisfy the water demand in the Hunter Valley by the 1970s. The building of Glennies Creek Dam began in August 1980, and was completed in June 1983. It has a water holding capacity of 283,000 ML, with a surface area of 1540 ha and a maximum depth of 56 m. The Lostock Dam is situated on the Paterson River, a major tributary of the Hunter River, about 65 km from Maitland. The construction of this dam began in 1969 and was completed in 1971. It has a water holding capacity of 20,000 ML, with a surface area of 220 ha and a maximum depth of 30 m. Comprehensive dam details can be found on the State Water website (State Water Corporation, 2014).

Chichester Dam and Grahamstown Dam are major drinking water suppliers for the Lower Hunter (Figure 38). The Chichester Dam is located north of Newcastle and within the Port Stephens

Council local government area in the Lower Hunter Region of NSW. The dam's main purpose is as a drinking water supply dam (the largest in the Hunter river basin), and it provides about 40% of the potable water for the Lower Hunter Region. The Chichester Dam is located at the top of the Williams river basin, and as the second largest drinking water supply in the Hunter river basin, provides about 35% of the potable water of the Lower Hunter Region.

1.1.5.1.3 Flooding history

The Hunter River has a long history of floods, the most notable being the February 1955 event. This flood was one of the most devastating natural disasters in Australia's history. Worst hit was the inland city of Maitland, and as a consequence, the 1955 Hunter Valley flood is often known as 'The Maitland Flood'. A total of 25 lives were claimed during a week of flooding that washed away 58 homes and damaged 103 beyond repair. More than 5000 homes were flooded and about 15,000 people were evacuated. More details for this flood are available from the Bureau of Meteorology website (Bureau of Meteorology, 2014). Another major flood event in the Hunter Valley occurred on 8 and 9 June 2007 when an intense low pressure system caused devastating storms to hit the city of Newcastle and the Central Coast and led to major flooding throughout the Lower Hunter Region**.**

1.1.5.2 Surface water quality

The Hunter river basin includes a large proportion of salt bearing sedimentary rocks and soils, and surface and underground drainage from this contributes natural salinity to the river. But activities such as coal mining, power generation, industry and land clearing have increased the level of salinity in the river.

In 1995, in response to the need to control saline water discharges into the Hunter River, the NSW Office of Water and the Environment Protection Authority, together with other interested organisations, developed the Hunter River Salinity Trading Scheme (HRSTS), an innovative method which reduces saline levels in the river while allowing mines and industry to discharge their excess water during periods of high flow thus maintaining stream water quality. The HRSTS has two major objectives: (i) to minimise the impact of saline water discharges on irrigation and other water uses, and on the aquatic environment of the Hunter River catchment; and (ii) to reduce pollution through saline water discharges at the least overall cost to the community.

The central idea of the HRSTS is to only discharge salty water during flood events. When the river is in low flow, no discharge is allowed; when the river is in high flow, limited discharge is allowed; when the river is in flood, unlimited discharge is allowed. The river is divided into blocks. For each block, scheme operators continually monitor the flow level and the ambient salinity and calculate how much salt can be added to the block. There are a total of 1000 salt discharge credits in the HRSTS. Different licence holders have different numbers of credits, which allow them to discharge salt into a river block in proportion to the credits they hold. Credits can be traded among licence holders. This gives each licence holder the flexibility to increase or decrease their allowable discharge from time to time.

The HRSTS was designed to suit the unique characteristics of the Hunter River catchment. The successful execution of the scheme depends on (i) rigorous data and modelling, (ii) a community prepared to work together and try new ideas, (iii) a focus on environmental outcomes (and a break with tradition), (iv) underpinning by legislation and (v) real time data and trading.

Before the HRSTS was introduced in 1995 there was significant conflict between primary producers and mining operators. Discharges from industry increased salt in the river at times making the water unsuitable for irrigation (Figure 39, Figure 40 and Figure 41). Note that the data used for Figure 39, Figure 40, Figure 41, Figure 42, Figure 43 and Figure 44 were provided by the Bureau of Meteorology. This was particularly evident at Glennies Creek on the Hunter River where the maximum electrical conductivity (EC) was about 2650 µS/cm in April 1994. This is much more than its salinity target of 900 µS/cm. Note that the EC of drinking water usually varies between 600 µS/cm and 1200 µS/cm.

The salinity of the Hunter River has been well controlled since the introduction of the HRSTS. Since 1995, EC has varied, the majority of time, from 300 µS/cm to 900 µS/cm for the three major salinity control sites – Denman (Figure 39), Glennies Creek (Figure 40) and Singleton (Figure 41) – on the Hunter River. River salinity has been mostly below the salinity target of 900 µS/cm at Glennies Creek and Singleton. However, river salinity at Denman has only sometimes met the salinity target of 600 µS/cm. Since 2007, there have been a significant number of days with an EC value more than 800 µS/cm.

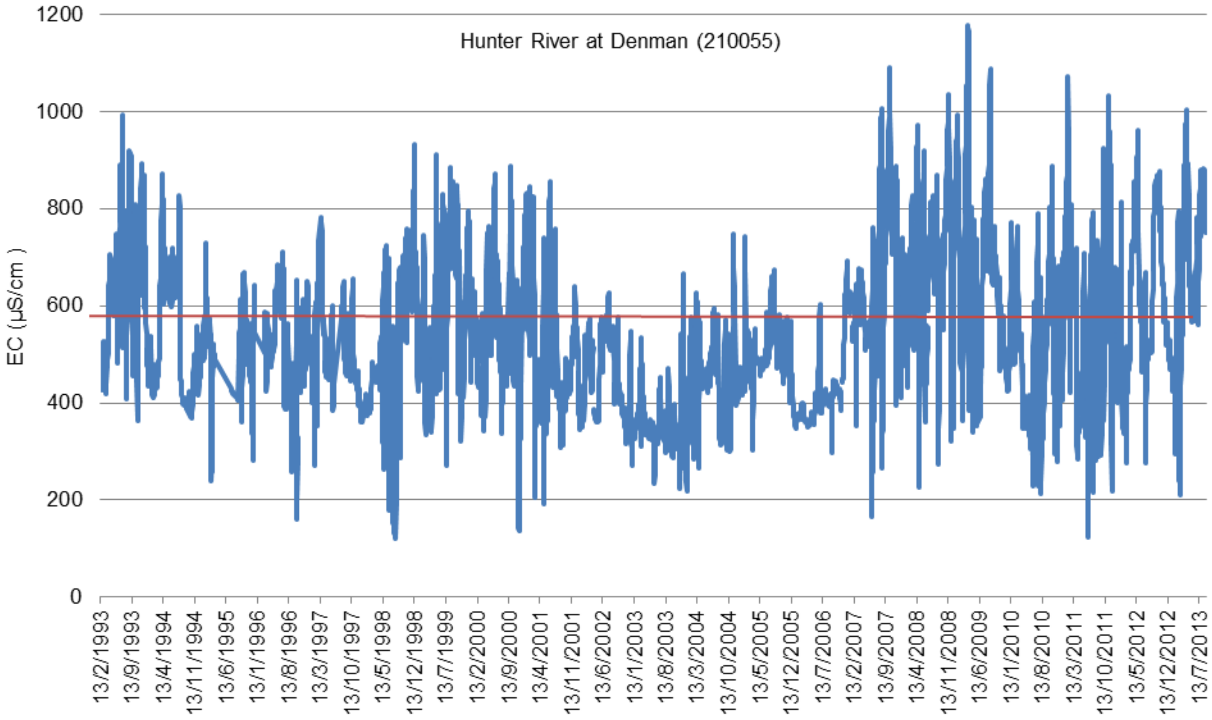

Figure 39 Daily variation of electrical conductivity (EC) at Denman on the Hunter River from 1993 to 2013 for the Hunter subregion

The red line shows the salinity target of 600 µS/cm.

The NSW Office of Water undertook water quality sampling at three sites on the Hunter River from October 2006 to December 2006, a period of extreme low flow conditions (NSW Office of Water, 2011). Nutrient concentrations during these low streamflow conditions were found reasonable, relatively consistent with median Hunter River values (Total Nitrogen 0.35 mg/L and

Soluble Phosphorus 0.005 mg/L). The assessed river turbidity levels were found to be above the long-term median values for the three sites.

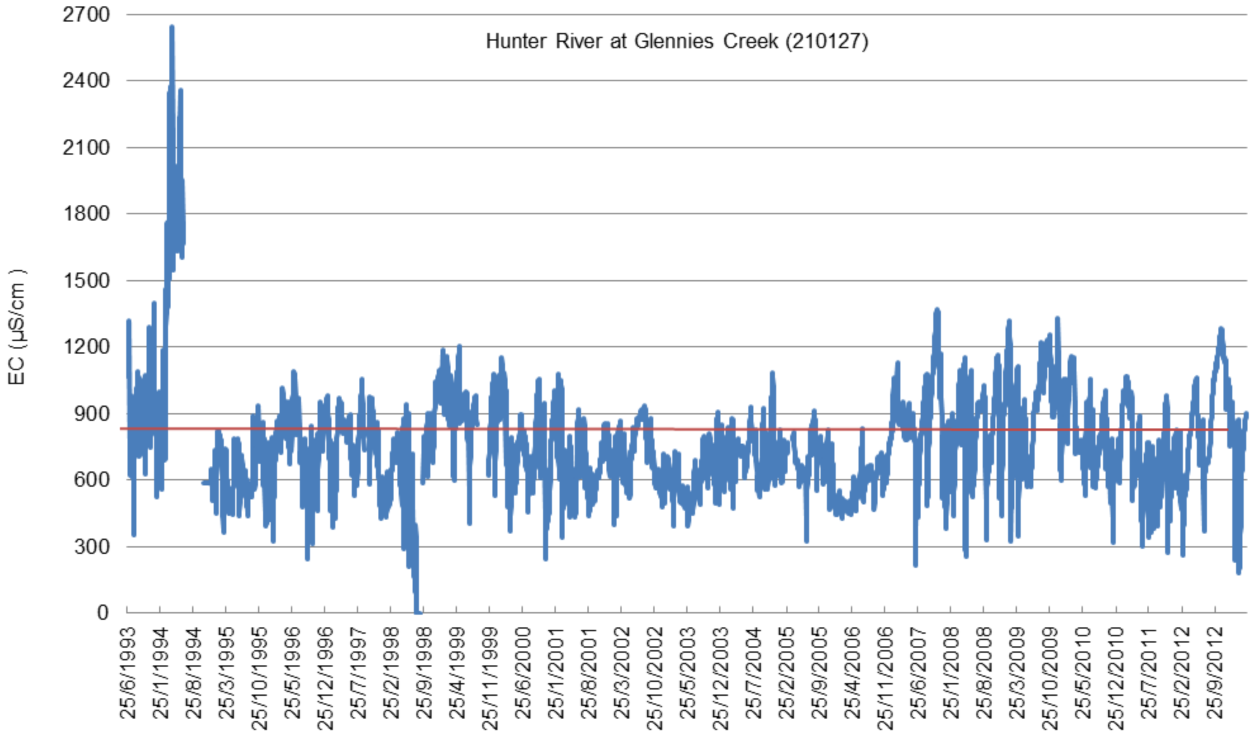

Figure 40 Daily variation of electrical conductivity (EC) at Glennies Creek on the Hunter River from 1993 to 2013 for the Hunter subregion

The red line shows the salinity target of 900 µS/cm.

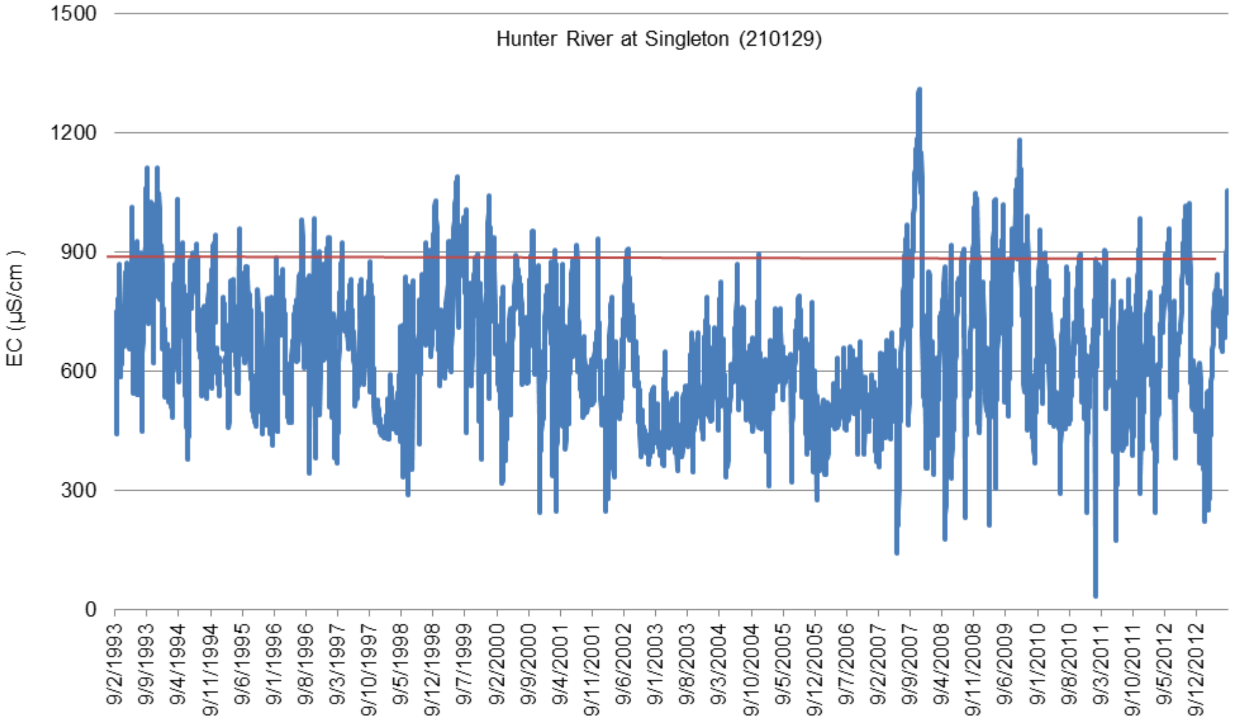

Figure 41 Daily variation of electrical conductivity (EC) at Singleton on the Hunter River from 1993 to 2013 for the Hunter subregion

The red line shows the salinity target of 900 µS/cm.

1.1.5.3 Surface water flow

1.1.5.3.1 Monthly and annual flow characteristics

Sixty streamflow gauges within the subregion have been selected for the analysis of monthly and annual streamflow characteristics. All the selected gauges have more than ten years of data since 1981.

Figure 42 shows monthly streamflow boxplots for the 60 streamflow gauges in the Hunter subregion. The monthly flow is distributed unevenly. High streamflow, that is wet season, occurs in February, March and June. Low streamflow, that is dry season, occurs from September to December.

A streamflow gauge (gauge number 210083) on the Hunter River was selected as an example to analyse inter-annual streamflow variability. Note that annual flow data in Figure 43 are missing for two years (1984 and 1985) because of missing daily flow data; for other years there are no missing daily streamflow data. For the past 40 years, the streamflow for the Hunter River has shown strong inter-annual variability. Wet years or dry years appeared every 5 to 10 years, indicating strong climate variability. Higher annual streamflow often occurred in the 1970s and later 1980s, while relatively lower annual flows occurred in the early 1980s, early 1990s, and early 2000s. In the 2010 to 2012 La Niña years, annual streamflow evidently recovered (Figure 43).

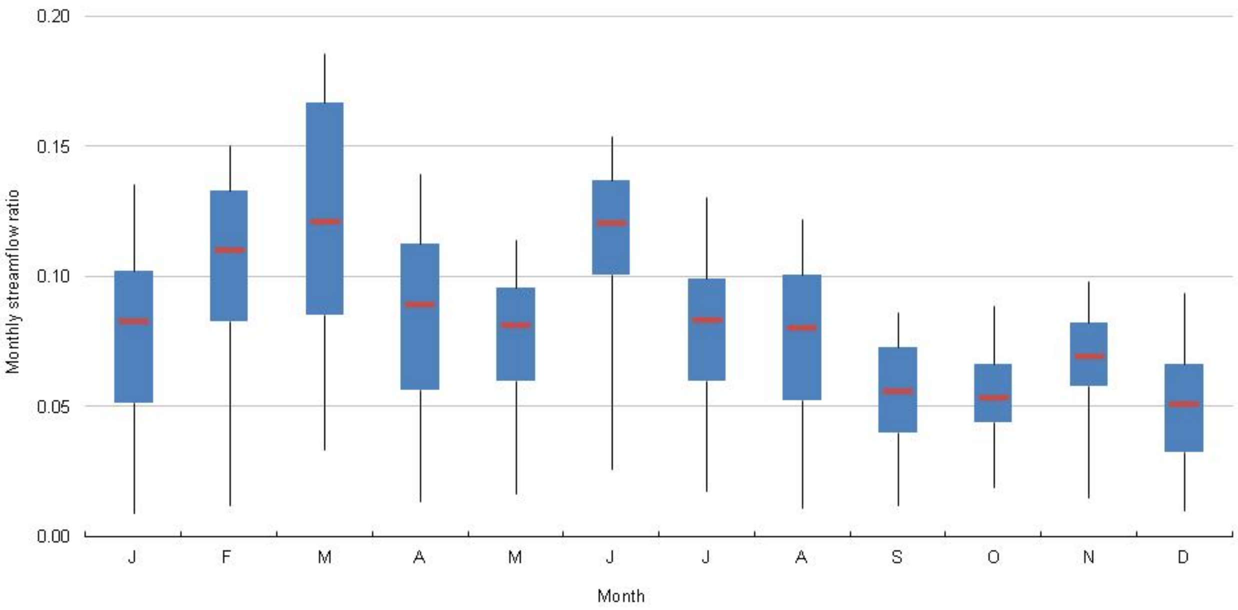

Figure 42 Monthly streamflow ratio (monthly mean divided by annual mean) distribution, summarised from 60 streamflow gauges within the Hunter river basin and Macquarie Tuggerah basin

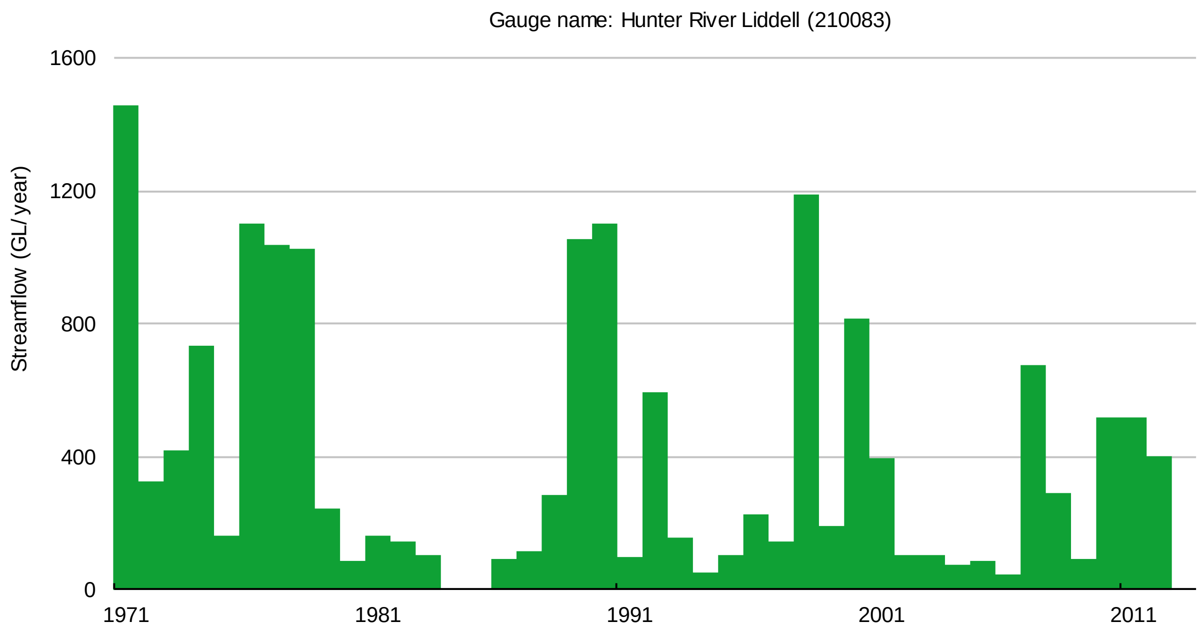

Figure 43 Annual flow time series for a streamflow gauge in the Hunter river basin

Gaps represent missing annual flow data.

1.1.5.3.2 Baseflow index analysis

Streamflow includes two components, quickflow and baseflow. Quickflow is the part of streamflow that originates from precipitation and soil water directly flowing into the stream, while baseflow is the part of streamflow that originates from groundwater seeping into the stream. Daily total streamflow is separated into baseflow and quickflow using a one-parameter filtering separation equation (Lyne and Hollick, 1979) that is expressed as:

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

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

Baseflow index (BFI) is here defined as the ratio of mean annual Q_b to mean annual Q_t. Figure 44 summarises the BFI for major rivers in the Hunter River basin and the Macquarie Tuggerah basin, respectively. BFI varies from 0.40 to 0.66 for the eight rivers (Glennies Creek, Goulburn River, Hunter River, Moonan Brook, Pages Creek, Paterson River, Williams River, and Wollombi Brook) located within the Hunter river basin, and varies from 0.44 to 0.49 for the two rivers (Ourimbah Creek and Wyong River) located within the Macquarie Tuggerah basin.

The BFI for the Hunter River varies from 0.49 at Singleton to 0.66 at Glenbawn, with the mean value of 0.57 obtained from 13 gauging sites (Figure 44). This means that 57% of the total streamflow for the Hunter River is contributed by baseflow, and 43% is contributed by quickflow.

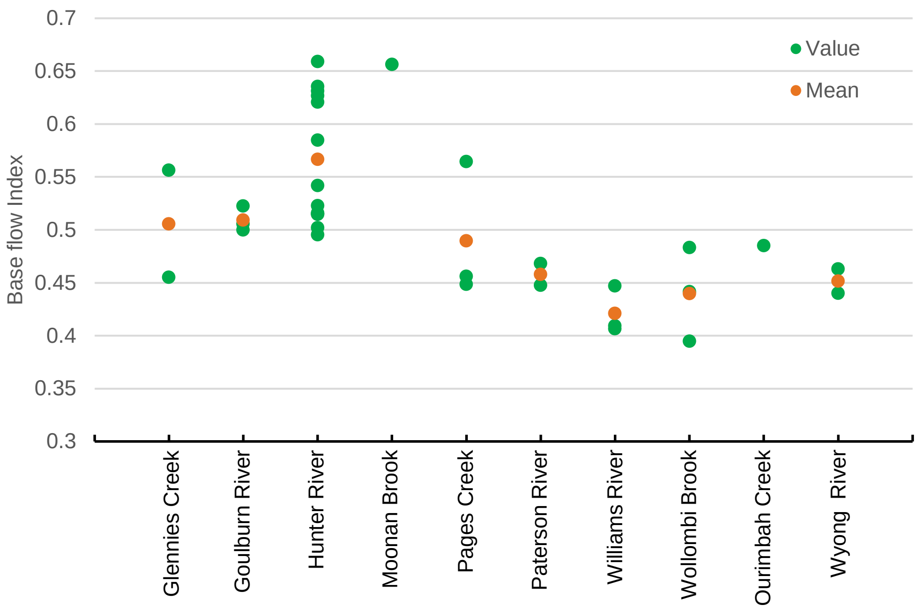

Figure 44 Baseflow index (mean annual baseflow divided by mean annual total streamflow) for major rivers in the Hunter subregion

The first eight rivers are within in the Hunter river basin; the last two rivers are within in the Macquarie Tuggerah basin. Each green dot represents a value for a gauging station.

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 the NSW *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.

Table 13 Summary of the applicable water sharing plans that cover surface water in the Hunter subregion

Water management area	Water sharing plan	Planned area	Basic information	Commenced and/or suspended and/or recommended
Hunter	The *Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources 2009* (DPI, 2009)	The Hunter unregulated rivers and creeks	• Long-term average annual extraction limits for different rivers. • Not pumping when no visible flow at the pumping site. • Three flow classes: (i) very low flow class, (ii) B class (for low flow) and (iii) C class (for the moderate to high range of flows).	Commenced on 1/8/2009 (Current version for 1/1/2014 to date)
Hunter	The *Water Sharing Plan for the Hunter Regulated River Water Source 2003* (DIPNR, 2004a)	The Hunter regulated rivers	• Long-term average annual extraction limit (217,000 ML/year) • Planned environmental water. • Adaptive environmental water • Basic landholder right • Domestic and stock rights (2592 ML/year in zone 1; 2375 ML/year in zone 2; 548 ML/year in zone 3).	Commenced on 1/7/2004 Suspended on 29/12/2006 Recommended on 16/9/2011 (Current version for 17/9/2014 to date)

Water management area	Water sharing plan	Planned area	Basic information	Commenced and/or suspended and/or recommended
Hunter	The *Water Sharing Plan for the Wybong Creek Water Source 2003* (DIPNR, 2003a)	The Wybong Creek	Five flow classes: (i) very low flow class (<1 ML/day), (ii) B class (1–7 ML/day), (iii) C class (7–16 ML/day), (iv) D class (16–100 ML/day) and (v) E class (>100 ML/day)	Commenced on 1/7/2004 Suspended on 18/8/2006 (Current version for 1/1/2014 to date)
Central Coast	The *Water Sharing Plan for the Jilliby Jilliby Creek Water Source 2003* (DIPNR, 2004b)	The Jilliby Jilliby Creek	Four flow classes: (i) very low flow class (<0.5 ML/day in year 1; <0.75 ML/day in year 2; 1 ML/day from year 3), (ii) B class (0.5–3.3 ML/day in year 1; 0.75–3.3 ML/day in year 2; 1.0–3.3 ML/day from year 3), (iii) C class (3.3–8.0 ML/day) and (iv) D class (>8.0 ML/day)	Commenced on 1/7/2004 (Current version for 1/1/2014 to date)
Central Coast	The *Water Sharing Plan for the Ourimbah Creek Water Source 2003* (DIPNR, 2003b)	The Ourimbah Creek	Six flow classes: (i) very low flow class (<4 ML/day), (ii) A class (4–7 ML/day), (iii) B class (7–25 ML/day), (iv) C class (25–60 ML/day), (v) D class (60– 160 ML/day) and (vi) E class (>160 ML/day)	Commenced on 1/7/2004 Suspended on 22/12/2006 Recommenced on 4/9/2010 (Current version for 1/1/2014 to date)
Lower North Coast	The *Water Sharing Plan for the* Karuah *River Water Source 2003* (DIPNR, 2004c)	The Karuah River	Four flow classes: (i) very low flow class (<5 ML/day), (ii) A class (5–18 ML/day), (iii) B class (18–87 ML/day) and (iv) C class (>87 ML/day)	Commenced on 1/7/2004 (Current version for 1/1/2014 to date)
Namoi	The *Water Sharing Plan for the Phillips Creek, Mooki River, Quirindi Creek and Warrah Creek Water Sources 2003* (DIPNR, 2004d)	The Quirindi Creek	Three flow classes: (i) very low flow class (<2 ML/day), (ii) C class (2–100 ML/day) and (iii) C class (>100 ML/day)	Commenced on 1/7/2004 (Current version for 1/1/2014 to date)

Table 13 summarises the major WSPs for surface water in the Hunter subregion. The major WSPs for the Hunter River include the WSP for the Hunter Regulated River Water Source and the WSP for the Hunter Unregulated and Alluvial Water Sources. Rules under the *Water Sharing Plan for the Hunter Unregulated and Alluvial Water Sources 2009* include protecting the environment, extractions, managing licence holders' water accounts, and water trading in the plan area; detailed information can be obtained from the NSW Office of Water in the Department of Primary Industries (DPI, 2009). The Hunter Regulated Rivers Water Source includes from the upstream limit of Glenbawn Dam water storage downstream to the estuary of the Hunter River, and from the upstream limit of Glennies Creek Dam water storage downstream to the junction with the Hunter River (Figure 38). The Hunter Regulated River Water Source is further divided into three management zones. As one of the 20 first-stage implemented WSPs, the WSP for the Hunter Regulated River Water Source was gazetted and commenced on 1 July 2004 and expired in June

2014, and the extension of the plan was approved by the Minister to run through until 1 July 2015. Details for the Hunter Regulated River Water Source can be found in DIPNR (2004a).

The streams within Macquarie Tuggerah basin are managed under the WSPs for the Central Coast area which commenced on 1 August 2009 and are due for extension in July 2020, except for Ourimbah Creek and Jilliby Jilliby Creek (their details shown in Table 12). The Ourimbah Creek and Jilliby Jilliby Creek WSPs was due in 2014, a merger with this plan is proposed which would result in a single WSP covering the unregulated water sources in the basin.

The lower Karuah and upper Namoi river basins are managed under WSPs within the Lower North Coast and Namoi water management areas, respectively (Table 13). More details on all WSPs within the Hunter subregion can be obtained from the NSW Office of Water website (NSW Office of Water, 2014).

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1.1.6 Surface water – groundwater interactions

Summary

Interactions between streams and alluvial aquifer and between the alluvial and surficial Permian fractured rock aquifers, are considered to occur in both directions in the Hunter subregion. Different rules apply in water sharing plans (WSPs) for the regulated and unregulated parts of the Hunter River alluvium. In the unregulated portions the alluvium and surface water systems are considered highly connected and managed together as a single unit, while in the regulated portions the alluvium is simply a separate unit from other geological units.

Fluxes within the alluvial aquifer are river leakage, diffuse rainfall recharge and upward flow from fractured rocks. River leakage is around four times greater than rainfall recharge to the alluvial aquifer, while baseflow discharge to streams is around two-thirds of discharge from the aquifer. Digital filtering of daily hydrographs estimate that more than 50% of river flow is baseflow discharge from alluvial aquifers, however in low flows or specific locations it may be close to 100%. Both mining operations and river regulation affect the behaviour of water levels in the alluvial aquifer, and can alter the direction and magnitude of water exchange between the river, alluvial aquifers and fractured rock aquifers.

1.1.6.1 Alluvial aquifer interactions

The alluvial aquifer of the Hunter subregion is considered as a regional discharge zone for the aquifers within the region (EPA, 2013), and when formulating WSPs for the region the alluvial aquifer is considered as its own unit (DPI, 2009; 2013). This treatment of the alluvial aquifer implies an interaction, a transfer of water, from the groundwater to surface water system through the alluvial aquifer (the distribution of the alluvium in the Hunter subregion is shown in Figure 37, Section 1.1.4). For example, the current WSP for the Regulated Hunter River Alluvium (DWE, 2009) gives rules on the drilling and operation of new bores in the alluvium near groundwater-dependent ecosystems. In general they must be more than 40 m from a first order or second order stream, unless they are drilled into underlying parent material and slotted at 30 m or deeper, and no impact on baseflow is demonstrated. This rule assumes that the aquifers can transfer water between each other, and affect stream baseflow in the regulated sections.

The main recharge mechanisms for the alluvial aquifer are: river leakage to the alluvium, direct rainfall recharge, and upward flow from Permian fractured rocks. River leakage is generally considered to be the largest recharge component, and in various modelling studies it has been fitted as up to four times greater than diffuse rainfall recharge (Worley Parsons, 2009; Heritage Computing, 2012). Further, in these studies and other meta-analyses the connection between the alluvial aquifer and underlying fractured rocks has been considered bi-directional (EPA, 2013).

Mining operations have been seen to affect groundwater gradients in the alluvial aquifer. In the case of a study at North Wambo Underground Mine, changes in the observed behaviour of hydrograph rise and recession was closely correlated to changes in mine operations and expansion of underground mining areas (Heritage Computing, 2012). Alluvial bores sufficiently downstream from operations showed no apparent effects. At the open-cut Mount Arthur Coal Mine, dewatering of Permian fractured rocks from mining operations led to a reversal of the pre-mining gradient between the alluvial aquifer and Permian fractured rocks, so that water levels were now higher in the alluvial aquifer (Australasian Groundwater and Environmental Consultants, 2013, p. 37, Figure 14). This did not result in a significant change in water levels in the alluvial aquifer despite occurring in a wetter period locally, which indicates either compensating leakage from the river, or only a limited connectivity between the two aquifers.

1.1.6.2 Streamflow interactions

Streamflow in the regulated Hunter subregion downstream of dams has been smoothed out somewhat by dam release management and river regulation. More consistent flows have led to less variable hydrographs in alluvial bores, probably as a result of greater stream leakage maintaining aquifer water levels (EPA, 2013). Mining operations that lead to an increase in leakage from the aquifer and result in increased river leakage, may lead to lower local salinity in the alluvium (Australasian Groundwater and Environmental Consultants, 2013, p. 38, Figure 15).

In the unregulated section of the Hunter River alluvium, the alluvial system is considered highly connected to the surface water system, and is managed as the same unit (DWE, 2009). Groundwater discharge is considered a portion of stream baseflow (Kellett et al., 1989; NSW Department of Planning, 2005). Total discharge from alluvium to river accounted for two-thirds of all discharge fluxes in a model of North Wambo Underground Mine, even with the river bed conductance set at a relatively low value (Heritage Computing, 2012). An increase in river salinity has been linked to reduced river flows and increases in inflow of saline water from deeper strata (Kellett et al., 1989, see p. 37, Figure 20; Biswas, 2010; EPA, 2013). When regulated or natural river flows are low, the stream salinity increases toward the salinity of the local alluvial aquifer and the proportion of baseflow can increase to near 100% (e.g. Biswas, 2010, p. 139, Figure 5.2).

Baseflow separation using digital signal processing methods (Lyne and Hollick, 1979) has been applied to the daily hydrograph of streams and river reaches within the Hunter subregion. They consistently estimate that on average around 50% of streamflow is discharge from the alluvial aquifer (44% to 63% from Biswas, 2010,Table 6.2, p. 191; 39% to 66% from Biswas, 2010, Figure 7, Section 1.1.5). Locally streams may be net gaining or losing (EPA, 2013), and the proportion of baseflow in the Upper Hunter varies both along the length of a reach and with the time of year (Biswas, 2010).

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1.1.7 Ecology

Summary

The major ‘natural bioregions’ of the Hunter subregion – as classified by the Interim Biogeographic Regionalisation of Australia (IBRA) – are the Sydney Basin (mainly Hunter, Kerrabee, Wyong, Yengo and Wollemi IBRA subregions) and the Brigalow Belt South (mainly the Liverpool Range IBRA subregion). The Hunter Valley is of great ecological significance because it represents the only major break in the Great Dividing Range, which provides a link between coastal and inland NSW, and includes an overlap between tropical and temperate climate zones. The lower Hunter Valley contains the Ramsar-listed Hunter Estuary Wetlands, as well as Port Stephens and Lake Macquarie. The Hunter subregion contains 27 endangered ecological communities, eight endangered populations, 116 threatened animal species listed under the NSW *Threatened Species Conservation Act 1995* (the TSC Act), of which 33 are also listed under the Commonwealth’s *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act), and 86 threatened plant species listed under the TSC Act, of which 50 are also listed under the EPBC Act. The EPBC Act also lists 39 species of migratory birds. Twelve groundwater-dependent ecosystems have been identified in the Hunter subregion, including wetlands associated with Newcastle, Sydney Basin, Tomago and Lower Goulburn River aquifers.

1.1.7.1 Ecological systems

The following description of the subregion is taken from the former Hunter-Central Rivers Catchment Management Authority (CMA) (DECCW, 2010a), the boundary of which was used when the Hunter subregion was defined in 2012. The former CMA covered an area of approximately 3.7 million hectares on the east coast of NSW, and extended from Newcastle in the east to the Merriwa Plateau and Great Dividing Range in the west, and from Taree in the north to Gosford in the south. The climate is subtropical with the greatest rainfall in coastal areas and the Barrington Tops; rainfall decreases further inland (see Section 1.1.2.3 for more detail). Major waterways are Port Stephens; the Manning, Karuah and Hunter rivers; and the coastal lakes of Wallis Lake, Lake Macquarie, Tuggerah Lake and Brisbane Water.

The Hunter Valley is of great ecological significance because (i) it represents the only major break in the Great Dividing Range and therefore provides a link between coastal and inland NSW and (ii) it contains an area of overlap between tropical and temperate zones known as the MacPherson-Macleay Overlap (Burbidge, 1960) in which the limits of many taxa are found. The CMA contains two World Heritage-listed areas – the Greater Blue Mountains and the Barrington Tops – as well as internationally significant wetlands listed under the Ramsar Convention on Wetlands including Myall Lakes and Hunter Estuary (McCauley, 2006). It contains approximately 116 national parks and nature reserves. The *2010 New South Wales State of the Catchments* (DECCW, 2010b) reported 126 species of flora and 152 species of fauna within the Hunter-Central Rivers CMA that are listed under either the *Threatened Species Conservation Act 1995* (the TSC Act) or the NSW *Fisheries Management Act 1994*.

The main bioregions defined by the Interim Biogeographic Regionalisation for Australia (IBRA; Environment Australia, 2000) that are also within the Hunter subregion are the Sydney Basin (mainly Hunter, Kerrabee, Wyong, Yengo and Wollemi IBRA subregions), which accounts for 77% of the subregion, and the Brigalow Belt South (mainly the Liverpool Range IBRA subregion), which accounts for 20% of the subregion (see Section 1.1.3). The remaining 3% is within the NSW North Coast and Nandewar IBRA bioregions. The key IBRA bioregions are described in detail in Table 14 (see also Figure 6 in Section 1.1.1).

Table 14 Key bioregions from the Interim Biogeographic Regionalisation for Australia within the Hunter subregion

IBRA[a] classification	Geology	Characteristic landforms	Typical soils	Vegetation
Sydney Basin bioregion				
Hunter subregion	A complex of Permian shales, sandstones, conglomerates, volcanics and coal measures. Bounded on the north by the Hunter Thrust fault and on the south by cliffs of Narrabeen Sandstone.	Pleistocene coastal barrier system in Newcastle bight. Rolling hills, wide valleys, with a meandering river system on a wide floodplain. River terraces are evident, the highest with silicified gravels. Streams can be brackish or saline at low flow. Numerous small swamps in upper catchment, extensive estuarine swamps behind the coastal barrier of beach and dunes.	A variety of harsh texture contrast soils on slopes and deep sandy loam alluvium on the valley floors. Small number of source bordering dunes on southern tributaries of the Hunter. Deep sands with Podosol profiles in dunes on the barrier, saline, organic muds in the estuary. Soil salinity is common on some bedrocks in the upper catchment.	Patches of rainforest brush in the lower valley. Forest and open woodland of white box, forest red gum, narrow-leaved ironbark, grey box, grey gum spotted gum, rough-barked apple and extensive of stands of swamp oak in upper reaches and foothills. River oak and river red gum along the streams. Coastal dune vegetation of blackbutt, smooth-barked apple, coast banksias and swamp mahogany. Mangroves, salt marsh and freshwater reed swamps in the estuary.
Kerrabee subregion	Triassic Narrabeen Group quartz and lithic sandstones and shales. Singleton coal measures exposed in valley floors. Numerous volcanic necks of Jurassic age and small areas of ridge top Cenozoic basalt flows. Quaternary sandy alluvium in main valleys.	Sandstone plateau with cliffed edges into wide valleys with sandy alluvial fill. Volcanic necks form circular depressions or low domes depending on relative erodibility of adjacent rock types.	Shallow sandy profiles, bare rock outcrop on plateau. Sandy texture contrast soils on slopes, harsh texture contrast soils on coal measures, deep sands and loams in alluvium. Basalts have red brown structured loams and clay loams, often buried by slope debris where the volcanic necks form depressions.	Yellow bloodwood, broad-leaved ironbark, rough-barked apple, grey gum with scribbly gum and shrubs and patches of dry heath on plateau. Rough-barked apple, forest red gum, grey box, white box, yellow box, fuzzy box, with Queensland blue grass and three-awned spear grass in valleys. River oak on the main streams. Volcanic necks and domes always support distinctive local vegetation, usually a box with grassy understorey.

IBRA[a] classification	Geology	Characteristic landforms	Typical soils	Vegetation
Wollemi subregion	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.	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.
Yengo subregion	Triassic Hawkesbury Sandstone, valleys incised to Narrabeen 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.	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.

IBRA[a] classification	Geology	Characteristic landforms	Typical soils	Vegetation
Wyong subregion	Triassic Narrabeen sandstones, Quaternary estuarine fills, and coastal barrier complexes.	Coastal fall of the Sydney Basin, rolling hills and sandstone plateau outliers. Beach, dune and lagoons of coastal barriers interspersed with coastal cliffs and rock platforms.	Texture contrast soils on lithic sandstones and shales. Loamy sands alluvium along creeks clean quartz sands on beaches and frontal dunes, Podosols in older hind dunes. Organic sands and muds in lagoons and swamps.	Smooth-barked apple, red bloodwood, brown stringybark, Sydney peppermint, spotted gum, bastard mahogany, northern grey ironbark and grey gum on hills and slopes. Prickly-leaved tea-tree and other shrubs with swamp mahogany, swamp oak, sedges and common reed on swampy creek flats. Open heath with banksia, tea-tree, coastal wattle, black she-oak and smooth-barked apple on barrier dunes. Limited areas of grey mangrove.
Brigalow Belt South bioregion				
Liverpool Range subregion	Multiple Cenozoic basalt flows with intervening sediments and ash fall material, overlying Jurassic quartz sandstones and shale.	Undulating plateau top with steep margins grading to long footslopes.	Stony red brown loams on ridges, shallow stony clay soils on steep slopes grading to deep black earths on lower slopes.	Plateau: open forest of silvertop stringybark, manna gum and mountain gum. Snow gum in cold air drainage hollows.Tallow wood, blackbutt and blue gum on eastern slopes, small areas of vine forest. Slopes:White box with rough-barked apple, belah in the creeks on northern aspects. Yellow box and Blakely's red gum on southern aspect.

[a] Interim Biogeographic Regionalisation of Australia (IBRA; Environment Australia, 2000)
Data: *The Bioregions of New South Wales: their biodiversity, conservation and history* (NSW National Parks and Wildlife Service, 2003)

1.1.7.2 Terrestrial species and communities

The Hunter subregion contains 27 endangered ecological communities and eight endangered populations (Table 15 and Table 16). There are 146 threatened animal species listed under the TSC Act, of which 85 are also listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act), and there are 90 threatened plant species listed under the TSC Act, of which 76 are also listed under either the EPBC Act or the China, Japan or Korea Australia Migratory Bird Agreement (Table 17 and Table 18).

Table 15 Endangered ecological communities within the Hunter-Central Rivers Catchment Management Authority and the Interim Biogeographic Regionalisation for Australia subregions

Endangered ecological communities as listed under either the TSC Act[a] or the EPBC Act[b] that are known or predicted to lie within both the Hunter-Central Rivers Catchment Management Authority and one or more of the IBRA[c] subregions listed in Table 14.

Community name (as listed under the TSC Act or the EPBC Act)d	TSC Act	EPBC Act
Central Hunter Grey Box-Ironbark Woodland in the New South Wales North Coast and Sydney Basin Bioregions	Endangered	Not listed
Central Hunter Ironbark-Spotted Gum-Grey Box Forest in the New South Wales North Coast and Sydney Basin Bioregions	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	Not listed
Freshwater Wetlands on Coastal Floodplains of the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Not listed
Fuzzy Box Woodland on alluvial Soils of the South Western Slopes, Darling Riverine Plains and Brigalow Belt South Bioregions	Endangered	Not listed
Hunter Floodplain Red Gum Woodland in the NSW North Coast and Sydney Basin Bioregions	Endangered	Not listed
Hunter Lowland Redgum Forest in the Sydney Basin and New South Wales North Coast Bioregions	Endangered	Not listed
Hunter Valley Footslopes Slaty Gum Woodland in the Sydney Basin Bioregion	Vulnerable	Not listed
Hunter Valley Vine Thicket in the NSW North Coast and Sydney Basin Bioregions	Endangered	Not listed
Hunter Valley Weeping Myall Woodland of the Sydney Basin Bioregion	Endangered	Critically endangered
Kincumber Scribbly Gum Forest in the Sydney Basin Bioregion	Critically endangered	Not listed
Kurri Sand Swamp Woodland in the Sydney Basin Bioregion	Endangered	Not listed
Littoral Rainforest in the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Critically endangered
Low woodland with heathland on indurated sand at Norah Head	Endangered	Not listed
Lower Hunter Spotted Gum-Ironbark Forest in the Sydney Basin Bioregion	Endangered	Not listed
Lower Hunter Valley Dry Rainforest in the Sydney Basin and NSW North Coast Bioregions	Vulnerable	Not listed
Lowland Rainforest in the NSW North Coast and Sydney Basin Bioregions	Endangered	Critically endangered
Quorrobolong Scribbly Gum Woodland 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
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

Community name (as listed under the TSC Act or the EPBC Act)d	TSC Act	EPBC Act
Themeda grassland on seacliffs and coastal headlands in the NSW North Coast, Sydney Basin and South East Corner Bioregions	Endangered	Not listed
Umina Coastal Sandplain Woodland in the Sydney Basin Bioregion	Endangered	Not listed
Warkworth Sands Woodland in the Sydney Basin Bioregion	Endangered	Not listed
White Box Yellow Box Blakely's Red Gum Woodland	Endangered	Critically endangered

[a] The NSW *Threatened Species Conservation Act 1995* (the TSC Act)
[b] The Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act)
[c] Interim Biogeographic Regionalisation of Australia (IBRA), (Environment Australia, 2000)
[d] Typology and punctuation are given as they are used in the legislation.
Data: BioNet – Atlas of NSW Wildlife (NSW Environment and Heritage, 2014)

Table 16 Endangered populations within the Hunter subregion

Endangered Populations as listed under the TSC Act[a] that are known or predicted to lie within the Hunter subregion – none were listed under the EPBC Act[b].

Scientific name[c]	Common name and/or description[c]	TSC Act
Dromaius novaehollandiae	Emu population in the New South Wales North Coast Bioregion and Port Stephens local government area	Endangered
Acacia pendula	*Acacia pendula* population in the Hunter catchment	Endangered
Eucalyptus camaldulensis	*Eucalyptus camaldulensis* population in the Hunter catchment	Endangered
Eucalyptus oblonga	*Eucalyptus oblonga* population at Bateau Bay, Forresters Beach and Tumbi Umbi in the Wyong local government area	Endangered
Eucalyptus parramattensis subsp. parramattensis	*Eucalyptus parramattensis* C. Hall. subsp. *parramattensis* in Wyong and Lake Macquarie local government areas	Endangered
Cymbidium canaliculatum	*Cymbidium canaliculatum* population in the Hunter Catchment	Endangered
Diuris tricolor	Pine Donkey Orchid population in the Muswellbrook local government area	Endangered
Leionema lamprophyllum subsp. obovatum	*Leionema lamprophyllum* subsp. *obovatum* population in the Hunter Catchment	Endangered

[a] The NSW *Threatened Species Conservation Act 1995* (the TSC Act)
[b] The Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act)
[c] Typology and punctuation are given as they are used in the legislation.
Data: BioNet – Atlas of NSW Wildlife (NSW Environment and Heritage, 2014)

Table 17 Threatened animal species within the Hunter subregion

Threatened animal species listed under either the TSC Act[a] or the EPBC Act[b] known to live within the Hunter subregion. '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	Species name	TSC Act	EPBC Act
Common Sandpiper	*Actitis hypoleucos*	Not listed	Migratory
Magpie Goose	*Anseranas semipalmata*	Vulnerable	Not listed
Regent Honeyeater	*Anthochaera phrygia*	Critically endangered	Endangered
Pink-tailed Legless Lizard	*Aprasia parapulchella*	Vulnerable	Vulnerable
New Zealand Fur-seal	*Arctocephalus forsteri*	Vulnerable	Not listed
Australian Fur-seal	*Arctocephalus pusillus doriferus*	Vulnerable	Not listed
Cattle Egret	*Ardea ibis*	Not listed	Migratory
Flesh-footed Shearwater	*Ardenna carneipes*	Vulnerable	Migratory
Ruddy Turnstone	*Arenaria interpres*	Not listed	Migratory
Australasian Bittern	*Botaurus poiciloptilus*	Endangered	Endangered
Bush Stone-curlew	*Burhinus grallarius*	Endangered	Not listed
Sharp-tailed Sandpiper	*Calidris acuminata*	Not listed	Migratory
Sanderling	*Calidris alba*	Vulnerable	Migratory
Red Knot	*Calidris canutus*	Not listed	Migratory
Curlew Sandpiper	*Calidris ferruginea*	Endangered	Migratory
Pectoral Sandpiper	*Calidris melanotos*	Not listed	Migratory
Little Stint	*Calidris minuta*	Not listed	Migratory
Red-necked Stint	*Calidris ruficollis*	Not listed	Migratory
Great Knot	*Calidris tenuirostris*	Vulnerable	Migratory
Gang-gang Cockatoo	*Callocephalon fimbriatum*	Vulnerable	Not listed
Glossy Black-Cockatoo	*Calyptorhynchus lathami*	Vulnerable	Not listed
Loggerhead Turtle	*Caretta caretta*	Endangered	Endangered
Eastern Pygmy-possum	*Cercartetus nanus*	Vulnerable	Not listed
Pied Honeyeater	*Certhionyx variegatus*	Vulnerable	Not listed
Large-eared Pied Bat	*Chalinolobus dwyeri*	Vulnerable	Vulnerable
Greater Sand-plover	*Charadrius leschenaultii*	Vulnerable	Migratory
Lesser Sand-plover	*Charadrius mongolus*	Vulnerable	Migratory
Green Turtle	*Chelonia mydas*	Vulnerable	Vulnerable
White-winged Black Tern	*Chlidonias leucopterus*	Not listed	Migratory
Speckled Warbler	*Chthonicola sagittata*	Vulnerable	Not listed
Spotted Harrier	*Circus assimilis*	Vulnerable	Not listed

Common name	Species name	TSC Act	EPBC Act
Brown Treecreeper (eastern subspecies)	*Climacteris picumnus victoriae*	Vulnerable	Not listed
Wallum Froglet	*Crinia tinnula*	Vulnerable	Not listed
Varied Sittella	*Daphoenositta chrysoptera*	Vulnerable	Not listed
Spotted-tailed Quoll	*Dasyurus maculatus*	Vulnerable	Endangered
Eastern Quoll	*Dasyurus viverrinus*	Endangered	Not listed
Wandering Albatross	*Diomedea exulans*	Endangered	Endangered/migratory
Dugong	*Dugong dugon*	Endangered	Not listed
Black-necked Stork	*Ephippiorhynchus asiaticus*	Endangered	Not listed
White-fronted Chat	*Epthianura albifrons*	Vulnerable	Not listed
Red Goshawk	*Erythrotriorchis radiatus*	Critically endangered	Vulnerable
Southern Right Whale	*Eubalaena australis*	Endangered	Endangered
Black Falcon	*Falco subniger*	Vulnerable	Not listed
Eastern False Pipistrelle	*Falsistrellus tasmaniensis*	Vulnerable	Not listed
Latham's Snipe	*Gallinago hardwickii*	Not listed	Migratory
Little Lorikeet	*Glossopsitta pusilla*	Vulnerable	Not listed
Painted Honeyeater	*Grantiella picta*	Vulnerable	Not listed
Sooty Oystercatcher	*Haematopus fuliginosus*	Vulnerable	Not listed
Pied Oystercatcher	*Haematopus longirostris*	Endangered	Not listed
White-bellied Sea-Eagle	*Haliaeetus leucogaster*	Not listed	Migratory
Black-breasted Buzzard	*Hamirostra melanosternon*	Vulnerable	Not listed
Giant Burrowing Frog	*Heleioporus australiacus*	Vulnerable	Vulnerable
Little Eagle	*Hieraaetus morphnoides*	Vulnerable	Not listed
Pale-headed Snake	*Hoplocephalus bitorquatus*	Vulnerable	Not listed
Broad-headed Snake	*Hoplocephalus bungaroides*	Endangered	Vulnerable
Stephens' Banded Snake	*Hoplocephalus stephensii*	Vulnerable	Not listed
Caspian Tern	*Hydroprogne caspia*	Not listed	Migratory
Comb-crested Jacana	*Irediparra gallinacea*	Vulnerable	Not listed
Southern Brown Bandicoot (eastern)	*Isoodon obesulus obesulus*	Endangered	Endangered
Black Bittern	*Ixobrychus flavicollis*	Vulnerable	Not listed
Golden-tipped Bat	*Kerivoula papuensis*	Vulnerable	Not listed
Swift Parrot	*Lathamus discolor*	Endangered	Endangered
Malleefowl	*Leipoa ocellata*	Endangered	Vulnerable
Broad-billed Sandpiper	*Limicola falcinellus*	Vulnerable	Migratory
Bar-tailed Godwit	*Limosa lapponica*	Not listed	Migratory

Common name	Species name	TSC Act	EPBC Act
Black-tailed Godwit	*Limosa limosa*	Vulnerable	Migratory
Green and Golden Bell Frog	*Litoria aurea*	Endangered	Vulnerable
Green-thighed Frog	*Litoria brevipalmata*	Vulnerable	Not listed
Littlejohn's Tree Frog	*Litoria littlejohni*	Vulnerable	Vulnerable
Square-tailed Kite	*Lophoictinia isura*	Vulnerable	Not listed
Southern Giant Petrel	*Macronectes giganteus*	Endangered	Endangered
Parma Wallaby	*Macropus parma*	Vulnerable	Not listed
Humpback Whale	*Megaptera novaeangliae*	Vulnerable	Vulnerable
Hooded Robin (south-eastern form)	*Melanodryas cucullata cucullata*	Vulnerable	Not listed
Black-chinned Honeyeater (eastern subspecies)	*Melithreptus gularis gularis*	Vulnerable	Not listed
Rainbow Bee-eater	*Merops ornatus*	Not listed	Migratory
Little Bentwing-bat	*Miniopterus australis*	Vulnerable	Not listed
Eastern Bentwing-bat	*Miniopterus schreibersii oceanensis*	Vulnerable	Not listed
Stuttering Frog	*Mixophyes balbus*	Endangered	Vulnerable
Giant Barred Frog	*Mixophyes iteratus*	Endangered	Endangered
Eastern Freetail-bat	*Mormopterus norfolkensis*	Vulnerable	Not listed
Southern Myotis	*Myotis macropus*	Vulnerable	Not listed
Turquoise Parrot	*Neophema pulchella*	Vulnerable	Not listed
Barking Owl	*Ninox connivens*	Vulnerable	Not listed
Powerful Owl	*Ninox strenua*	Vulnerable	Not listed
Eastern Curlew	*Numenius madagascariensis*	Not listed	Migratory
Little Curlew	*Numenius minutus*	Not listed	Migratory
Whimbrel	*Numenius phaeopus*	Not listed	Migratory
Corben's Long-eared Bat	*Nyctophilus corbeni*	Vulnerable	Vulnerable
Sooty Tern	*Onychoprion fuscata*	Vulnerable	Not listed
Blue-billed Duck	*Oxyura australis*	Vulnerable	Not listed
Olive Whistler	*Pachycephala olivacea*	Vulnerable	Not listed
Eastern Osprey	*Pandion cristatus*	Vulnerable	Not listed
Giant Dragonfly	*Petalura gigantea*	Endangered	Not listed
Yellow-bellied Glider	*Petaurus australis*	Vulnerable	Not listed
Squirrel Glider	*Petaurus norfolcensis*	Vulnerable	Not listed
Brush-tailed Rock-wallaby	*Petrogale penicillata*	Endangered	Vulnerable
Scarlet Robin	*Petroica boodang*	Vulnerable	Not listed
Flame Robin	*Petroica phoenicea*	Vulnerable	Not listed

Common name	Species name	TSC Act	EPBC Act
Pink Robin	*Petroica rodinogaster*	Vulnerable	Not listed
Red-tailed Tropicbird	*Phaethon rubricauda*	Vulnerable	Not listed
Brush-tailed Phascogale	*Phascogale tapoatafa*	Vulnerable	Not listed
Koala	*Phascolarctos cinereus*	Vulnerable	Vulnerable
Ruff	*Philomachus pugnax*	Not listed	Migratory
Sperm Whale	*Physeter macrocephalus*	Vulnerable	Not listed
Glossy Ibis	*Plegadis falcinellus*	Not listed	Migratory
Pacific Golden Plover	*Pluvialis fulva*	Not listed	Migratory
Grey Plover	*Pluvialis squatarola*	Not listed	Migratory
Grey-crowned Babbler (eastern subspecies)	*Pomatostomus temporalis temporalis*	Vulnerable	Not listed
Long-nosed Potoroo	*Potorous tridactylus*	Vulnerable	Vulnerable
Eastern Chestnut Mouse	*Pseudomys gracilicaudatus*	Vulnerable	Not listed
New Holland Mouse	*Pseudomys novaehollandiae*	Not listed	Vulnerable
Red-crowned Toadlet	*Pseudophryne australis*	Vulnerable	Not listed
Gould's Petrel	*Pterodroma leucoptera leucoptera*	Vulnerable	Endangered
Kermadec Petrel (west Pacific subspecies)	*Pterodroma neglecta neglecta*	Vulnerable	Vulnerable
Black-winged Petrel	*Pterodroma nigripennis*	Vulnerable	Not listed
Providence Petrel	*Pterodroma solandri*	Vulnerable	Migratory
Grey-headed Flying-fox	*Pteropus poliocephalus*	Vulnerable	Vulnerable
Wompoo Fruit-Dove	*Ptilinopus magnificus*	Vulnerable	Not listed
Rose-crowned Fruit-Dove	*Ptilinopus regina*	Vulnerable	Not listed
Superb Fruit-Dove	*Ptilinopus superbus*	Vulnerable	Not listed
Little Shearwater	*Puffinus assimilis*	Vulnerable	Not listed
Australian Painted Snipe	*Rostratula australis*	Endangered	Endangered
Yellow-bellied Sheathtail-bat	*Saccolaimus flaviventris*	Vulnerable	Not listed
Greater Broad-nosed Bat	*Scoteanax rueppellii*	Vulnerable	Not listed
Diamond Firetail	*Stagonopleura guttata*	Vulnerable	Not listed
Little Tern	*Sternula albifrons*	Endangered	Migratory
Freckled Duck	*Stictonetta naevosa*	Vulnerable	Not listed
Mallee Emu-wren	*Stipiturus mallee*	Not listed	Endangered
Masked Booby	*Sula dactylatra*	Vulnerable	Migratory
Shy Albatross	*Thalassarche cauta*	Vulnerable	Vulnerable
Grey-headed Albatross	*Thalassarche chrysostoma*	Not listed	Endangered

Common name	Species name	TSC Act	EPBC Act
Black-browed Albatross	*Thalassarche melanophris*	Vulnerable	Vulnerable
Red-legged Pademelon	*Thylogale stigmatica*	Vulnerable	Not listed
Grey-tailed Tattler	*Tringa brevipes*	Not listed	Migratory
Wood Sandpiper	*Tringa glareola*	Not listed	Migratory
Wandering Tattler	*Tringa incana*	Not listed	Migratory
Common Greenshank	*Tringa nebularia*	Not listed	Migratory
Marsh Sandpiper	*Tringa stagnatilis*	Not listed	Migratory
Buff-breasted Sandpiper	*Tryngites subruficollis*	Not listed	Migratory
Eastern Grass Owl	*Tyto longimembris*	Vulnerable	Not listed
Masked Owl	*Tyto novaehollandiae*	Vulnerable	Not listed
Sooty Owl	*Tyto tenebricosa*	Vulnerable	Not listed
Rosenberg's Goanna	*Varanus rosenbergi*	Vulnerable	Not listed
Eastern Cave Bat	*Vespadelus troughtoni*	Vulnerable	Not listed
Terek Sandpiper	*Xenus cinereus*	Vulnerable	Migratory

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

Table 18 Threatened plant species known to grow within the Hunter subregion

Threatened plant species listed under either the TSC Act[a] or the EPBC Act[b] that are known to grow within the Hunter subregion. Typology and punctuation are given as they are used in the legislation.

Common name	Species name	TSC Act	EPBC Act
White-flowered Wax Plant	*Cynanchum elegans*	Endangered	Endangered
Thick-leaf Star-hair	*Astrotricha crassifolia*	Vulnerable	Vulnerable
Hoary Sunray	*Leucochrysum albicans var. tricolor*	Not listed	Endangered
	Olearia cordata	Vulnerable	Vulnerable
	Ozothamnus tesselatus	Vulnerable	Vulnerable
Austral Cornflower	*Rhaponticum australe*	Extinct	Not listed
Heath Wrinklewort	*Rutidosis heterogama*	Vulnerable	Vulnerable
	Senecio linearifolius var. dangarensis	Endangered	Not listed
Coast Groundsel	*Senecio spathulatus*	Endangered	Not listed
Narrow-leafed Wilsonia	*Wilsonia backhousei*	Vulnerable	Not listed
Spreading Guinea Flower	*Hibbertia procumbens*	Endangered	Not listed
	Tetratheca glandulosa	Vulnerable	Not listed
Black-eyed Susan	*Tetratheca juncea*	Vulnerable	Vulnerable
	Epacris purpurascens var. purpurascens	Vulnerable	Not listed
Sand Spurge	*Chamaesyce psammogeton*	Endangered	Not listed
Large-leafed Monotaxis	*Monotaxis macrophylla*	Endangered	Not listed
Rainforest Cassia	*Senna acclinis*	Endangered	Not listed
	Pultenaea sp. Olinda	Endangered	Not listed
	Dillwynia tenuifolia	Vulnerable	Not listed
	Kennedia retrorsa	Vulnerable	Vulnerable
Coast Headland Pea	*Pultenaea maritima*	Vulnerable	Not listed
	Acacia dangarensis	Endangered	Not listed
Ausfeld's Wattle	*Acacia ausfeldii*	Vulnerable	Not listed
Bynoe's Wattle	*Acacia bynoeana*	Endangered	Vulnerable
Flockton Wattle	*Acacia flocktoniae*	Vulnerable	Vulnerable
Downy Wattle	*Acacia pubescens*	Vulnerable	Vulnerable
	Velleia perfoliata	Vulnerable	Vulnerable
	Maundia triglochinoides	Vulnerable	Not listed
Tranquility Mintbush	*Prostanthera askania*	Endangered	Endangered
Singleton Mint Bush	*Prostanthera cineolifera*	Vulnerable	Vulnerable
Wollemi Mint-bush	*Prostanthera cryptandroides subsp. cryptandroides*	Vulnerable	Vulnerable
	Prostanthera discolor	Vulnerable	Vulnerable

Common name	Species name	TSC Act	EPBC Act
Somersby Mintbush	*Prostanthera junonis*	Endangered	Endangered
Mount Vincent Mint-bush	*Prostanthera stricta*	Vulnerable	Vulnerable
Fraser's Screw Fern	*Lindsaea fraseri*	Endangered	Not listed
	Baeckea kandos	Endangered	Endangered
Netted Bottle Brush	*Callistemon linearifolius*	Vulnerable	Not listed
Charmhaven Apple	*Angophora inopina*	Vulnerable	Vulnerable
	Darwinia biflora	Vulnerable	Vulnerable
	Darwinia glaucophylla	Vulnerable	Not listed
	Darwinia peduncularis	Vulnerable	Not listed
Camfield's Stringybark	*Eucalyptus camfieldii*	Vulnerable	Vulnerable
Capertee Stringybark	*Eucalyptus cannonii*	Vulnerable	Not listed
Singleton Mallee	*Eucalyptus castrensis*	Endangered	Not listed
Broken Back Ironbark	*Eucalyptus fracta*	Vulnerable	Not listed
Slaty Red Gum	*Eucalyptus glaucina*	Vulnerable	Vulnerable
Craven Grey Box	*Eucalyptus largeana*	Endangered	Not listed
Narrow-leaved Black Peppermint	*Eucalyptus nicholii*	Vulnerable	Vulnerable
	Eucalyptus parramattensis subsp. decadens	Vulnerable	Vulnerable
Pokolbin Mallee	*Eucalyptus pumila*	Vulnerable	Vulnerable
	Eucalyptus sp. Howes Swamp Creek	Endangered	Endangered
	Homoranthus darwinioides	Vulnerable	Vulnerable
Biconvex Paperbark	*Melaleuca biconvexa*	Vulnerable	Vulnerable
Grove's Paperbark	*Melaleuca groveana*	Vulnerable	Not listed
Magenta Lilly Pilly	*Syzygium paniculatum*	Endangered	Vulnerable
	Caladenia porphyrea	Endangered	Not listed
Thick Lip Spider Orchid	*Caladenia tessellata*	Endangered	Vulnerable
	Corunastylis sp. Charmhaven (NSW896673)	Critically endangered	Not listed
Red Helmet Orchid	*Corybas dowlingii*	Endangered	Not listed
Leafless Tongue Orchid	*Cryptostylis hunteriana*	Vulnerable	Vulnerable
Spider orchid	*Dendrobium melaleucaphilum*	Endangered	Not listed
	Diuris bracteata	Endangered	Extinct
Small Snake Orchid	*Diuris pedunculata*	Endangered	Endangered
Rough Doubletail	*Diuris praecox*	Vulnerable	Vulnerable
Pine Donkey Orchid	*Diuris tricolor*	Vulnerable	Not listed
Variable Midge Orchid	*Genoplesium insignis*	Endangered	Not listed

Common name	Species name	TSC Act	EPBC Act
Illawarra Greenhood	*Pterostylis gibbosa*	Endangered	Endangered
Dark Greenhood	*Pterostylis nigricans*	Vulnerable	Not listed
Wyong Sun Orchid	*Thelymitra sp. adorata*	Critically endangered	Not listed
	Prasophyllum sp. Wybong	Not listed	Critically endangered
Bluegrass	*Dichanthium setosum*	Vulnerable	Vulnerable
Scrambling Lignum	*Muehlenbeckia costata*	Vulnerable	Not listed
Tall Knotweed	*Persicaria elatior*	Vulnerable	Vulnerable
Hairy Geebung	*Persoonia hirsuta*	Endangered	Endangered
North Rothbury Persoonia	*Persoonia pauciflora*	Critically endangered	Critically endangered
Small-flower Grevillea	*Grevillea parviflora subsp. parviflora*	Vulnerable	Vulnerable
	Grevillea shiressii	Vulnerable	Vulnerable
Clandulla Geebung	*Persoonia marginata*	Vulnerable	Vulnerable
Bodalla Pomaderris	*Pomaderris bodalla*	Vulnerable	Not listed
Scant Pomaderris	*Pomaderris queenslandica*	Endangered	Not listed
Denman Pomaderris	*Pomaderris reperta*	Critically endangered	Critically endangered
Silky Pomaderris	*Pomaderris sericea*	Endangered	Vulnerable
Trailing Woodruff	*Asperula asthenes*	Vulnerable	Vulnerable
	Philotheca ericifolia	Not listed	Vulnerable
Austral Toadflax	*Thesium australe*	Vulnerable	Vulnerable
	Derwentia blakelyi	Vulnerable	Not listed
	Commersonia rosea	Endangered	Endangered
	Lasiopetalum longistamineum	Vulnerable	Vulnerable
	Rulingia procumbens	Vulnerable	Vulnerable
	Zannichellia palustris	Endangered	Not listed

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

1.1.7.3 Aquatic species and communities

The lower Hunter Valley contains some of the most significant wetlands in NSW including the Ramsar-listed Hunter Estuary Wetlands, as well as Port Stephens and Lake Macquarie (DECCW, 2009). The Hunter estuary contains the second largest area of mangroves in NSW and significant saltmarsh habitat occurs in and around the shores of Lake Macquarie. These habitats are important as feeding and roosting sites for a large seasonal population of shorebirds and as a waylay site for migratory birds. It is also important habitat for threatened amphibians. The Hunter estuary provides important nursery habitat for marine organisms including commercial species of fish and prawns. The Port Stephens estuary supports 22 migratory and ten breeding shorebird species. The estuary, together with rivers, creeks and tributaries under tidal influence, are included in the Port Stephens-Great Lakes Marine Park. Forests of swamp mahogany and paperbark in the lower Hunter Valley lowlands are important habitat for threatened species such as the grey-headed flying-fox, swift parrot and koala (DECCW, 2009).

The NSW Office of Water and the Office of Environment and Heritage have used a risk analysis framework (Serov et al., 2012) to identify groundwater-dependent ecosystems (GDEs) overlying NSW coastal groundwater sources. The conceptual framework classifies GDEs based on the degree to which they depend on groundwater access and their priority for management actions. It allows potential and actual impacts of proposed activities on GDEs to be assessed in accordance with the NSW *Water Management Act 2000*. The Hunter subregion contains 12 GDEs identified within this framework (see Figure 11 in Section 1.1.2 and Table 19) of which four are listed under the NSW *State Environmental Planning Policy No. 14 – Coastal Wetlands* (SEPP 14).

No species were identified in the subregion from the NSW Department of Primary Industries (DPI) *Fishing and Aquaculture Threatened and Protected Species Viewer* (DPI, 2014). However, DPI note that the Viewer should not be used to infer species absence and have recently added the dragonfly *Archaeophya adamsi*, which may occur in the southernmost extent of the Hunter subregion, to their list of threatened species (DPI, 2013). The Darling River Hardyhead (*Craterocephalus amniculus*) has also been added as an endangered population in June 2014. Other aquatics species identified in state or Commonwealth Acts were the green turtle, loggerhead turtle, dugong, southern right whale, humpback whale and sperm whale (Table 15).

Table 19 Groundwater-dependent ecosystems in the Hunter subregion

Name	Groundwater source	Water sharing plan
Hexham Swamp[a]	Newcastle	Hunter Unregulated and Alluvial Water Sources
Pambalong Swamp	Newcastle	Hunter Unregulated and Alluvial Water Sources
Parnell Spring	Sydney Basin – Hunter/Central Coast	Northern Fractured and Porous Rock Groundwater Sources (under development)
Wild Bull Spring	Sydney Basin – Upper Hunter	Northern Fractured and Porous Rock Groundwater Sources (under development)
Galloping Swamp[a]	Tomago Tomaree Stockton Coastal Sands (Tomago)	Tomago Tomaree Stockton Groundwater Sources
Blind Harrys Swamp	Tomago Tomaree Stockton Coastal Sands (Tomago)	Tomago Tomaree Stockton Groundwater Sources
Deep Swamp	Tomago Tomaree Stockton Coastal Sands (Tomago)	Tomago Tomaree Stockton Groundwater Sources
Sandhole Swamp[a]	Tomago Tomaree Stockton Coastal Sands (Tomago)	Tomago Tomaree Stockton Groundwater Sources
Woodberry Swamp[a]	Newcastle	Hunter Unregulated and Alluvial Water Sources
Wappinguy Spring	Lower Goulburn River	Hunter Unregulated and Alluvial Water Sources
Ginger Beer Springs	Sydney Basin - Upper Hunter	Northern Fractured and Porous Rock Groundwater Sources (under development)
Reedy Swamp	Tomago Tomaree Stockton Coastal Sands (Tomago)	Tomago Tomaree Stockton Groundwater Sources

[a] Wetlands listed under the NSW *State Environmental Planning Policy No. 14 – Coastal Wetlands* (SEPP 14).

The water sharing plan (WSP) for the Hunter unregulated and alluvial water sources (Department of Water and Energy, 2009) identifies 14 species of endangered frogs, seven species of endangered birds, two endangered flora species and one endangered macroinvertebrate.

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