Australian Government

BIOREGIONAL ASSESSMENTS

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

Context statement for the Gloucester subregion

Product 1.1 from the Northern Sydney Basin Bioregional Assessment

28 May 2014

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 <www.bioregionalassessments.gov.au>.

Department of the Environment

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

Bureau of Meteorology

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

CSIRO

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

Geoscience Australia

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

ISBN-PDF 978-1-4863-0256-7, ISBN-Word 978-1-4863-0269-7

Citation

McVicar TR, Langhi L, Barron OV, Rachakonda PK, Zhang YQ, Dawes WR, Macfarlane C, Holland KL, Wilkes PG, Raisbeck-Brown N, Marvanek SP, Li LT and Van Niel TG (2014) Context statement for the Gloucester subregion. Product 1.1 from the Northern Sydney Basin Bioregional Assessment. Department of the Environment, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia.

Authorship is listed in relative order of contribution.

Copyright

Disclaimer

Cover photograph

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

Credit: Heinz Buettikofer, CSIRO.

Australian Government
Department of the Environment
Bureau of Meteorology
Geoscience Australia

CSIRO

V20140612

Contents

Figures

Tables

Contributors to the Technical Programme

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

First Assistant Secretary	Department of the Environment: Suzy Nethercott-Watson
Programme Director	Department of the Environment: Edwina Johnson
Technical Programme Director	Bureau of Meteorology: Bronwyn Ray
Projects Director	CSIRO: David Post
Principal Science Advisor	Department of the Environment: Peter Baker
Science Directors	CSIRO: Brent Henderson Geoscience Australia: Trevor Dhu
Programme management	Department of the Environment: Ebony Coote, Anisa Coric, Geraldine Cusack, James Hill, Broni McMaster, Craig Watson Bureau of Meteorology: Graham Hawke, Louise Minty CSIRO: Damien Barrett, Carol Couch, Scott Keyworth, Warwick McDonald Geoscience Australia: Bruce Kilgour, Stuart Minchin
Project Leaders	CSIRO: Tim McVicar, David Rassam, Wendy Welsh Geoscience Australia: Kriton Glenn
Assets	Bureau of Meteorology: Brendan Moran Department of the Environment: Dave Holt, Brad Moore, David Robertson, Jin Wang
Bioregional Assessment Information Platform	Bureau of Meteorology: Bronwyn Ray CSIRO: David Lemon Geoscience Australia: Brian Cannell, Neal Evans
Communications	Department of the Environment: Crystal Bradley, Amanda Cox Bureau of Meteorology: Mel Martin CSIRO: Tsuey Cham, Leane Regan Geoscience Australia: David Beard, Chris Thompson
Ecology	CSIRO: Tanya Doody, Brendan Ebner, Alexander Herr, Kate Holland, Craig MacFarlane, Tracey May, Heather McGinness, Patrick Mitchell, Justine Murray, Anthony O'Grady, Chris Pavey, Jodie Pritchard, Nat Raisbeck-Brown, Ashley Sparrow, Georg Wiehl

Geology	CSIRO: Deepak Adhikary, Luke Connell, Emanuelle Frery, Cedric Griffiths, Jane Hodgkinson, Rob Jeffrey, Dane Kasperczyk, James Kear, Laurent Langhi, Zhejun Pan, Kaydy Pinetown, Matthias Raiber, Hayley Rohead-O'Brien, Regina Sander, Peter Schaubs, Garth Warren, Paul Wilkes, Andrew Wilkins, Yanhua Zhang Geoscience Australia: Jon Clarke, Tim Evans, Steven Lewis, John Magee, Bruce Radke, Martin Smith
Geography	Bureau of Meteorology: Natasha Herron
Geographic information systems	CSIRO: Phil Davies, Malcolm Hodgen, Steve Marvanek Geoscience Australia: Joseph Bell, Luke Caruana, Katherine Fontaine, Gerard Stewart
Groundwater modelling	CSIRO: Olga Barron, Russell Crosbie, Tao Cui, Warrick Dawes, Lei Gao, Sreekanth Janardhanan, Catherine Moore, Luk Peeters, Praveen Kumar Rachakonda, Wolfgang Schmid, Chris Turnadge, Binzhong Zhou
Hydrogeology	CSIRO: Konrad Miotlinski Geoscience Australia: Hashim Carey, Rebecca Cassel, Scott Cook, Laura Gow, Wenping Jiang, Jim Kellett, Sarah Marshall, Rebecca Norman, Jessica Northey, Tim Ransley, Gerhard Schoning, Emily Slatter, Martin Smith, Peter Somerville, Ross Spulak, Baskaran Sundaram, KokPiang Tan, Luke Wallace, Gabrielle Yates
Information management	Department of the Environment: David Holt Bureau of Meteorology: Jill McNamara, Brendan Moran CSIRO: Nick Car, Andrew Freebairn, Mick Hartcher, Geoff Hodgson, Brad Lane, Trevor Pickett, Tim Smith, Matt Stenson, Garry Swan Geoscience Australia: Luke Caruana, Penny Kilgour, Matti Peljo, Gail Ransom
Products	CSIRO: Maryam Ahmad, Daniel Aramini, Heinz Buettikofer, Will Francis, Simon Gallant, Karin Hosking, Frances Marston, Becky Schmidt, Sally Tetreault-Campbell, Catherine Ticehurst, Audrey Wallbrink Geoscience Australia: Veronika Galinec, Penny Kilgour, Daniel Rawson
Risk and uncertainty	CSIRO: Simon Barry, Susan Cuddy, Jeffery Dambacher, Jess Ford, Keith Hayes, Geoff Hosack, Dan Pagendam, Carmel Pollino
Support	Bureau of Meteorology: John Timermanis, Sarah van Rooyen CSIRO: Rose Geus Geoscience Australia: Michael Langdon, Tenai Luttrell
Surface water hydrology	CSIRO: Santosh Aryal, Jie Chen, Mat Gilfedder, Fazlul Karim, Lingtao Li, Dave McJannet, Tom Van Niel, Neil Viney, Bill Wang, Ang Yang, Yongqiang Zhang Geoscience Australia: Wenping Jiang

Acknowledgements

This technical product was reviewed by several groups:

- Discipline Leaders: Russell Crosbie (hydrogeology, CSIRO) and Jim Kellett (hydrogeology, Geoscience Australia), Alexander Herr (ecology, CSIRO), Steven Lewis (geology, Geoscience Australia), Becky Schmidt (products, CSIRO), Neil Viney (surface water hydrology, CSIRO)
- Senior Science Leaders: David Post (Projects Director), Trevor Dhu (Science Director, Geoscience Australia), Brent Henderson (Science Director, CSIRO)
- Technical Assurance Reference Group: Chaired by Peter Baker (Principal Science Advisor, Department of the Environment), this group comprises officials from the New South Wales, Queensland, South Australian and Victorian governments.

Introduction

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

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 publicly available, providing the opportunity for all other interested parties, including community, industry and government regulators, 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 experts, such as from state governments or universities, are 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 Hawkesbury-Nepean, Georges River and Wollongong Coast subregions, within the Southern Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

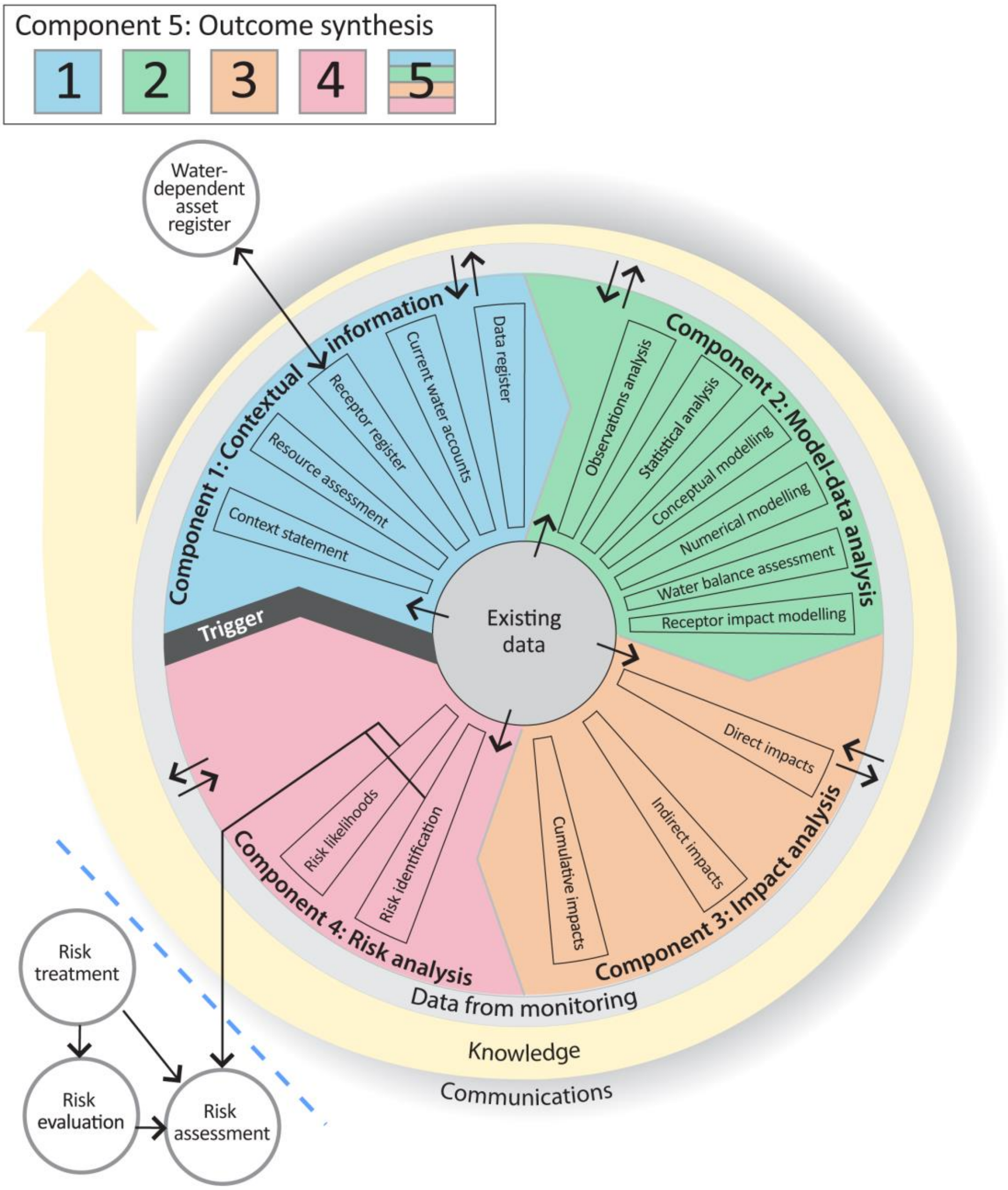


Figure 1 Schematic diagram of the bioregional assessment methodology

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 risk identification and risk likelihood components are conducted within a bioregional assessment and may contribute to risk evaluation, risk assessment and risk treatment undertaken externally.

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 publicly available, 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 the BA methodology. Figure 2 shows the information flow within a BA. Table 1 lists the content provided in the technical products, with cross-references to the part of the BA methodology that specifies it. The red ovals in both Figure 2 and Table 1 indicate the information presented for 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 the following website: <www.bioregionalassessments.gov.au>.

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. The copyright owners of the following figures, however, did not grant permission to do so: Figure 22 and Figure 23. It should be assumed that third parties are not entitled to use this material without permission from the copyright owner.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151.0° East for the Northern Sydney Basin bioregion and two standard parallels of –18.0° and –36.0°.

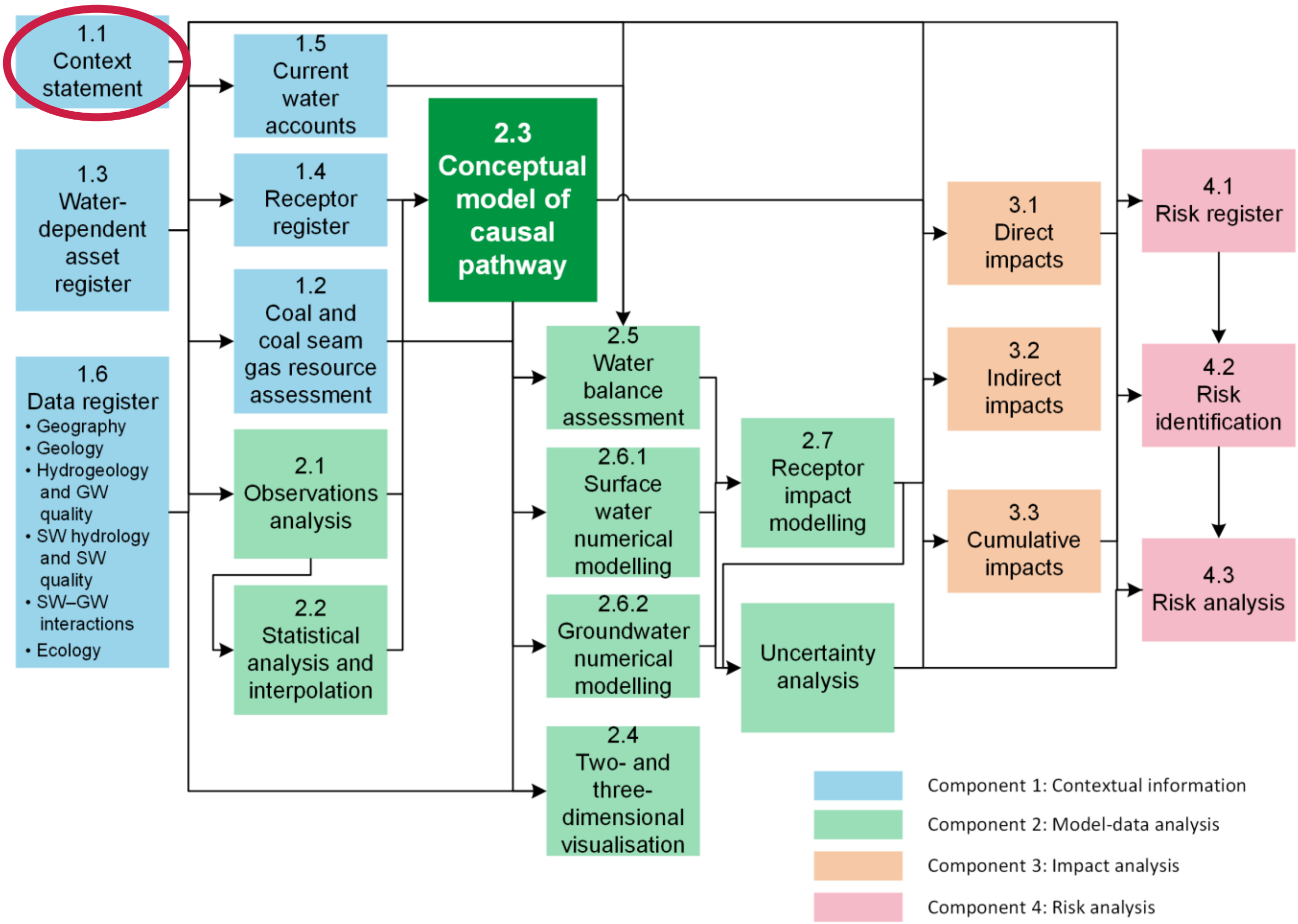


Figure 2 The simple decision tree indicates the flow of information through a bioregional assessment

The red oval indicates the information covered in this report.

Table 1 Technical reports 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 1. Merged cells indicate that more than one product is reported in one report. The red oval indicates the information covered in this report. A suite of other technical and communication products – such as maps, registers and factsheets – will also be developed through the bioregional assessments.

	Product code	Information	Section in the BA methodology[a]	Report
Component 1: Contextual information for the Gloucester 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	[b]
	1.6	Description of the data register	2.5.1.6	■
Component 2: Model-data analysis for the Gloucester subregion	2.1	Observations analysis	2.5.2.1	
	2.2	Statistical analysis and interpolation	2.5.2.2	
	2.3	Conceptual modelling	2.5.2.3, 4.3	■
	2.4	Two- and three-dimensional representations	4.2	[c]
	2.5	Water balance assessment	2.5.2.4	■[b]
	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 Gloucester subregion	3.1	Direct impacts	5.2.1	■
	3.2	Indirect impacts	5.2.2	
	3.3	Cumulative impacts of mining	5.2.3	
	3.4	Baseline for other sectors	5.2.4	
Component 4: Risk analysis for the Gloucester subregion	4.1	Risk register	2.5.4, 5.3	■
	4.2	Risk identification	2.5.4, 5.3	
	4.3	Risk analysis	2.5.4, 5.3	
Component 5: Outcome synthesis for the Northern Sydney basin bioregion	5.1	Synthesis of contextual information	2.5.5	■
	5.2	Synthesis of model-data analysis	2.5.5	
	5.3	Synthesis of impact analysis	2.5.5	
	5.4	Synthesis of risk analysis	2.5.5	

[a] Barrett et al. (2013)

[b] Product 1.5 (Current water accounts and water quality) will be included in the report for product 2.5 (Water balance assessment).

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

References

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 1 November 2013, <www.environment.gov.au/coal-seam-gas-mining/pubs/methodology-bioregional-assessments.pdf>.

1.1 Context statement for the Gloucester subregion

The context statement summarises the current extent of knowledge on the ecology, hydrology, geology and hydrogeology of a bioregion. It provides baseline information that is relevant to understanding the regional context of water resources within which coal seam gas and coal mining development is occurring. 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 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; it is essentially a literature review of existing information. Thus, some figures are reproduced from other sources and the look

1.1.1 Bioregion

The Gloucester 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 Southern Sydney Basin bioregion in the South. It covers an area of about 17,390 km^2.

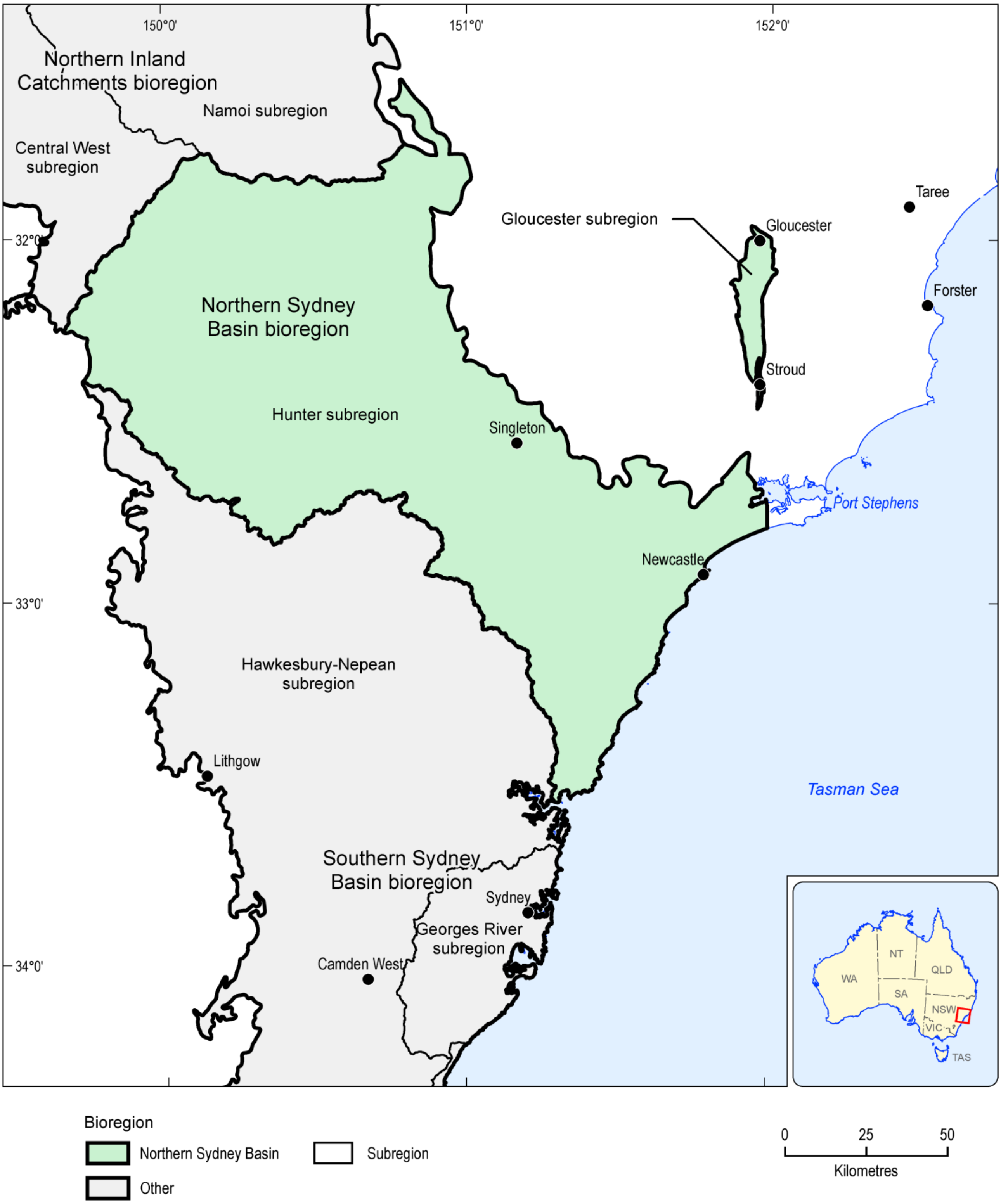


Figure 3 Gloucester and Hunter subregions in the Northern Sydney Basin bioregion

Note: adjacent subregions within the Southern Sydney Basin bioregion and Northern Inland Catchment bioregion are also shown.

The Gloucester subregion covers about 347.5 km^2 and is currently the smallest bioregional assessment subregion. The Gloucester subregion is defined by the geological Gloucester Basin (Roberts et al., 1991).

1.1.1.1 Definitions used

Figure 4 illustrates a number of jurisdictional boundaries used throughout this content statement. The Gloucester subregion is wholly contained within the area managed by the Hunter-Central Rivers Catchment Management Authority (CMA; DIPNR, 2013) – note that from 1 January 2014, in NSW CMAs have evolved into Local Land Services (LLS). The Gloucester subregion also sits wholly within the Karuah-Manning subregion of the NSW North Coast bioregion designated by the Interim Biogeographic Regionalisation for Australia (IBRA; SEWPaC, 2012). The Gloucester subregion is contained within two NSW local government areas (Australian Bureau of Statistics, 2013), being the Gloucester and Great Lakes shires.

Figure 4 Assorted jurisdictional boundaries relative to the Gloucester subregion

Source data: (i) Catchment management authority boundaries from NSW Department of Infrastructure Planning and Natural Resources (DIPNR; 2013), (ii) Interim Biogeographic Regionalisation for Australia (IBRA) boundaries from SEWPaC (2012), and (iii) local government boundaries from Australian Bureau of Statistics (2013).

References

Australian Bureau of Statistics (2013) Australian Standard Geographical Classification (ASGC) Digital Boundaries, Australia (cat. no. 1259.0.30.001).

SEWPaC (2012) Interim Biogeographic Regionalisation for Australia (IBRA), Version 7. Australian Government Department of Sustainability Environment Water Population and Communities, Canberra.

DIPNR (2013) Catchment Management Authority Areas of Operation. New South Wales Department of Infrastructure Planning and Natural Resources. Viewed <www.cma.nsw.gov.au/>.

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

1.1.2 Geography

Summary

The Northern Sydney Basin bioregion covers an area of about 17,390 km^2, of which the Gloucester subregion covers about 348 km^2. The Gloucester subregion is defined by the geological Gloucester Basin. It is located just north of the Hunter Valley in NSW, it is approximately 85 km north-northeast of Newcastle and relative to proximal regional centres is 60 km south-west of Taree and 55 km west of Forster. The subregion extends 55 km north–south (at its longest) and 15 km east–west (at its widest). Elevation in the subregion ranges from 10 to 515 m (Australian Height Datum), and it is mostly undulating with relative low slopes; some steep slopes are found at the edge of the subregion in bordering mountain ranges. Soils are mainly Kurosol (62.3%); both Rudosol and Ferrosol are also present. Pre-European vegetation was dominated by eucalypt forest and current vegetation cover is mainly persistent vegetation, associated with the border forests and grazing (the primary land use); vegetation in the grazing areas grows more in summer. Vegetation height exceeds 30 m in the forests. There are numerous rivers in the subregion which straddles a catchment divide; northern-flowing rivers contributing to the Manning River and discharging to the Tasman Sea beyond Taree and the southern-flowing rivers contributing to the Karuah River and discharging into Port Stephens. About 5000 people live in the subregion, primarily located in the towns of Gloucester and Stroud. Water for these towns is extracted from local rivers, and there are no major dams or major wetlands in the subregion. From a groundwater perspective it is a closed system. The climate is sub-tropical, characterised by summer dominant precipitation. Average precipitation over the last 30 years (1982 to 2012) for the subregion was 1095 mm/year with potential evapotranspiration (PET) of 1587 mm/year. 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 generations from the Gloucester subregion.

1.1.2.1 Physical geography

The Gloucester subregion is located just north of the Hunter Valley in NSW, it is approximately 85 km north-northeast of Newcastle and relative to proximal regional centres is 60 km south-west of Taree and 55 km west of Forster. It is located east of the Barrington Tops and west of the Myall Lakes, both of which have high international conservation value (McCauley, 2006, Section 3.3 Land Use). The subregion is defined by the geological Gloucester Basin (Roberts et al., 1991), this is 55 km north–south (at its longest) and 15 km east–west (at its widest). The Newcastle 1:250 000 topographic map (Mapsheet SI5602, Geoscience Australia, 2006) shows that several mountain ranges running approximately north–south bound the subregion on the western edge: they are (from south to north) Linger and Die Ridge and Lawlers Range. It is bounded on the eastern edge (also from south to north) by Brogdens Pinnacles, Copper Mine Ridge, the western foothills of Terreel Ridge and Banks Rocks. Buckleys Range is located in the south-east of the subregion

(Mapsheet SI5602, Geoscience Australia, 2006). In the subregion, land–surface elevation ranges from 10 to 515 m (Australian Height Datum (AHD), Figure 5); it exceeds 1000 m (AHD) in the nearby Barrington Tops (located outside the subregion). Within the subregion the small east–west ridge that is the catchment divide between the Avon River catchment and Mammy Johnsons River catchment (which forms the divide between the larger Manning River and the Karuah River basins, see Figure 7) is visible in Figure 5. Figure 6 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 centre of the valley and relatively steep in the two bounding mountain ranges. The maximum slope in the subregion is 47 degrees, with some steep slopes being encountered in surrounding mountain areas. There are distinct break-of-slopes where the mountains and valley meet (Figure 6).

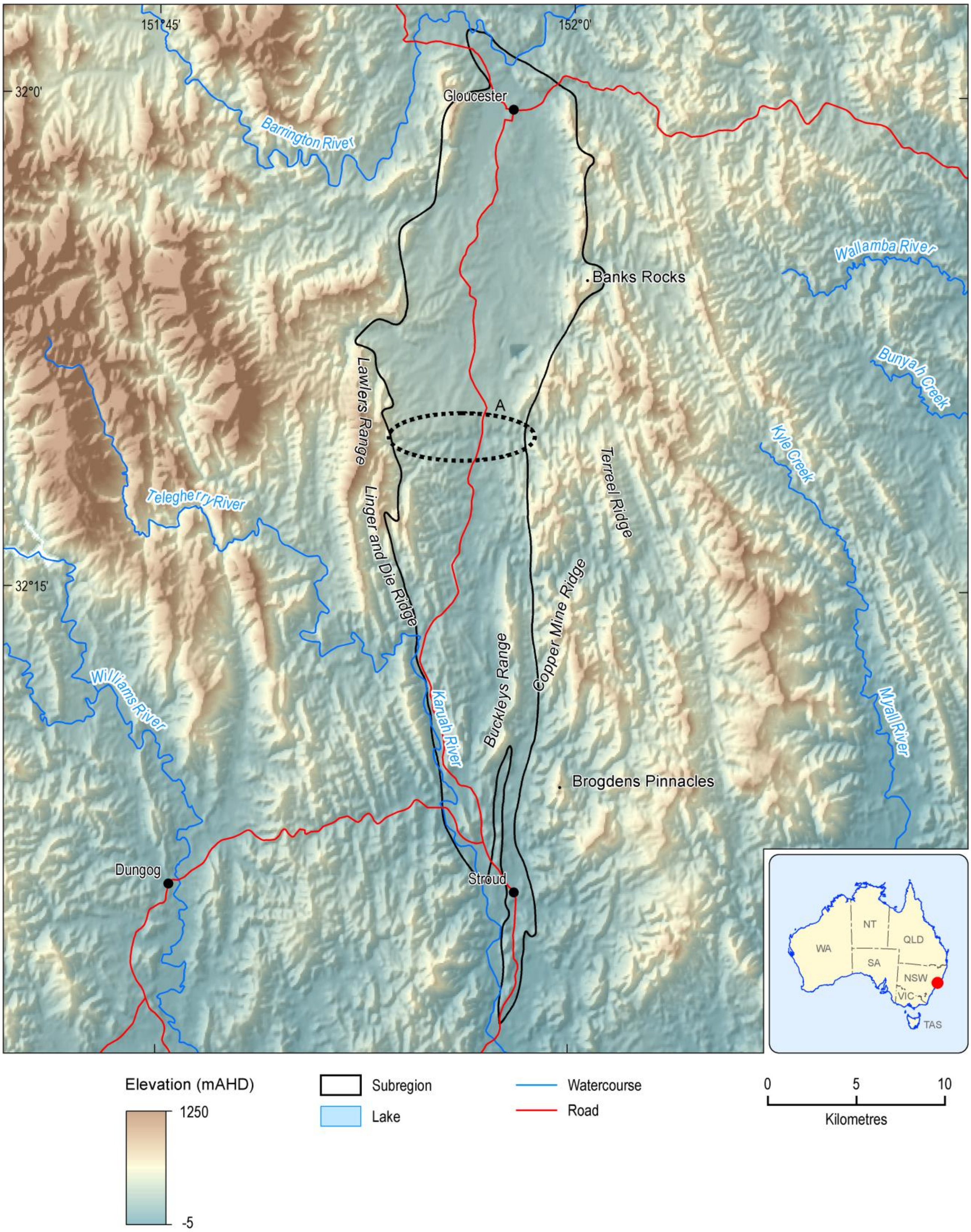


Figure 5 Surface elevation and mountain ranges of the Gloucester subregion

The black dotted ellipse (A) contains the east–west aligned ridge that defines the boundary between the Avon River and Mammy Johnsons River catchments (which forms the divide between the larger Manning River and the Karuah River basins).
Source data: Gallant et al. (2011)

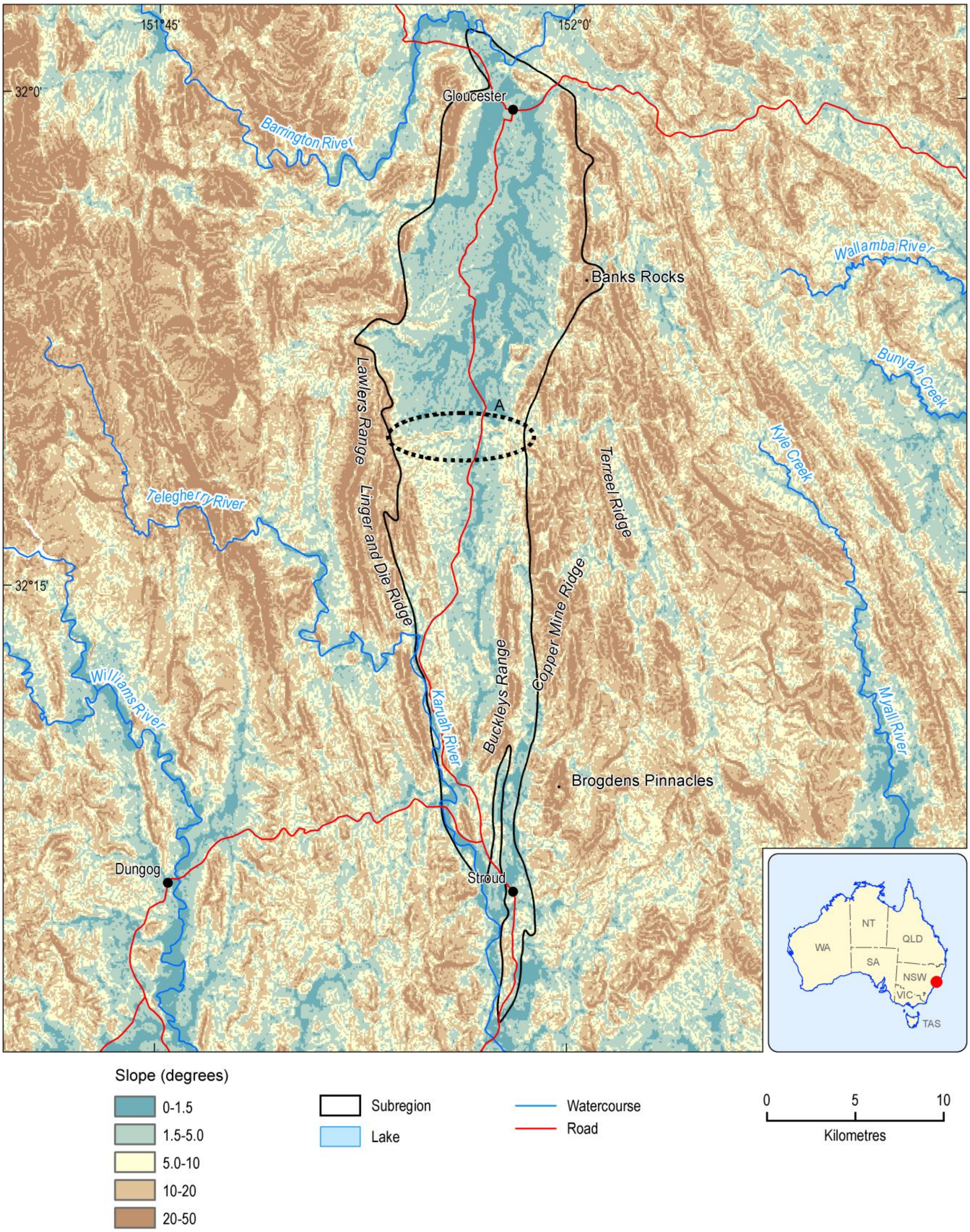
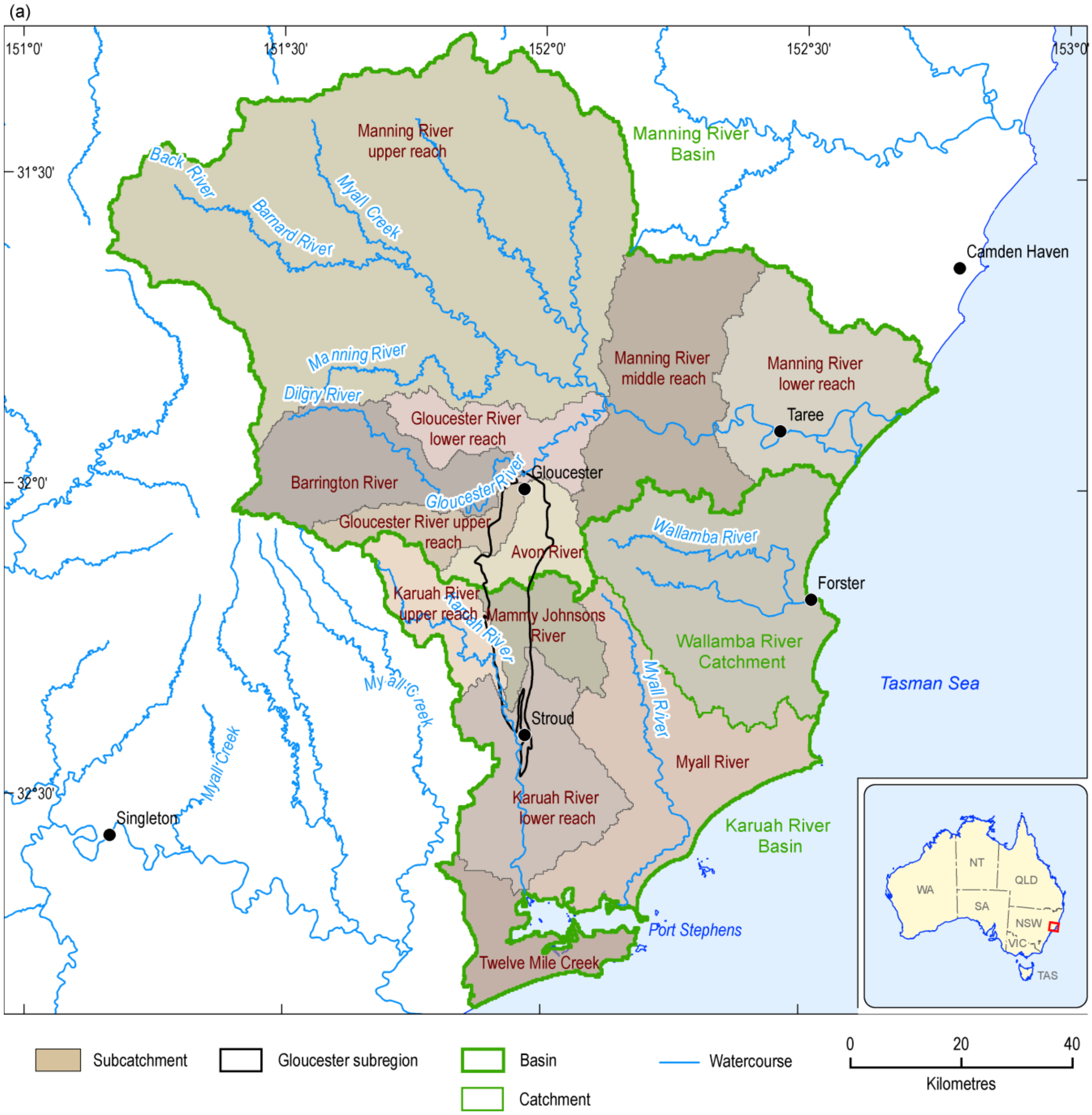


Figure 6 Land surface slopes for the Gloucester subregion

The black dotted ellipse (A) contains the east–west aligned ridge that defines the boundary between the Avon River and Mammy Johnsons River catchments (which forms the divide between the larger Manning River and the Karuah River basins).
Source data: Gallant et al. (2011)

While there are no major wetlands located in the subregion (i.e. those listed in international, national or state databases), many of the rivers have riparian vegetation along the banks. Figure 7 shows that from a surface water perspective the Gloucester subregion straddles the headwaters of parts of two surface water basins being: (i) the Manning River Basin and (ii) the Karuah River Basin. The north-flowing area of the Gloucester subregion drains parts of the Avon River, Gloucester River and Barrington River catchments – all tributaries of the Manning River, which flows past the town of Taree and beyond, to discharge to the Tasman Sea (Figure 7). The south flowing area of the Gloucester subregion drains parts of the Mammy Johnsons River and Karuah River catchments before discharging into Port Stephens (Figure 7).

There is no groundwater connectivity beyond the Gloucester subregion (Parsons Brinckerhoff, 2012a, pp. xxv, 30, 31; SRK, 2010, p. 45). From a groundwater perspective it is a ‘closed system’ with groundwater discharging to lower portions of the landscape and being evaporated through riparian vegetation (Parsons Brinckerhoff, 2012a, pp. 30-31). Over the last 10 years the regional hydrogeology of the Gloucester subregion has only been characterised during commercial assessment of energy resources; there are no other available sources.


(a)
151°0'
151°30'
152°0'
152°30'
153°0'
31°30'
32°0'
32°30'
Manning River upper reach
Manning River Basin
Back River
Barnard River
Myall Creek
Manning River
Dilgry River
Gloucester River lower reach
Manning River middle reach
Manning River lower reach
Camden Haven
Taree
Barrington River
Gloucester River
Gloucester
Gloucester River upper reach
Avon River
Wallamba River
Forster
Karuah River upper reach
Karuah River
Mammy Johnsons River
Wallamba River Catchment
Myall Creek
Myall River
Tasman Sea
Stroud
Myall River
Singleton
Myall Creek
Karuah River lower reach
Karuah River Basin
Port Stephens
Twelve Mile Creek
NT
QLD
WA
SA
NSW
VIC
TAS
Subcatchment
Gloucester subregion
Basin
Catchment
Watercourse
0
20
40
Kilometres

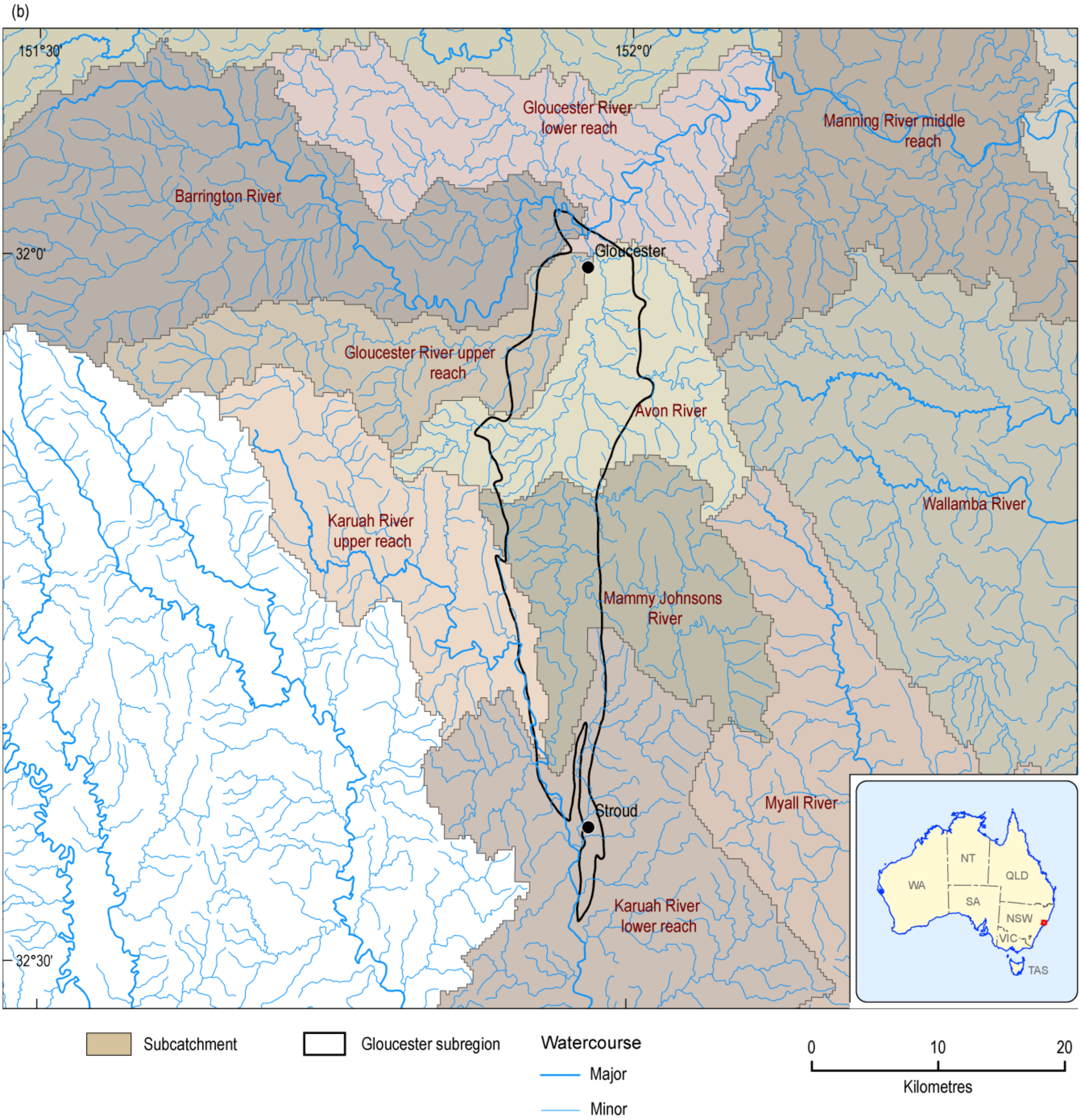


Figure 7 Relevant surface water basins, catchments and subcatchments of the Gloucester subregion

(a) shows the entire Manning River and Karuah River basins with their major watercourses and (b) shows an enlargement of just the Gloucester subregion with both the major and minor watercourses.
Source data: Geoscience Australia (2006)

The Gloucester subregion is comprised of two ASRIS (Australian Soil Resource Information System) physiographic classes (Figure 8): (i) Macleay-Barrington Fall (covering 225.5 km^2 or 65% of the subregion) and (ii) Liverpool-Barrington Plateaus (covering 121.9 km^2 or 35% of the subregion). Their descriptions and those of the physiographic classes in the surrounding areas in the vicinity of the subregion are provided in Table 2.

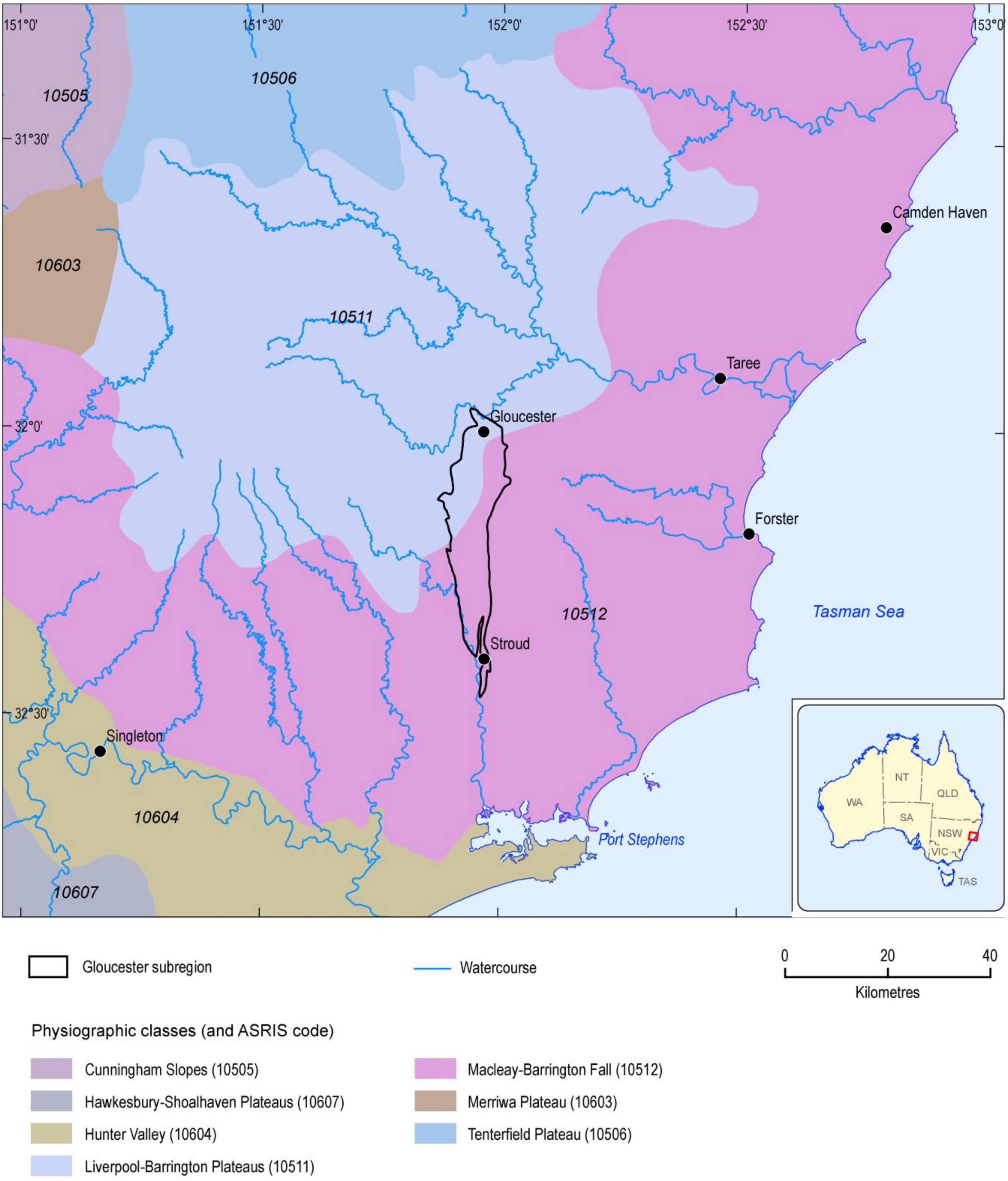


Figure 8 Physiographic classes of the Gloucester subregion

Source data: Pain et al. (2011)

Table 2 Description of physiographic classes in the Gloucester subregion, and surrounding areas, shown in Figure 8

Class	Class name	Class description
10505	Cunningham Slopes	Ridges and valleys in metamorphic rocks
10506	Tenterfield Plateau	Undulating granitic plateau with higher residuals including basalt cappings
10511	Liverpool-Barrington Plateaus	Dissected basaltic plateaus
10512	Macleay-Barrington Fall	Plateau flank dissected into narrow strike ridges and valleys
10603	Merriwa Plateau	Rolling basalt upland with sandstone cliffs
10604	Hunter Valley	Undulating to low hilly country on weak rocks, with alluvial and sandy littoral plains
10607	Hawkesbury-Shoalhaven Plateaus	Deeply dissected sandstone plateaus

Source data: Pain et al. (2011)

There are three main soils found in the Gloucester subregion – Kurosol (62.3%), Rudosol (18.0%) and Ferrosol (15.8%) – together covering about 95% of the subregion. Other soils such as Dermosol (3.4%), Tenosol (0.4%) and Sodosol (0.1%) are also present (Figure 9). Their characteristics are briefly introduced below, ordered by descending area. 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 the upper 0.2m of the B horizon is strongly acid (pH <5.5). 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. 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. Dermosols are located in the south of the subregion in lower slope landscape positions, adjacent to the Karuah River, around the town of Stroud, and they 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. Tenosols in the vicinity of the Gloucester 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. Parent materials include Permian sandstones and conglomerates of the Leloma Formation (Scheibner and Basden, 1998). 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.

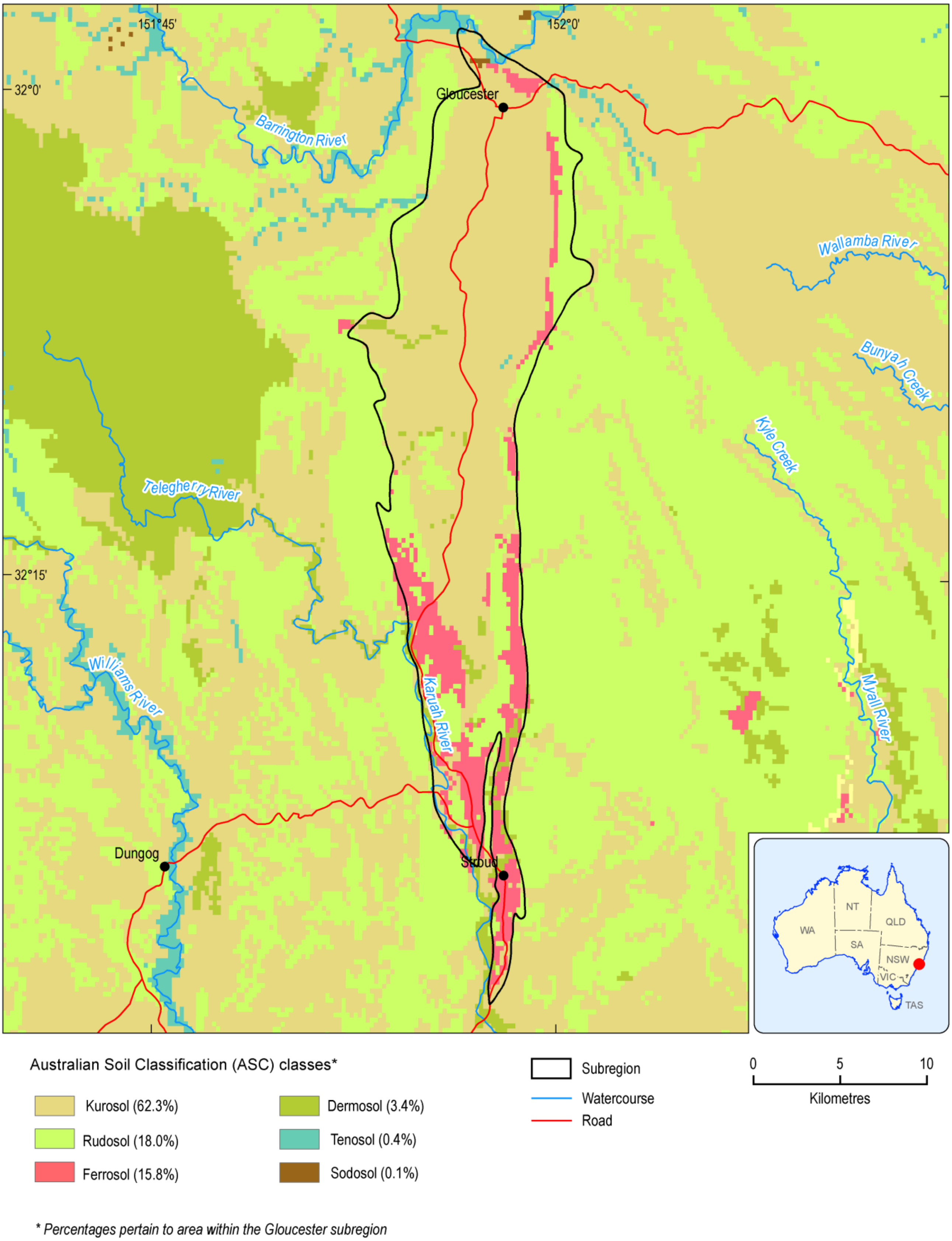


Figure 9 Australian Soil Classification (ASC) classes in the Gloucester subregion

Source data: Australian Soil Resource Information System (ASRIS) (2011). National soil data provided by the Australian Collaborative Land Evaluation Program ACLEP, endorsed through the National Committee on Soil and Terrain NCST (www.clw.csiro.au/aclep).

Figure 10 shows that prior to European settlement and its associated land-clearing, the dominant overstorey vegetation in the subregion was: (i) canopy coverage in the range of 30 to 70%, (ii) eucalypt dominated, and (iii) either 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) and low coastal heath was, and is, present in the coastal lowlands north-east of Port Stephens (Figure 10). Since European settlement there has been much vegetation clearing and the current major vegetation types are shown in Figure 11. The majority of the subregion contains non-native vegetation; remnant stands of native forests are found on the slopes of the mountain ranges at the edge of the subregion. Adjacent to the subregion, especially in eastern and western directions, there are tracts of eucalypt forest, sub-tropical rainforest and cool temperate rainforest dominated by *Nothofagus* species present (Figure 11).

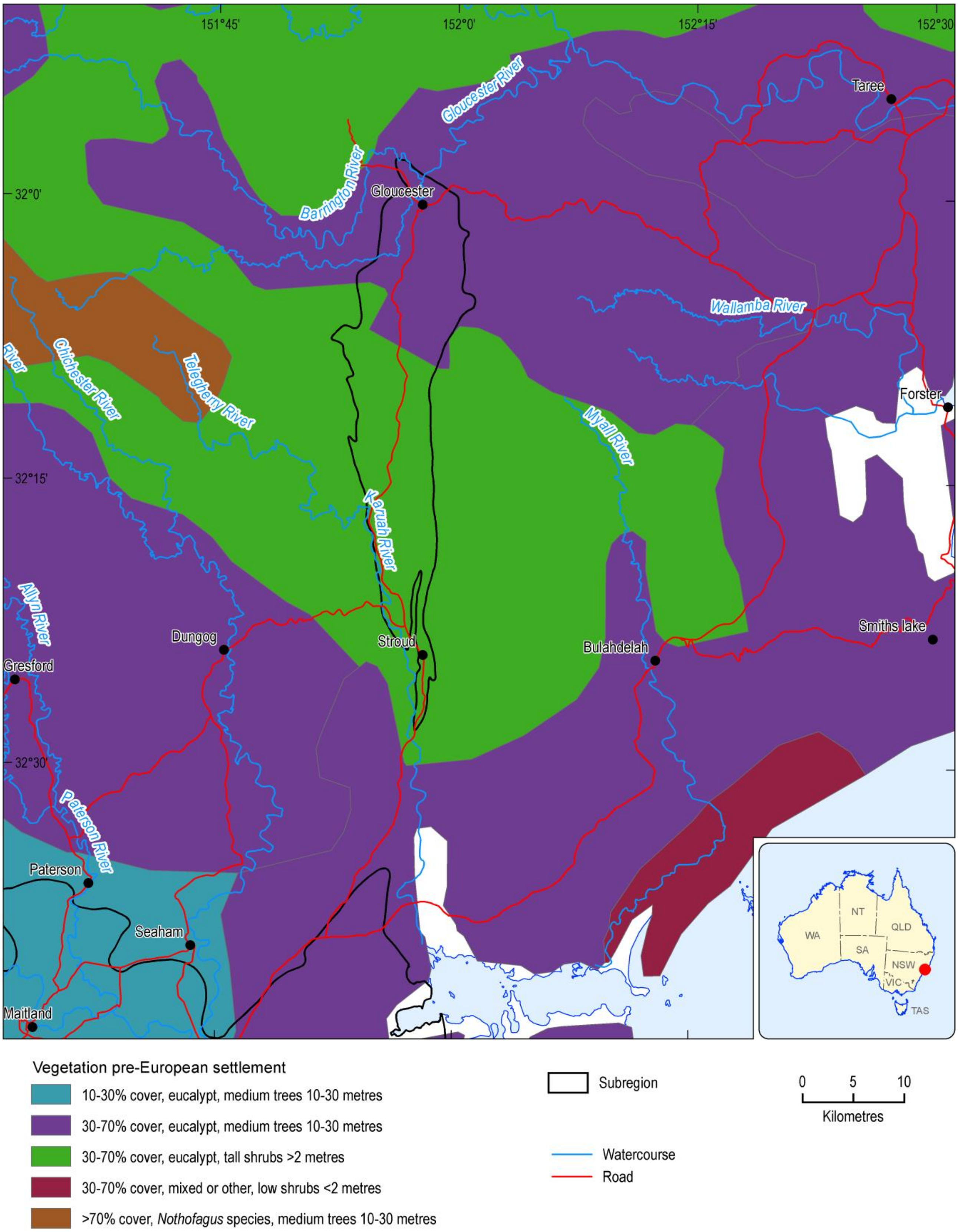


Figure 10 Pre-European vegetation in the Gloucester subregion

Source data: Carnahan (1976); Australian Survey and Land Information Group (AUSLIG) (1990)

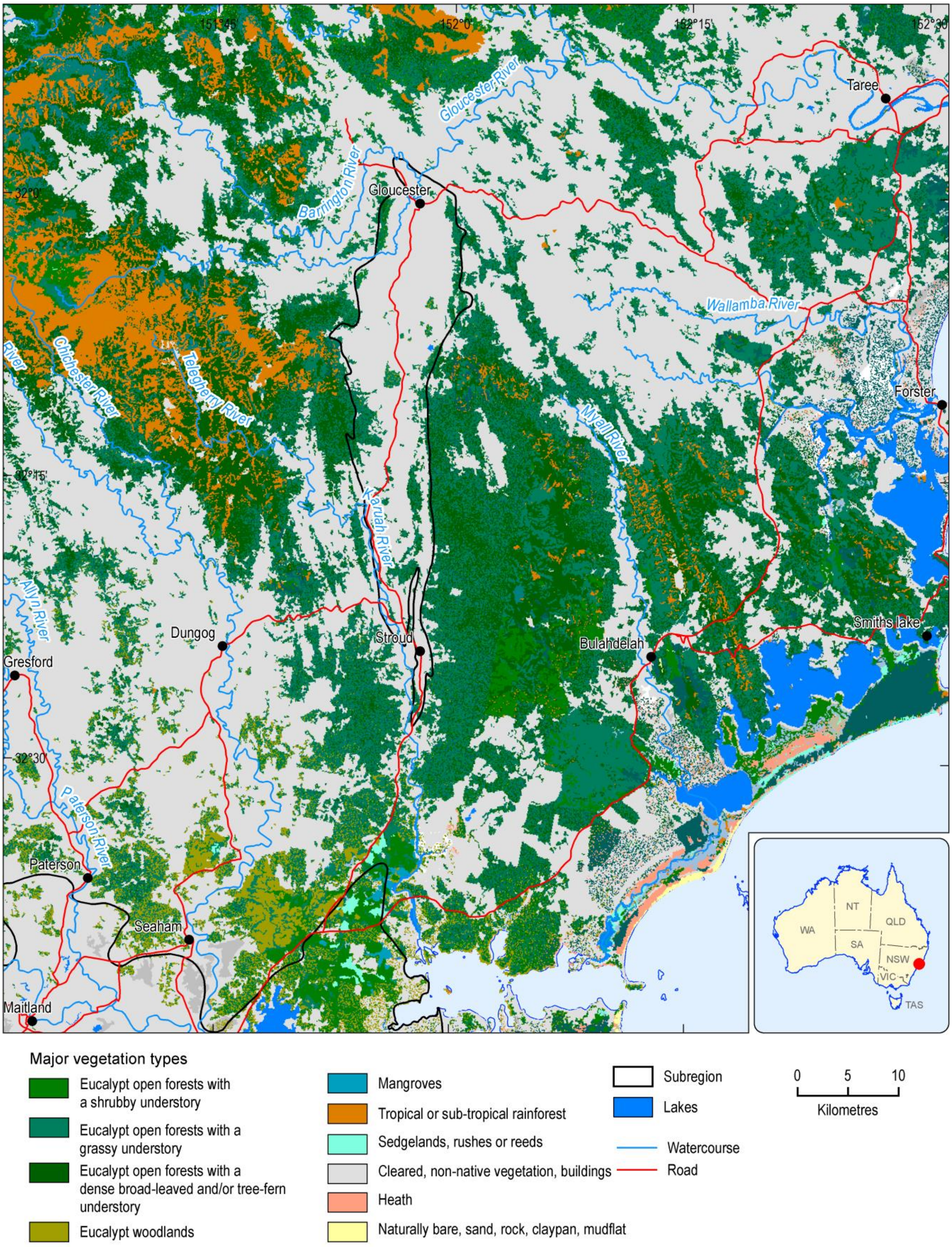


Figure 11 Current major vegetation types in the Gloucester subregion

Source data: Australian Government Department of Sustainability Environment Water Population and Communities (2012)

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 12 shows that the total vegetation cover, derived from the MODIS satellite instrument for 2000 to 2012, for most of the subregion varies from 50 to 70%, with the total vegetation cover of the forests at the edge of the subregion (and in the forests surrounding the subregion) exceeding approximately 90%. Most of the vegetation cover is persistent, in that it is ‘green’ for most of the year. Figure 12 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 70% vegetation cover over a three to four month period (Figure 12). Within the subregion this evergreen (or persistent) nature of the land cover associated with grazing systems is well known with the average monthly dynamics of the recurrent component illustrating strong ‘summer’ growth from December to May (Figure 13).

Vegetation height can be derived from satellite instruments, specifically lidar (Simard et al., 2011) and, using this data source, Figure 14 shows that the persistent vegetation encountered over much of the Gloucester subregion is short (i.e. ~5 m high in the 1 km resolution grids calculated using data captured in 2005) and that the forests on the edge and those surrounding the subregion have heights exceeding 20 m. While much of the land use in the subregion is grazing (Figure 16), 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 average cell heights.

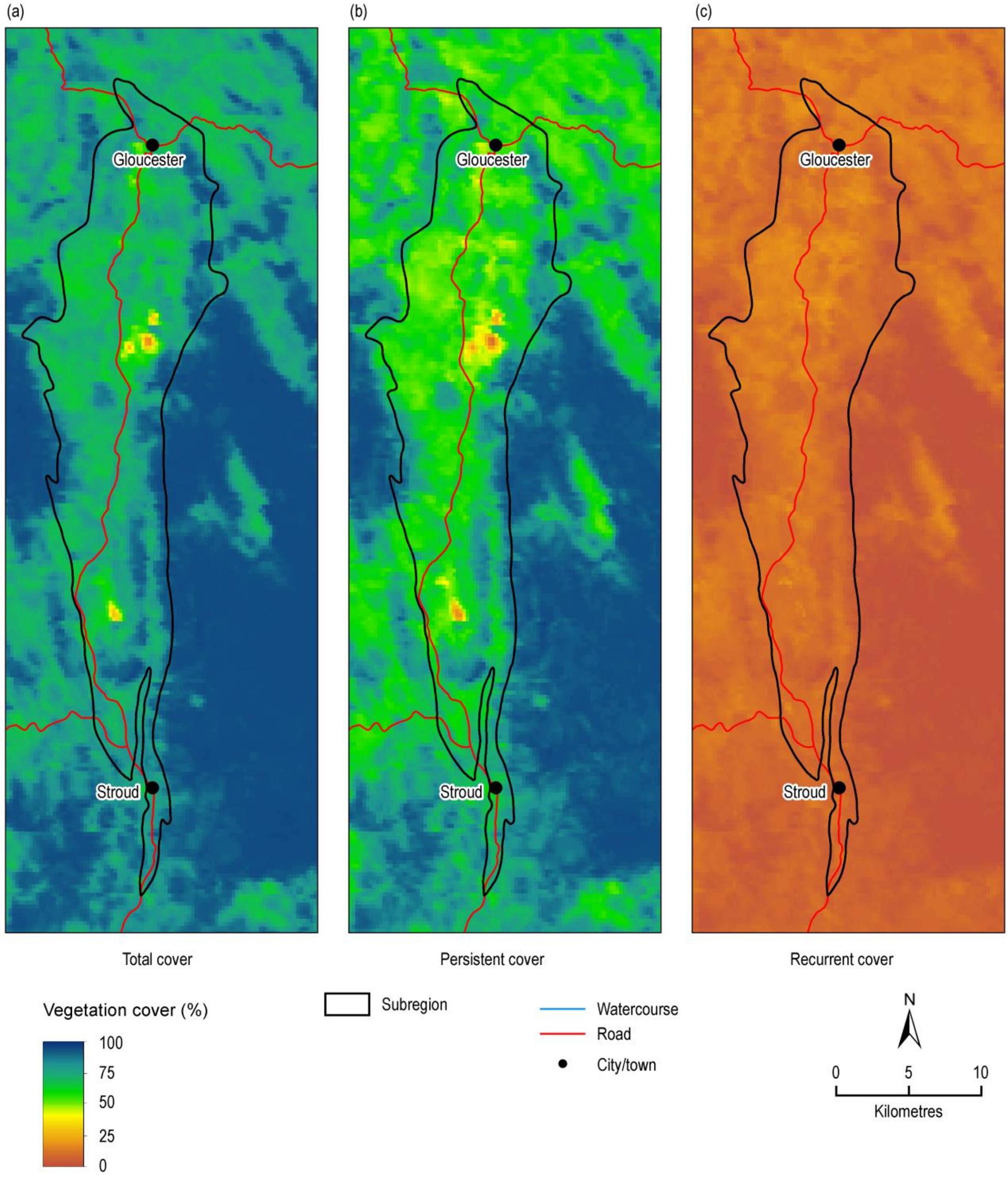


Figure 12 Vegetation cover in the Gloucester subregion

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

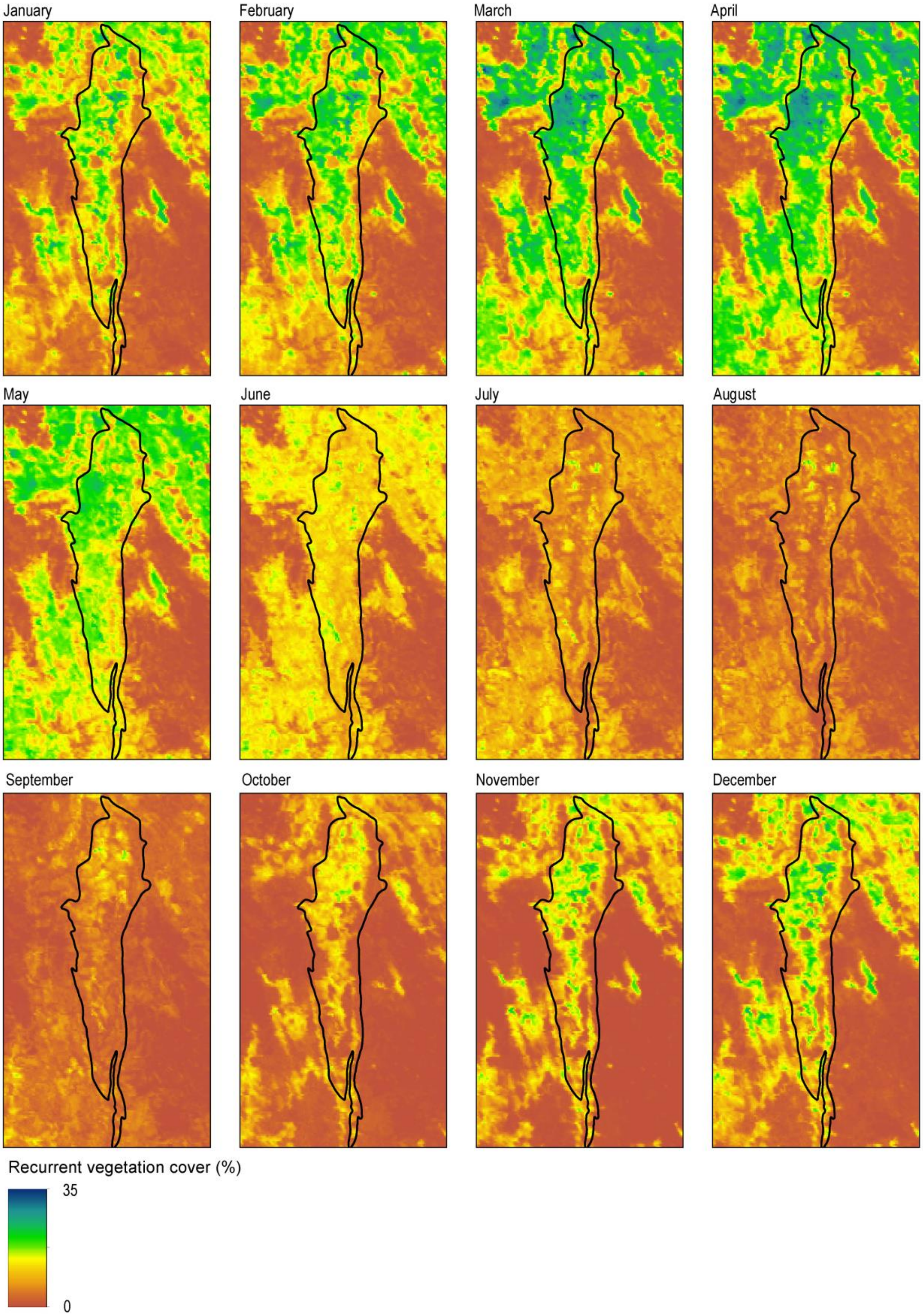


Figure 13 Monthly recurrent land cover in the Gloucester subregion

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

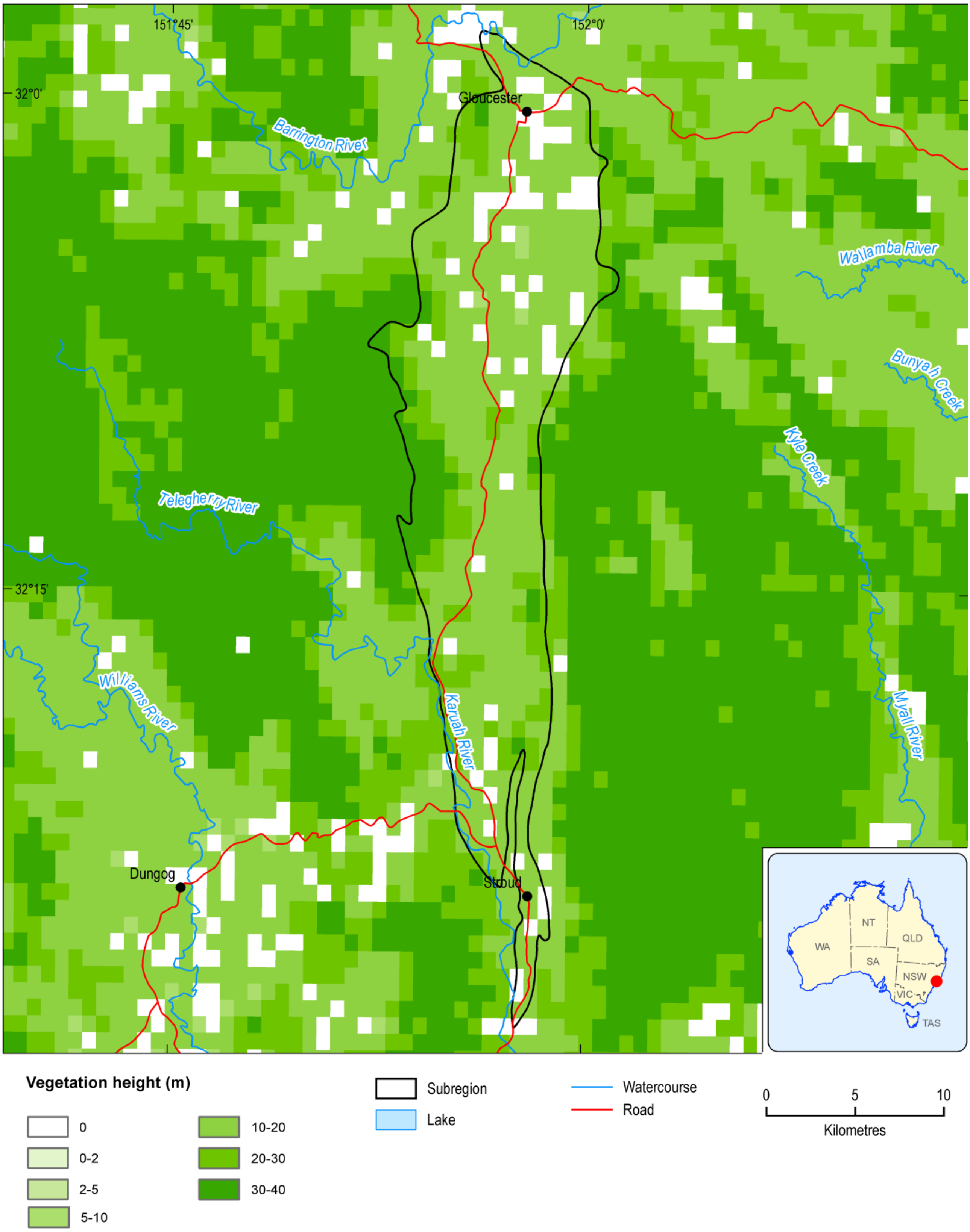


Figure 14 Vegetation height of the Gloucester subregion

Source data: Simard et al. (2011)

1.1.2.2 Human geography

The human population in the Gloucester subregion is mainly concentrated in the towns of Gloucester (approximately 2350 according to the 2011 Australian Census; Australian Bureau of Statistics (ABS), 2011) and Stroud (approximately 697 inhabitants); see Figure 15. In total it is estimated that about 5000 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.

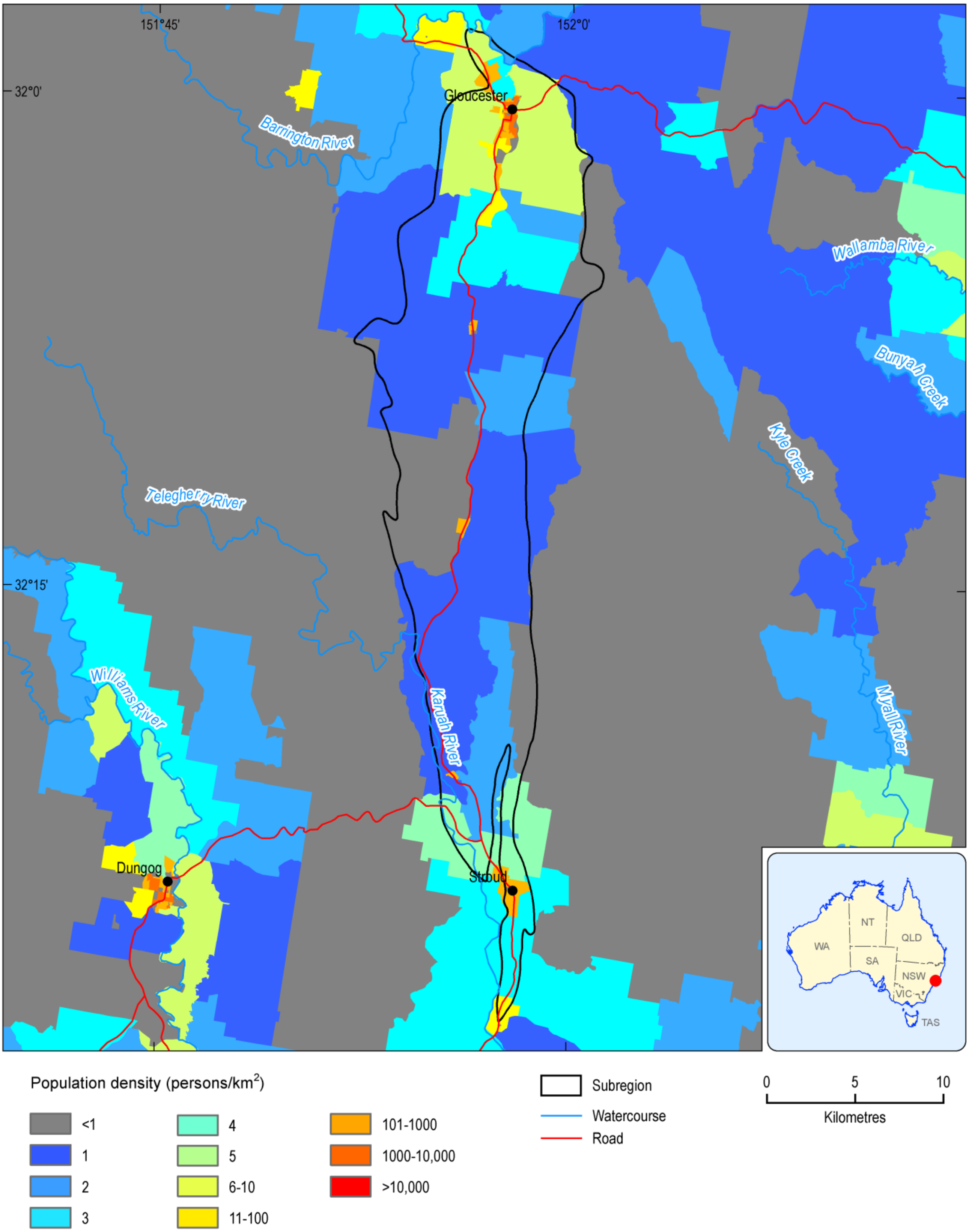


Figure 15 Human population density in the Gloucester subregion

Source data: Australian Bureau of Statistics (ABS) (2011)

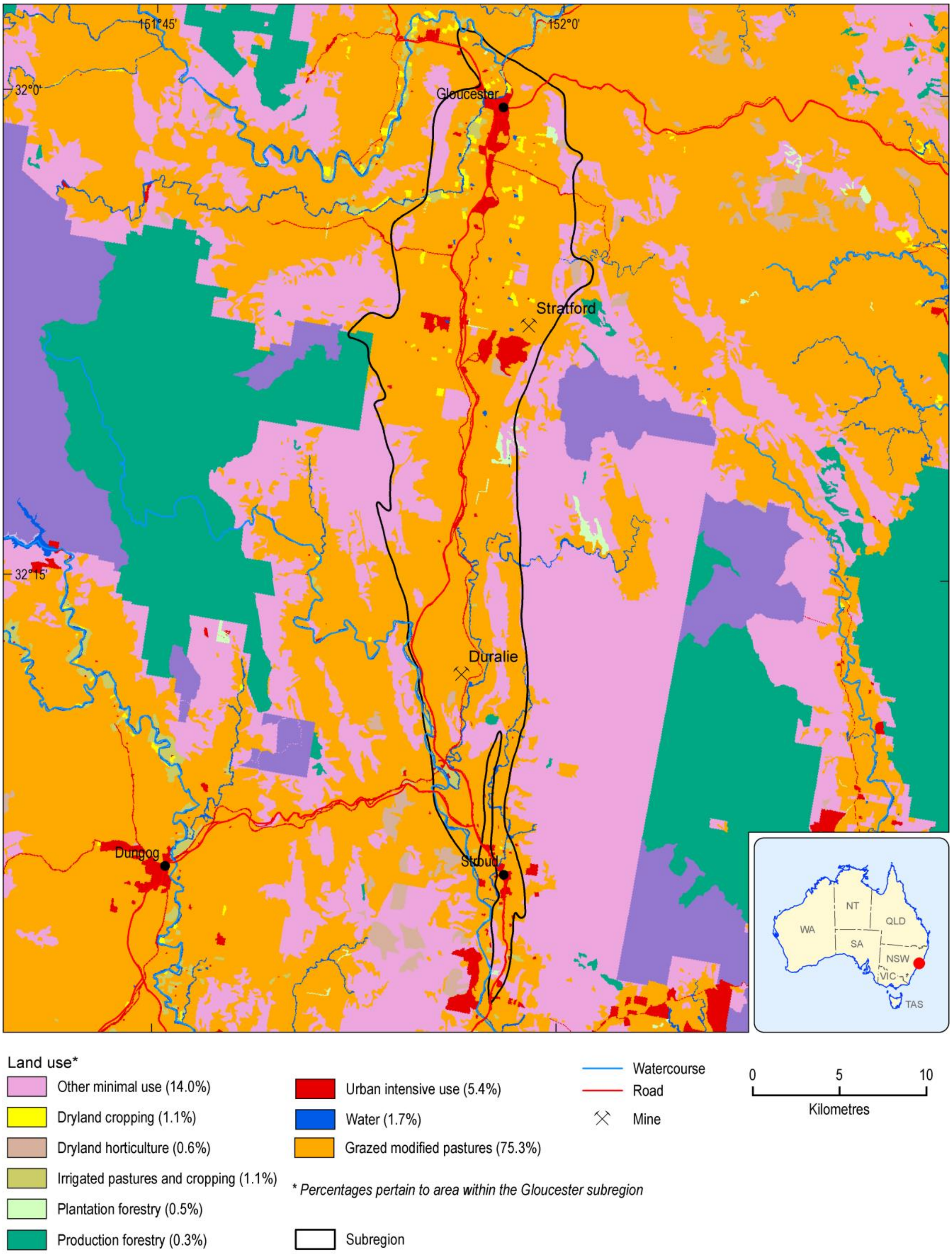


Figure 16 Land use in the Gloucester subregion

Source data: Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) (2012)

Current land use in the Gloucester subregion is primarily (i.e. ~75% of the subregion) grazed modified pastures (Figure 16). The land use of the remaining quarter of the area varies including urban, plantation forestry, dryland and irrigated cropping, and others (Figure 16).

There are no major dams on rivers in the Gloucester subregion; there are numerous small farm dams located through the area. Water use in the subregion is primarily for agricultural production (i.e. grazing and limited crop irrigation) with minor water use being for aquaculture (i.e. one fish farm). In both cases the water is derived from any mixture of local surface runoff, bore water (i.e. ground water) and extracted river water. Water for the towns of Gloucester and Barrington is extracted from the Barrington River upstream of its confluence with the Gloucester River with the water treatment plant located in the town of Gloucester. The annual average usage by the towns of Gloucester and Barrington (a combined population of ~3100) is 345 ML/year. The annual average usage by the towns of Stroud and Stroud Road (a combined population of 1300) is 140 ML/year, which is taken from Karuah River weir upstream of Stroud and the water treatment plant is located in Stroud. Information about the water offtake volumes and population served was provided by Lisa Andersons (Product Quality Systems, MidCoast Water, 18 December 2013).

1.1.2.3 Climate

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. (2010), with meteorological data, other than daily average 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 landsurface, defining how much sunlight is reflected) in the radiation calculations) and daily average 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, with the long-term (i.e. 1900 to 2012) subregion-average precipitation being approximately 1100 mm/year (Figure 17). Like much of Australia there is considerable inter-annual variability, with some years receiving high precipitation (e.g. 1963 received 1890 mm/year) and consecutive years of lower than average precipitation (e.g. 1979 to 1983) that indicate drought conditions (Figure 17). This analysis shows temporal variability of a key hydrological variable: precipitation. Climate also exhibits spatial variability and Figure 18(a) shows the 1982 to 2012 annual average precipitation varies spatially over the subregion. In the broader vicinity of the subregion this ranges from 960 to 1400 mm/year; the higher precipitation values are associated with higher elevations (Figure 5). In the subregion over the last 30 years (i.e. 1982 to 2012) the annual average precipitation is 1095 mm/year, with the maximum and minimum being 1196 and 1023 mm/year, respectively. PET in the broader vicinity of the subregion varies from 1400 to 1700 mm/year, and, as expected, the spatial pattern is complementary to precipitation. Areas receiving high amounts of precipitation 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 average PET is 1587 mm/year, and with the maximum and minimum being 1622 and 1485 mm/year, respectively.

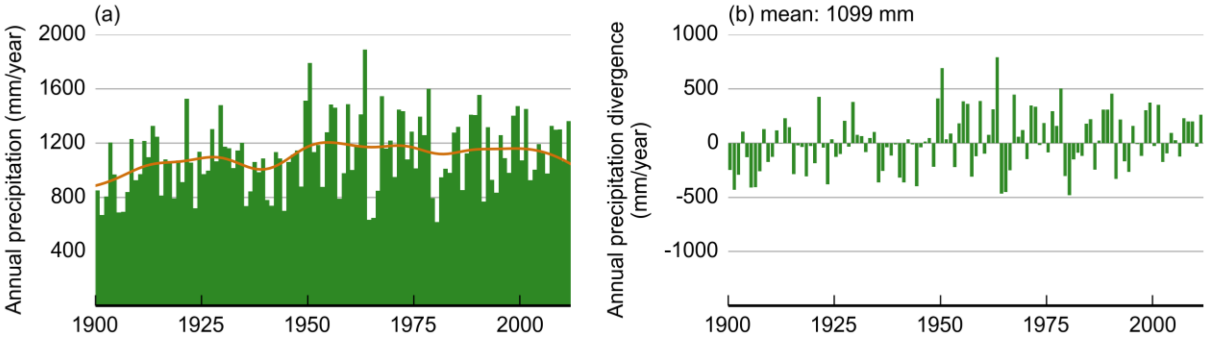


Figure 17 Temporal characteristics of annual precipitation for the Gloucester subregion

(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. Source data: Jones et al. (2009)

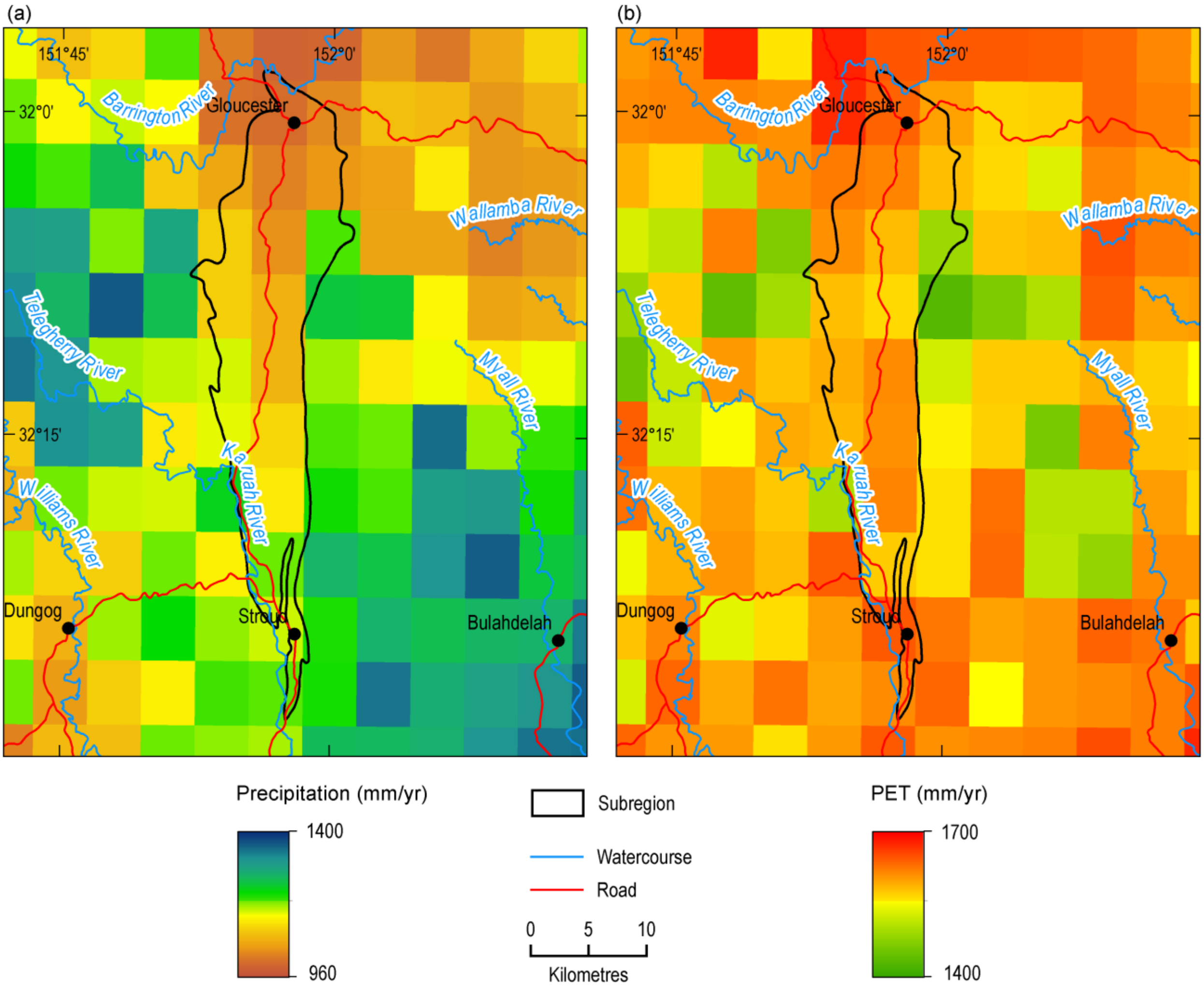


Figure 18 Spatial variation of 1982 to 2012 (a) annual average precipitation and (b) annual average PET for the Gloucester subregion

Source data: (i) precipitation from Jones et al. (2009); (ii) PET from Donohue et al. (2010)

Within a year there is a strong seasonal cycle in precipitation (Figure 19). On average, the rainy season extends from December to March, with the winter months (i.e. July to September, inclusive) being the drier part of the year. When monthly P is compared to monthly PET we see that P has a similar magnitude to PET with PET being greater than P for most (not all) months. The Gloucester 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 Gloucester 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 precipitation (relative for Australian conditions) there will be high levels of AET and associated vegetation growth (see Figure 12 and Figure 13).

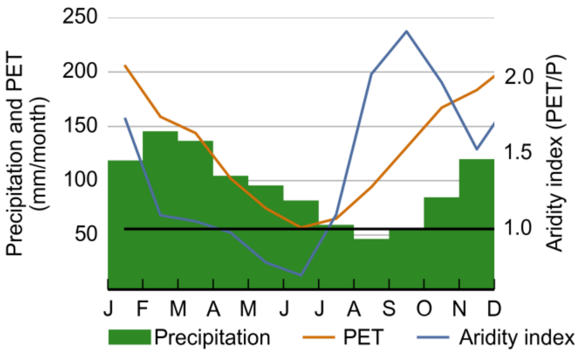


Figure 19 Average monthly precipitation (P), potential evapotranspiration (PET) and aridity index for the Gloucester subregion

Source data: (i) precipitation is from Jones et al. (2009); (ii) PET is from Donohue et al. (2010)

Figure 20 shows average monthly conditions over the last 30-years (i.e. 1982 to 2012), and below this there is temporal variability for precipitation, PET and the climatic 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 climatic factors (Figure 20).

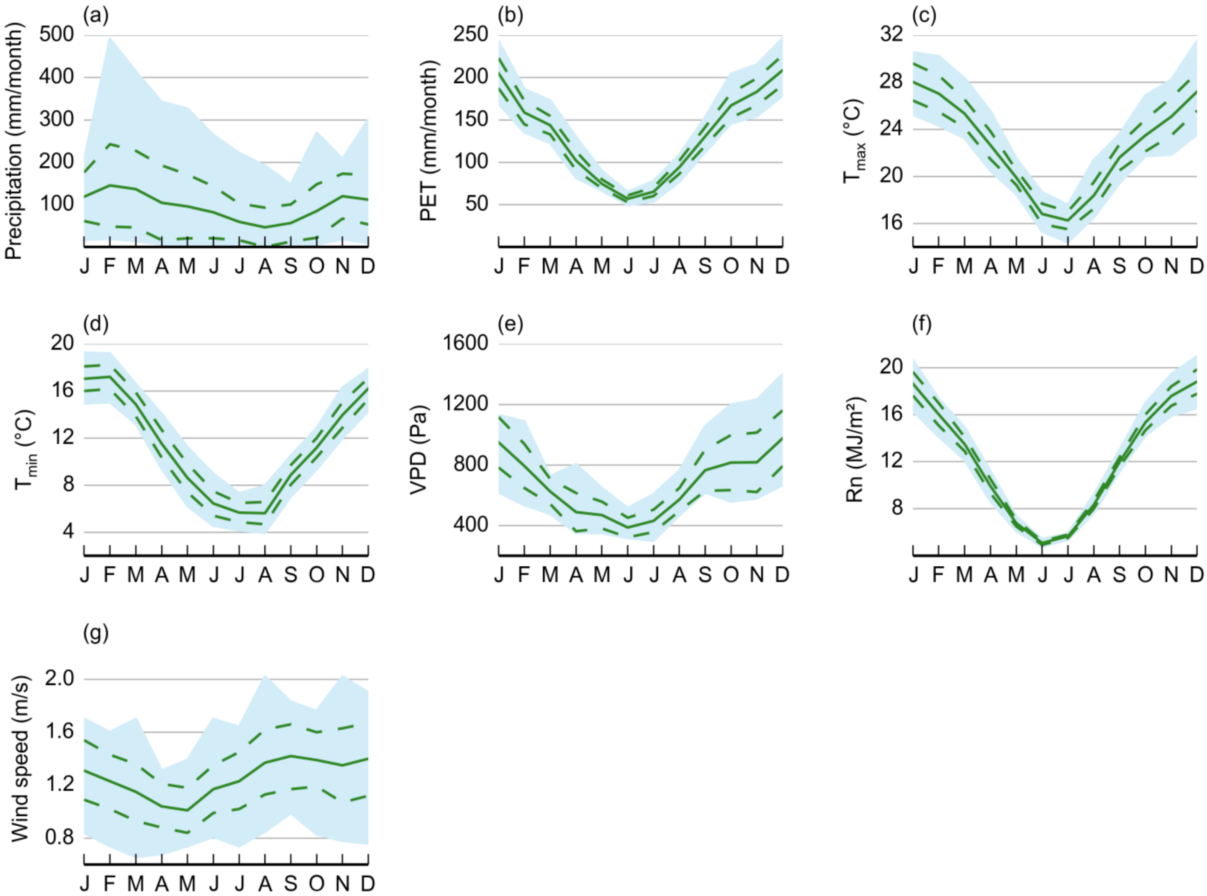


Figure 20 Monthly average values of precipitation, potential evapotranspiration and other climate factors

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

Monthly trends of precipitation, PET and all variables driving PET are shown in Figure 21. 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 declining. Declining rates of PET are due to declining amounts of net radiation and wind speed (in all months) 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., 2010; Donohue et al., 2011; McVicar et al., 2012a).

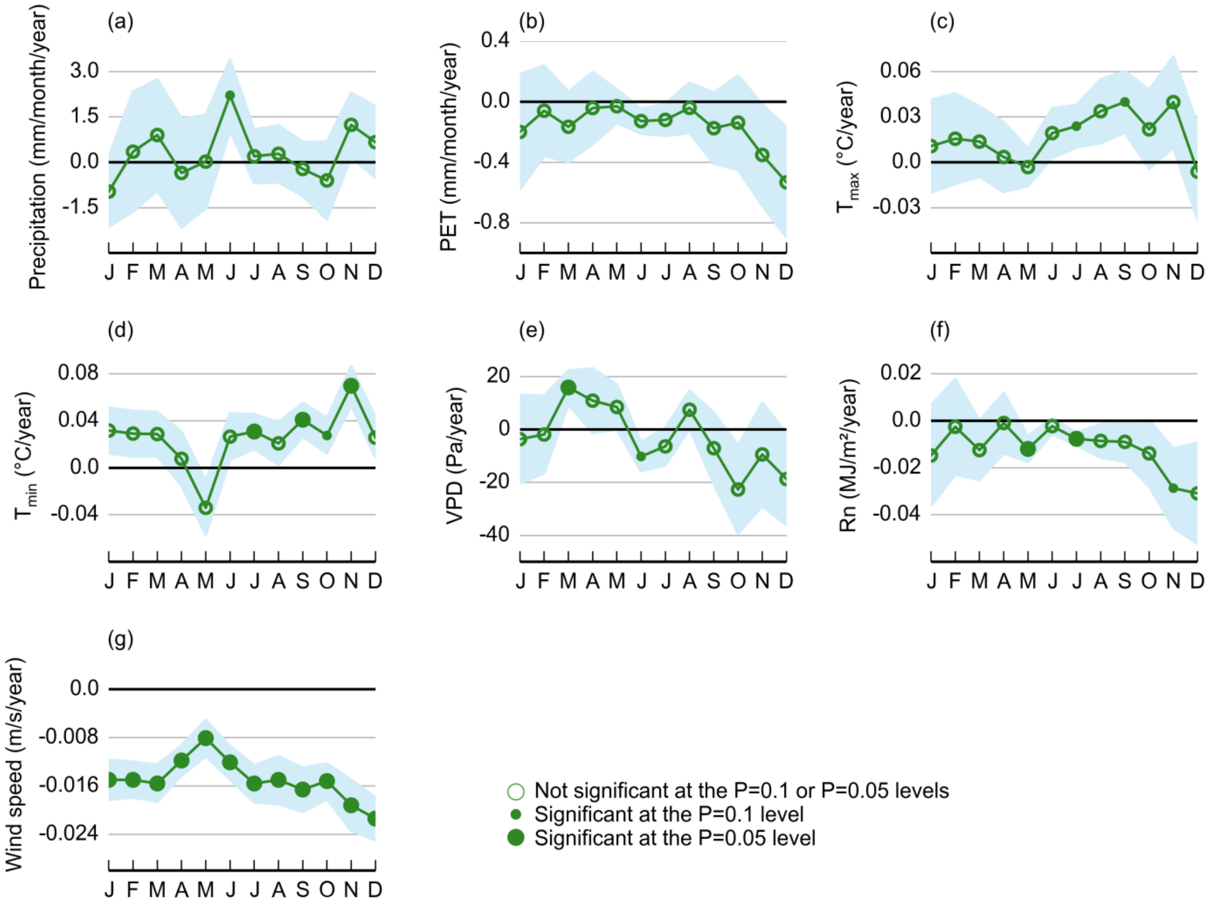


Figure 21 Annual trend by month of precipitation, potential evapotranspiration and other climate factors

Charts show: (a) precipitation, (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 Gloucester 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).

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

While future climate projections produced by global climate models are unsure (GCMs; Lim and Roderick, 2009; Sun et al., 2011), one approach is to use their output and assess what future projections of rainfall and runoff will be. Using 15 CGMs 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 historic daily climate records to provide future daily climate projections of P and PET that can used in a rainfall-runoff model. Compared to the global average 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 historic 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 Manning River and Karuah River catchments, which form the broader context that the Gloucester subregion sits in (see Figure 7). Table 3 shows that for both catchments about two-thirds of the GCMs selected suggest there will be some decline in P. Taking account for the range of projections that may occur for the one-degree rise in temperatures (associated with 2030) there is approximately a –8%, –2% and 3% change in P projected for the dry extreme, median and wet extreme, respectively. For a 2-degree rise in temperatures (associated with 2070), these values are approximately –16%, –4% and 6%, respectively (Table 3).

Table 3 Summary of projected impacts of climate change on rainfall for the broad vicinity of the Gloucester subregion

			1 °C of global warming			2 °C of global warming		
Basin	Historic P (mm/year)	# GCM (of out 15) projecting a decrease in future P	Dry extreme	Median	Wet Extreme	Dry extreme	Median	Wet Extreme
Manning River	1091	10	–8%	–2%	3%	–16%	–4%	7%
Karuah River	1225	9	–9%	–2%	3%	–17%	–5%	5%

Source data: Post et al. (2012; their Table 2)

To model future projects of 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 4 shows that the Post et al. (2012) modelling results suggest for a one-degree rise in temperatures (associated with 2030) there is approximately a –20%, –8% and 4% change in Q projected for the dry extreme, median and wet extreme, respectively. For a two-degree rise in temperatures (associated with 2070), these values are approximately –38%, –14% and 8%, respectively (Table 4). As noted previously the Gloucester 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., 2010; McVicar et al., 2012a; McVicar et al., 2012b) are not included in the resultant Q calculations. Hence the values presented in Table 4 are approximate projections only, as recent key process understanding is not encapsulated in the modelling.

Table 4 Summary of projected impacts of climate change on runoff for the broad vicinity of the Gloucester subregion

			1 °C of global warming			2 °C of global warming		
Basin	Historic Q (mm/year)	# GCM (of out 15) projecting a decrease in future runoff	Dry extreme	Median	Wet Extreme	Dry extreme	Median	Wet Extreme
Manning River	250	11	−20%	−7%	5%	−37%	−12%	10%
Karuah River	367	12	−21%	−9%	2%	−39%	−16%	5%

Source data: Post et al. (2012; their Table 3)

References

Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES) (2012) Catchment Scale Land Use Mapping for Australia Update November 2012 (CLUM Update 11/12) dataset. Australian Bureau of Agricultural and Resource Economics and Sciences (ABARES), Canberra.

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

Australian Government Department of Sustainability Environment Water Population and Communities (2012) Australia - Present Major Vegetation Subgroups - NVIS Version 4.1 (Albers 100m analysis product). Canberra.

Australian Soil Resource Information System (ASRIS) (2011) ASRIS - Australian Soil Resource Information System. Australian Soil Classification Dominant Soil Order (250m raster). Canberra. <http://www.asris.csiro.au/downloads/NSG/asc.zip>.

Australian Survey and Land Information Group (AUSLIG) (1990) Atlas of Australian Resources, Vol. 6, Vegetation. Deptartment of Administrative Services, Commonwealth Government Printer, Canberra.

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

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

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

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

Donohue RJ, Roderick ML and McVicar TR (2011) Assessing the differences in sensitivities of runoff to changes in climatic conditions across a large basin. Journal of Hydrology 406(3-4), 234-244. DOI: 10.1016/j.jhydrol.2011.07.003.

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

Gallant J, Dowling T, Read A, Wilson N, Tickle P and Inskeep C (2011) 1 second SRTM-derived Digital Elevation Models User Guide. Geoscience Australia, Canberra. Viewed 31 January 2014, <http://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=72759>.

Geoscience Australia (2006) GeoData Topo 250K Series 3 Topographic Data. Canberra, ACT, Australia http://www.ga.gov.au/oracle/agsocat/geocat_brief.php?catno=64164.

IPCC (2007) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al.,. Cambridge University Press, Cambridge, UK.

Isbell RF (2002) The Australian Soil Classification. CSIRO, Melbourne, Australia.

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

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

Lim W and Roderick M (2009) An Atlas of the Global Water Cycle: Based on the IPCC AR4 models. ANU E Press, Canberra.

McCauley A (2006) Vegetation Survey and Mapping of the Hunter, Central and Lower North Coast Region of NSW. A report prepared for the Hunter-Central Rivers Catchment Management Authority by the HCCREMS team at the Environment Division of Hunter Councils Inc., NSW. Viewed 18 September 2013, <http://www.hccrems.com.au/RESOURCES/HCCREMS-Publications.aspx>.

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

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

McVicar TR, Van Niel TG, Li LT, Roderick ML, Rayner DP, Ricciardulli L and Donohue RJ (2008) Wind speed climatology and trends for Australia, 1975-2006: Capturing the stilling phenomenon and comparison with near-surface reanalysis output. Geophysical Research Letters 35, L20403, doi:20410.21029/22008GL035627. DOI: doi:10.1029/2008GL035627.

Paget M and and King E (2008) MODIS Land data sets for the Australian region. CSIRO Marine and Atmospheric Research, Canberra.

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

Parsons Brinckerhoff (2012a) Phase 2 Groundwater Investigations – Stage 1 Gas Field Development Area: Gloucester Gas Project, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. *Parsons Brinckerhoff Australia Pty Limited*, Sydney. Viewed 12 Aug 2013, <http://agk.com.au/gloucester/assets/pdf/PB%20Gloucester%20Groundwater%20Report%20Phase%202%20Text.pdf>.

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

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

Scheibner E and Basden H (1998) Geology of New South Wales - Synthesis. Volume 2 Geological Evolution. Geological Survey of New South Wales Memoir (Geology).

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

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

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

1.1.3 Geology

Summary

The Gloucester subregion is underlain by the geological Gloucester Basin, an elongated northerly trending sedimentary basin. It contains up to 2500 m of faulted, deformed and eroded coal-bearing Permian sedimentary and volcanic rocks that rest unconformably on Carboniferous strata of the Late Paleozoic New England Fold Belt.

The Gloucester Basin is interpreted as a fault-bounded depositional trough that was active during the Permian period. It presently contains steeply dipping beds and faults on its flanks that flatten towards the central basin axis. These structural elements suggest that the regional structural architecture was either synclinal or a reactivated extensional graben.

Early normal and syn-depositional faults occur commonly in the basin and in many cases have been reactivated by later tectonism of the Hunter-Bowen Orogeny. This resulted in normal, strike-slip and reverse faults, with an apparent high density near the flanks of the basin. Throughout the basin north-east, north-west and east striking normal and strike-slip faults also occur. Coal exploration drilling on the eastern basin flank has shown local duplication of coal seams, suggesting the presence of low angle thrust faults parallel to the basin axis. These may be attributed to compressional tectonism during the Late Permian orogenic phase.

The Permian coal measures (Dewrang Group and Gloucester Coal Measures) overlie the Alum Mountain Volcanics. These stratigraphic units consist of coal-bearing shallow marine, deltaic and alluvial sedimentary rocks that were deposited in a tectonically active basin. By the Late Permian period, following the cessation of deposition, deformation and uplift during the early stages of the Hunter-Bowen Orogeny resulted in partial erosion of the Permian rock units.

The Dewrang Group includes two coal seams that are mined at the Duralie Coal Mine in the southern closure of the main synclinal structure of the Gloucester Basin. The Stratford and Bowen Road open-cut operations extract coal from upper and middle seams of the Gloucester Coal Measures. To date, the basin is an area of significant interest for coal seam gas exploration.

1.1.3.1 Geological structural framework

The Gloucester subregion is underlain by the geological, coal-bearing Gloucester Basin (Figure 22), a north-south trending basin approximately 55 km long with a width of 15 km at its widest point. It closes to the north (near the town of Gloucester) and to the south (near the Stroud Road) and has been previously referred to as a strongly deformed syncline, the Stroud-Gloucester Syncline or Trough (Roberts et al., 1991, p. 12).

The present definition of the structural framework for the Gloucester Basin relies on: (i) sparse two-dimensional seismic reflection data (Roberts et al., 1991; Grieves and Saunders, 2003), (ii) interpolation of surface geological mapping (Roberts et al., 1991), (iii) correlation of coal seams from borehole data (Grieves and Saunders, 2003), (iv) observations in open-cut mines (Grieves and

Saunders, 2003), and (v) geophysical surveys (Parsons Brinckerhoff, 2013, p. 56). The low density and poor resolution of the seismic data, the limited number of outcropping structures and the high degree of lateral stratigraphic variation in the basin result in significant uncertainty about the location and orientation of subsurface structural features.

The axial trace of the Gloucester Basin is sinuous but generally strikes north to north-east (Figure 22; Roberts et al., 1991, p. 283). Seismic interpretation suggests the basin is a fault-bounded trough, with initial fault displacements during the Permian period (Roberts et al., 1991, p. 283). Coal seams outcropping on the basin flanks dip steeply, up to 60° (but mainly 30° to 50°) towards the basin axis (Roberts et al., 1991; AECOM, 2009, p. 17–23; Merrick and Alkhatib, 2012, p. 10; Brown et al., 1996, p. 55). Brown et al. (1996) provided evidence suggesting a flattening of coal seam dip towards the central axis of the basin. The basin’s structural elements (such as dip distribution and axial geometry) have been used to suggest, in some parts of the basin, a synclinal geometry. However, most of the steeply dipping beds are bounded by faults on the edge of the basin. As such, an alternative interpretation is that the steeply dipping beds are discrete slivers of sedimentary rock units deformed and rotated within fault zones. This type of structural architecture is well exposed and documented in the dominantly extensional Permian Collie Basin in Western Australia, where sequences that ordinarily dip less than 10° across the basin are tilted in fault zones on the basin flanks with dips greater than 70° (Le Blanc Smith, 1993). Roberts et al. (1991) also suggested that the north-western edge of the Gloucester Basin and the flexure of the eastern basin are controlled by both normal and shear faults.

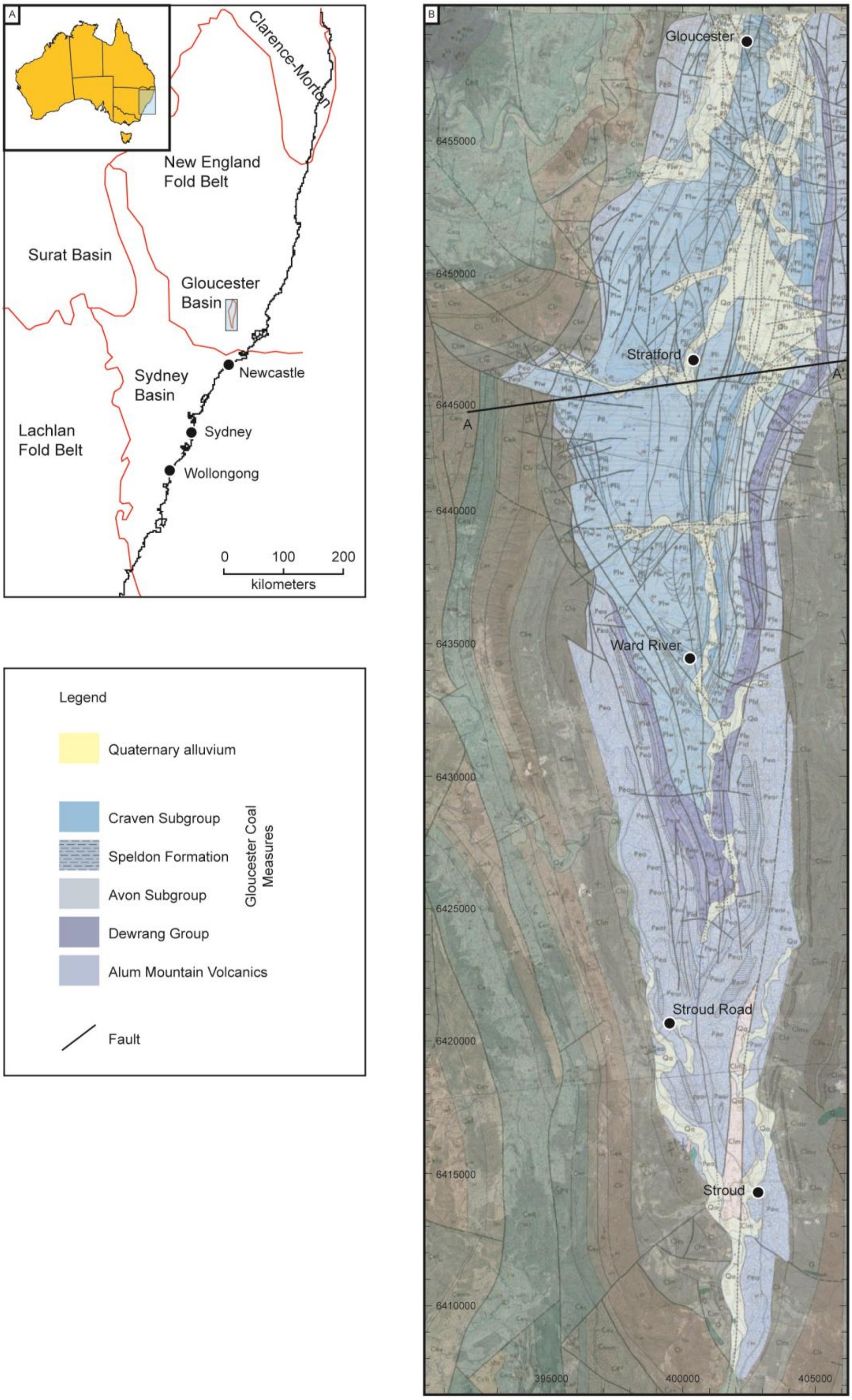


Figure 22 The Gloucester Basin

(A) Location of the Gloucester Basin. (B) Geological map of the Gloucester Basin with the Permian coal-bearing units highlighted (note the northern end of the basin is not shown). Detail of the cross-section ‘A–A’ is shown in Figure 23. For further description of the formation’s name, age and composition see the 1:100,000 Dungog geological map in Roberts et al. (1991).
Source: Roberts et al. (1991). Note that this figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of NSW Trade & Investment.

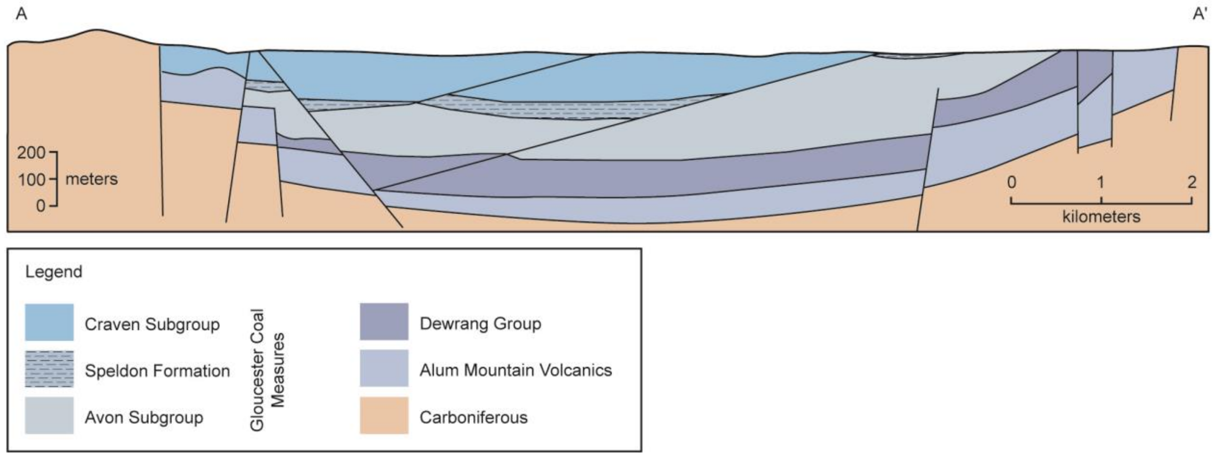


Figure 23 Simplified regional cross-section for the Gloucester Basin

The Quaternary alluvium is not shown. Location of the cross-section 'A–A' within the Gloucester Basin is shown in Figure 22. Source: Roberts et al. (1991). Note that this figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of NSW Trade & Investment.

1.1.3.1.1 Structure

The Gloucester Basin is interpreted as a fault controlled depositional trough of tectonic origin (Roberts et al., 1991, p.167). Faults in the Gloucester Basin have been geologically mapped on the surface, intersected by drilling, interpreted from seismic data or identified as lineaments on aerial photos and remotely sensed imagery (SRK Consulting, 2010; Roberts et al., 1991). Nevertheless, all of these datasets have some limitations and, consequently, the location and orientation of many faults are ambiguous in some areas (SRK Consulting, 2010; Roberts et al., 1991, p. 284).

Normal, strike-slip and reverse faults are characteristic of the basin. They occur throughout all of the Permian strata in the basin but have greater density near the flanks where dips are commonly sub-vertical (Roberts et al., 1991). Fault orientations are generally northerly striking with dips toward the central axis. North-east, north-west and east striking normal and strike-slip faults are reported near the margins or cutting through the Permian sequence with displacements of up to 60 m (Roberts et al., 1991, p. 283; Merrick and Alkhatib, 2012, p. 10; SRK Consulting, 2010). Coal exploration drilling on the eastern flank suggests several low angle (0° to 60°, Merrick and Alkhatib, 2012) thrust faults parallel to the basin axis, with apparent repetition and thickening or stacking of coal seams and accentuation of dip (Brown et al., 1996, p. 10). Folding of basin strata is also widespread with a general northerly trend (Roberts et al., 1991, p. 283; SRK Consulting, 2010). This can locally accentuate the dip of the strata and result in dip reversal (SRK Consulting, 2010).

1.1.3.2 Stratigraphy and rock type

The Gloucester Basin includes the known extent of the Permian Coal Measures and Alum Mountain Volcanics (Figure 24). The Permian sequences lie unconformably on low permeability Carboniferous strata and no flow boundaries are assumed along the edges of the Permian basin (Merrick and Alkhatib, 2012, p. 37).

The complex interplay of tectonic extensional faulting and high rates of sediment supply produced significant lateral stratigraphic variability in the Permian sequences of the Gloucester Basin (AGL, 2010).

1.1.3.2.1 Alum Mountain Volcanics

The basal stratigraphic unit of the Gloucester Basin is the Alum Mountain Volcanics, an approximately 200 m thick Early Permian sequence of bimodal volcanic and interbedded sedimentary rocks. Some volcanic flows are separated by thin layers of siltstone, conglomerate and coal (AECOM, 2009, p. 17–23). This volcanic unit lies unconformably on Late Carboniferous conglomeratic rocks, such as the Muirs Creek Conglomerate.

1.1.3.2.2 Dewrang Group

The early Late Permian Dewrang Group, which formed in shallow to marginal marine environments, disconformably overlies the Alum Mountain Volcanics. It consists of coarse- and medium-grained sandstone interbedded with lesser siltstone, shale, conglomerate and coal seams. There are three stratigraphic formations in the Dewrang Group which, from oldest to youngest, are the Durallie Road Formation, Weismantels Formation, and Mammy Johnsons Formation. Coal seams occur in the two uppermost formations.

1.1.3.2.3 Gloucester Coal Measures

Avon Subgroup

The Late Permian Avon Subgroup is the stratigraphic base of the Gloucester Coal Measures. It is divided into two formations (Waukivory Creek and Dogtrap Creek formations) that between them contain seven coal seams.

- Waukivory Creek Formation

In contrast to the older Dewrang Group, the deposition of the Waukivory Creek Formation occurred in a terrestrial coastal plain to upper delta plain environment (AECOM, 2009, p. 17–4). This formation contains five discrete coal members which, from oldest to youngest, are the Parkers Road, Valley View, Glen Road, Rombo, and Triple coal members. These coal seams are best developed in the eastern basin (AGL, 2010). The Parkers Road Coal Member is widespread in the basin with thick seams of approximately 5 m (AECOM, 2009, p. 17–4).

- Dog Trap Creek Formation

The Dog Trap Creek Formation consists of three coal members: the Bucketts Way, Glenview and Marker Two coal members. The formation is characterised by coarsening upward sedimentary sequences, bioturbated mudstone layers and crevasse splay structures. It was deposited in a lower delta plain environment which formed during marine transgression. Minor fluvial-derived deposits are interpreted as evidence for restricted uplift or tectonic activity, with a number of growth faults reported (Roberts et al., 1991, p. 179; AGL, 2010).

Speldon Formation

The deposition of the Speldon Formation is interpreted as the culmination of the marine transgression which formed the earlier Dogtrap Creek Formation. It contains well bedded medium- to fine-grained sandstone with minor siltstone layers. The depositional environment precluded development of significant coal. Growth faults are reported in this unit (AECOM, 2009, p. 17–4).

Craven Subgroup

The Late Permian Craven Subgroup forms the upper part of the Gloucester Coal Measures and is divided into five formations which include nine coal seams. The Craven Subgroup has significantly less marine-derived sediment than the Avon Subgroup or the Speldon Formation.

- Wenham Formation

The Wenham Formation contains about 25 m of fine-grained sandstone and coal (Bowens Road Coal Member).

- Wards River Conglomerate

The Wards River Conglomerate is widespread in the Gloucester Basin and contains conglomerate with minor sandstone, shale and rare carbonaceous shale which was deposited in an alluvial fan environment. Although it forms the entire Gloucester Coal Measures in the western part of the basin, it is very much reduced in thickness along the eastern margin where it occurs stratigraphically above the Wenham Formation (AECOM, 2009, p. 17–5).

- Jilleon Formation

The Jilleon Formation consists of a fine-grained sandstone, shale and mudstone sequence with four coal members. It was deposited in an alluvial plain environment (AGL, 2010). The Jilleon Formation contains the Roseville and the less consistent Tereel (or Fairbairns Lane) coal members in the basal sequence and the Cloverdale Coal Member in the upper sequence. The Cloverdale Coal Member contains a distinct tuff band used for correlation between wells. The formation onlaps and is eventually replaced by the Wards River Conglomerate in the west of the basin (AGL, 2010).

- Leloma Formation

The Leloma Formation (or Woods Road Formation) contains siltstone, sandstone and numerous thin coal seams, such as the Deards, Bindaboo, Jo Doth and Linden coal members as well as several thin unnamed coals (AGL, 2010). The sediments which formed these rocks were deposited in an upper alluvial plain environment. Correlation of coal seams is particularly difficult in this formation as they vary significantly in thickness and commonly split over relatively short distances (AGL, 2010).

- Crowthers Road Conglomerate

The Crowthers Road Conglomerate marks the stratigraphic top of the Permian sequence in the Gloucester Basin. It consists of conglomerate and medium- to coarse-grained sandstone deposited in a series of alluvial fans which were sourced from the older Carboniferous rock formations to the west and north of the basin. It is generally confined to the western and northern basin (AGL, 2010).

1.1.3.2.4 Quaternary sediments

The surficial sediments in the Gloucester Basin consist of unconsolidated alluvial and swamp sediments (sand, gravel, silt and clay) which variably infill the valley floor of the main rivers and creeks. The alluvial sediments do not have a consistent thickness and generally conform to the basin paleovalleys (SRK Consulting, 2010). The sediments are geologically young (Quaternary) and are not formally named.

1.1.3.3 Basin history

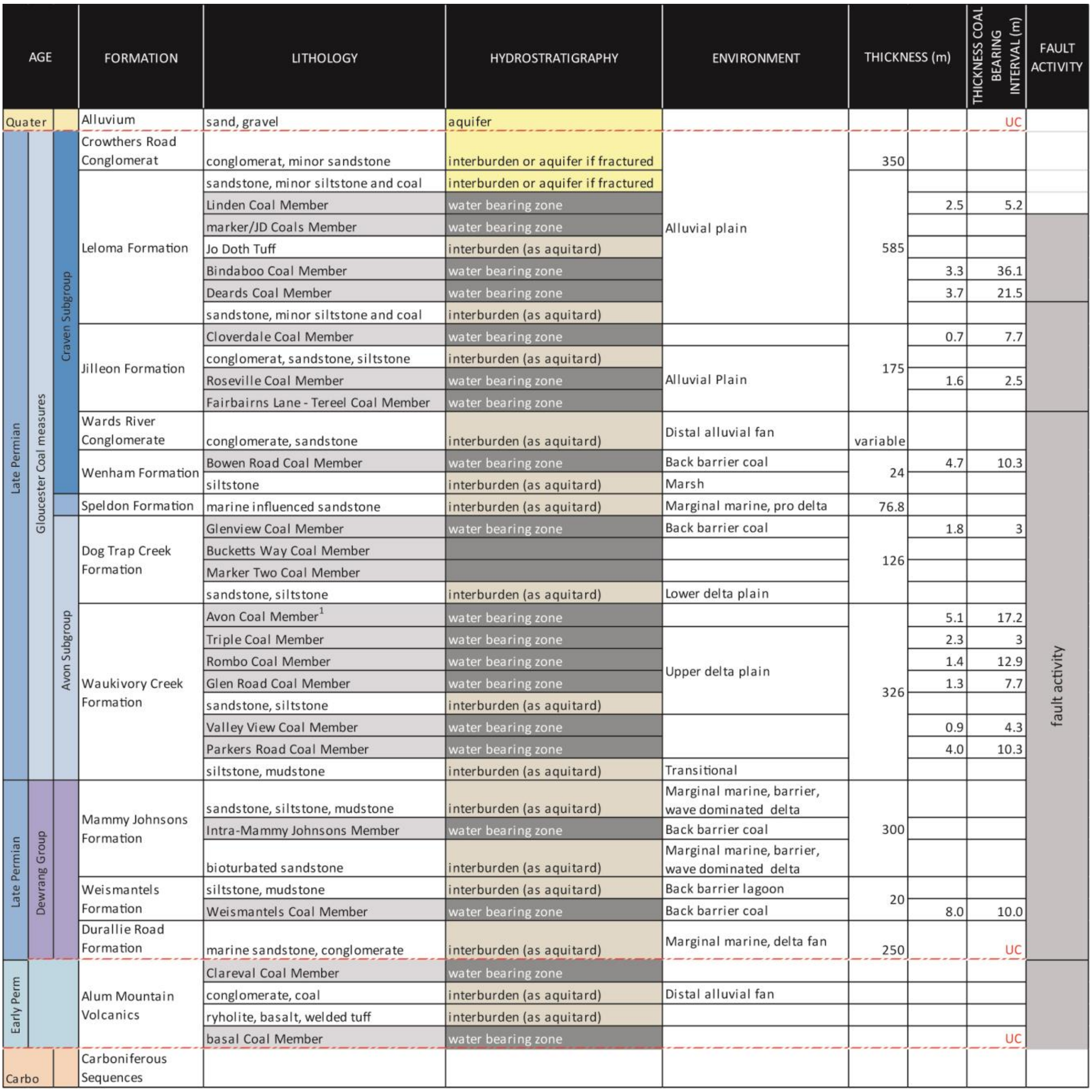
The present geological architecture of the Gloucester Basin suggests that it has experienced a complex structural history. Early normal and syn-depositional faults are widespread and extensive, and in many cases have been reactivated by the later Hunter-Bowen Orogeny (AGL, 2010). The main tectonic episodes proposed for the Permian development of the basin are summarised below (Grieves and Saunders, 2003; SRK Consulting, 2005, 2010):

- Early to Late Permian extension resulted in normal and strike-slip reactivation of older pre-Permian faults, particularly around the margins of the basin and the development of syn-depositional faults (north and east). This coincides with the phase of extension and sedimentation defined by Cawood et al. (2011) in the Sydney-Gunnedah-Bowen Basin and coeval with roll back of the Pacific Plate. Fault activity has been interpreted during the deposition of the Early Permian Alum Mountain Volcanics (Roberts et al., 1991, p. 167). Faulting also controlled (to varying degrees) the deposition of most Permian coal-bearing strata in the basin (Roberts et al., 1991, p. 284; Harrington et al., 1989, p. 64).
- Late Permian compression (north-east shortening) and tilting of the basin during the early stages of the Hunter-Bowen Orogeny, resulted in reactivation and inversion of many faults, and new thrust faulting and erosion.

1.1.3.3.1 Paleogeography

Harrington et al. (1989, p. 64) described the paleogeography of the Gloucester Basin. Deposition in the basin was initiated and controlled by northerly faults active during sedimentary infilling. This began in the Early Permian period, when fluvial gravel and sand deposits formed at the base of the unit and were interbedded with the Alum Mountain Volcanics.

By the late Early Permian period, sedimentation occurred in a shallow near-shore marine environment with a barrier and freshwater lagoon complex and wave-dominated fan delta system (Dewrang Group). Relative uplift of the surrounding highlands led to a change in sedimentary dynamics at the start of deposition of the Gloucester Coal Measures, marked by fluvial valley infill deposits (Avon Subgroup; Hancock, 1974). A marine transgression followed with the deposition of beach and marine sands (Speldon Formation). The remainder of the Gloucester Coal Measures has significantly less marine influence, and includes evidence for a depositional hiatus (Wenham Formation) overlain by advancing alluvial fan deposits of the Wards River Conglomerate, after the reactivation of marginal faults (Harrington et al., 1989, p. 64). The Jilleon, Leloma and Crowthers Road formations were deposited in terrestrial meandering, alluvial plain and braided outwash environments (Harrington et al., 1989, p. 64; Roberts et al., 1991, p. 184).



AGE			FORMATION	LITHOLOGY	HYDROSTRATIGRAPHY	ENVIRONMENT	THICKNESS (m)		THICKNESS COAL BEARING INTERVAL (m)	FAULT ACTIVITY
Quater			Alluvium	sand, gravel	aquifer				UC	
Late Permian	Gloucester Coal measures	Craven Subgroup	Crowthers Road Conglomerat	conglomerat, minor sandstone	interburden or aquifer if fractured	Alluvial plain	350			
			Leloma Formation	sandstone, minor siltstone and coal	interburden or aquifer if fractured		585			
				Linden Coal Member	water bearing zone			2.5	5.2	
				marker/JD Coals Member	water bearing zone					
				Jo Doth Tuff	interburden (as aquitard)					
				Bindaboo Coal Member	water bearing zone			3.3	36.1	
				Deards Coal Member	water bearing zone			3.7	21.5	
				sandstone, minor siltstone and coal	interburden (as aquitard)					
			Jilleon Formation	Cloverdale Coal Member	water bearing zone		175	0.7	7.7	
				conglomerat, sandstone, siltstone	interburden (as aquitard)	Alluvial Plain				
				Roseville Coal Member	water bearing zone			1.6	2.5	
				Fairbairns Lane - Tereel Coal Member	water bearing zone					
			Wards River Conglomerate	conglomerate, sandstone	interburden (as aquitard)	Distal alluvial fan	variable			fault activity
			Wenham Formation	Bowen Road Coal Member	water bearing zone	Back barrier coal	24	4.7	10.3	
				siltstone	interburden (as aquitard)	Marsh				
			Speldon Formation	marine influenced sandstone	interburden (as aquitard)	Marginal marine, pro delta	76.8			
		Avon Subgroup	Dog Trap Creek Formation	Glenview Coal Member	water bearing zone	Back barrier coal	126	1.8	3	
				Bucketts Way Coal Member						
				Marker Two Coal Member						
				sandstone, siltstone	interburden (as aquitard)	Lower delta plain				
			Waukivory Creek Formation	Avon Coal Member[1]	water bearing zone		326	5.1	17.2	
				Triple Coal Member	water bearing zone	Upper delta plain		2.3	3	
				Rombo Coal Member	water bearing zone			1.4	12.9	
				Glen Road Coal Member	water bearing zone			1.3	7.7	
				sandstone, siltstone	interburden (as aquitard)					
				Valley View Coal Member	water bearing zone			0.9	4.3	
				Parkers Road Coal Member	water bearing zone			4.0	10.3	
				siltstone, mudstone	interburden (as aquitard)	Transitional				
Late Permian	Dewrang Group		Mammy Johnsons Formation	sandstone, siltstone, mudstone	interburden (as aquitard)	Marginal marine, barrier, wave dominated delta	300			
				Intra-Mammy Johnsons Member	water bearing zone	Back barrier coal				
				bioturbated sandstone	interburden (as aquitard)	Marginal marine, barrier, wave dominated delta				
			Weismantels Formation	siltstone, mudstone	interburden (as aquitard)	Back barrier lagoon	20			
				Weismantels Coal Member	water bearing zone	Back barrier coal		8.0	10.0	
			Durallie Road Formation	marine sandstone, conglomerate	interburden (as aquitard)	Marginal marine, delta fan	250		UC	
Early Perm			Alum Mountain Volcanics	Clareval Coal Member	water bearing zone					
				conglomerate, coal	interburden (as aquitard)	Distal alluvial fan				
				ryholite, basalt, welded tuff	interburden (as aquitard)					
				basal Coal Member	water bearing zone				UC	
Carbo			Carboniferous Sequences							

Figure 24 Permian lithostratigraphy in the Gloucester Basin

[1] The duplicate use of Avon is not formally recognised in the Australian Stratigraphic Units Database

Source data: (i) Brown et al. (1996), (ii) AECOM (2009), (iii) SRK Consulting (2010), (iv) Pells Consulting (2012) and (v) the Australian Stratigraphic Names Database.

1.1.3.4 Coal and hydrocarbons

1.1.3.4.1 Coal

Early attempts were made to mine coal on a small scale at Gloucester and Dewrang, but the steep dips of the seams at these localities, the numerous minor folds and faults, and the high watertable made mining initially hazardous and uneconomical (Loughnan, 1954). Renewed exploration by various companies in the 1980s delineated economic coking and thermal coal deposits in the region in the Stratford area (Harrington et al., 1989) between Weismantels and Stroud Road.

Coal seams in the Gloucester Basin are characterised by considerable lateral splitting, with only six of the 20 or more seams correlated across the syncline from the western and eastern halves of the basin (Pells Consulting, 2012, p. 12). Coal seams are present within the three main Permian stratigraphic groups of the Gloucester Basin:

- The Alum Mountain Volcanics include two coals seams, despite earlier work suggesting that it is barren of coal (AECOM, 2009, p. 14–24).
- The Dewrang Group includes two coals seams that are the coal resource of the Duralie Coal Mine in the southern closure of the main basin synclinal structure (Merrick, 2009, p. B–8).
- The Gloucester Coal Measures are considered to be equivalent to the Late Permian Wittingham Coal Measures of the Hunter Coalfield, northern Sydney Basin (Roberts et al., 1991, p. 324). The coals in the Gloucester Coal Measures are generally vitrain rich and intensely cleated which would suggest good permeability and significant potential for coal seam gas resources (Brown et al., 1996, p. 55). The Stratford and Bowen Road open-cut operations extract coal from upper and middle seams of the Gloucester Coal Measures.

1.1.3.4.2 Hydrocarbons

No conventional hydrocarbons are produced from the Gloucester Basin.

To date the basin is an area of significant interest for coal seam gas exploration (Weber and Bocking, 1995) and an area on the eastern limb of the basin's main syncline near Stratford is currently being investigated in detail for coal seam gas production.

1.1.3.5 Potential basin connectivities

The Gloucester Basin contains Permian sedimentary and volcanic rock units that rest unconformably on Carboniferous strata of the Late Paleozoic New England Fold Belt. No other basin lies on the top of the Gloucester Basin and therefore no connectivity is expected.

References

AECOM (2009) Gloucester gas project environmental assessment. Report for AGL Gloucester LE Pty Ltd, Gloucester, NSW.

AGL (2010) Wards River 5, well completion report. AGL Gloucester LE Pty Ltd, Gloucester, New South Wales.

Brown K, Casey DA, Enever JR, Facer RA and Wright K (1996) New South Wales coal seam methane potential. Petroleum bulletin 2. New South Wales Department of Mineral Resources, Sydney.

Cawood PA, Leitch EC, Merle RE and Nemchin AA (2011) Orogenesis without collision: stabilizing the Terra Australis accretionary orogen, eastern Australia. GSA Bulletin 123(11–12), 2240–2255. DOI: 10.1130/B30415.1.

Geoscience Australia (2013) Australian Stratigraphic Units Database. Viewed 6 March 2014, <http://www.ga.gov.au/products-services/data-applications/reference-databases/stratigraphic-units.html>.

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

Hancock SL (1974) The geology of the Craven-Kyle Range region. Honours Thesis, University of Newcastle, New South Wales.

Harrington HJ, Brakel AT, Hunt JW, Wells AT, Middleton MF, O'Brien PE, Hamilton DS, Beckett J, Weber CR, Radke SJ, Totterdell M, Swaine DJ and Schmidt PW (1989). Permian coals of eastern Australia. Bulletin 231. Bureau of Mineral Resources, Canberra.

Le Blanc Smith G (1993) Geology and Permian Coal resources of the Collie Basin, Western Australia. Report 38. Geological Survey of Western Australia, Perth.

Loughnan FC (1954) The Permian coal measures of the Stroud-Gloucester Trough. Journal and Proceedings of the Royal Society of New South Wales 88, 106–113.

Merrick NP and Alkhatib M (2012) Groundwater assessment: a hydrogeological assessment in support of the Stratford coal project environmental impact statement. Stratford Coal Pty Ltd, New South Wales.

Merrick NP (2009) Duralie extension project groundwater assessment: a hydrogeological assessment of the Duralie extension project environmental assessment. Duralie Coal Pty Ltd, New South Wales .

Parsons Brinckerhoff (2013) Hydrogeological conceptual model of the Gloucester Basin. AGL Upstream Investments Pty Ltd, St Leonards, New South Wales.

Pells Consulting (2012) Gloucester CSG Project – impacts on groundwater: review of aspects of the phase 2 report by Parsons Brinkerhoff. Pells Consulting, MacMasters Beach, New South Wales.

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

SRK Consulting (2005) Gloucester Basin geological review. A J Lucas Coal Technologies Pty Ltd and Molopo Australia Ltd, Australia.

SRK Consulting (2010) Gloucester Basin stage 1 gas field development project preliminary groundwater assessment and initial conceptual hydrogeological model. AGL Energy Limited, Australia.

Weber CR and Bocking M (1995) A review of coal bed methane exploration in New South Wales. In: Morton, DJ, Alder JD, Grierson IJ, Thomas CE (eds) Proceedings of 1995 New South Wales Petroleum Symposium. Petroleum Exploration Society of Australia (NSW Branch), Sydney.

1.1.4 Hydrogeology and groundwater quality

Summary

This summary is based on information sourced from environmental impact assessments (EIAs) undertaken by coal mining and coal seam gas (CSG) companies operating in the Gloucester subregion, and on other related documents, such as critiques or peer reviews.

The Gloucester subregion is defined by the underlying Gloucester Basin, a closed hydrogeological system, containing two main aquifers: an alluvial aquifer and an aquifer hosted by a bedrock weathered profile occurring within 150 metres below ground level (mbgl). Hydraulic conductivity reduces exponentially with depth – anything from one to tens of metres per day in an alluvial aquifer and from 10^{-2} m/day to 10^{-6} m/day in weathered rock aquifers. There are a series of fault systems, known or inferred, some of which are associated with higher permeability zones in the shallow weathered bedrock profile. However, these fault systems' connectivity to deeper coal seams and their effects on overall hydrogeological conditions are not well known.

A topographical divide across the middle of the Gloucester Basin influences groundwater and surface water flow. From this divide, regional groundwater flow is predominantly towards the south and the north. Groundwater quality data indicate in-situ mineralisation, with groundwater salinity levels increasing with depth from nearly fresh to brackish. There are also elevated concentrations of strontium, iron, bromine and methane in both aquifers.

Groundwater recharge in alluvial aquifers is associated with river flow and rainfall events, while in other aquifer systems recharge is mainly from rainfall. The recharge estimation varies from zero to 28% of rainfall. Localised discharge occurs to the rivers or as baseflow (3 to 12% of rainfall) and diffuse discharge occurs through vegetation use of shallow groundwater (0.5% of rainfall). In addition, groundwater outflow from the Gloucester Basin occurs along the northern and southern boundaries but was estimated as only a small portion of the groundwater balance (0.06% rainfall). Three groundwater numerical models are available for the Gloucester Basin.

Current groundwater use (up to approximately 0.52 GL/year) comprises commercial or industrial, irrigation, mining, stock, domestic and farming activities.

1.1.4.1 Groundwater systems

1.1.4.1.1 Hydrogeological characteristics of the Gloucester Basin formations

Based on the geological setting and discrete structural-sedimentary formation (see Figure 22 and 23, Chapter 1.1.3), the Gloucester Basin which underlies the Gloucester subregion, is characterised as a closed hydrogeological system. Multiple groundwater studies (Australasian Groundwater and Environmental, 2013; Heritage Computing, 2009; 2012; Parsons Brinckerhoff, 2012a; 2012b; 2012c; 2013b) describe four main hydrogeological units within the basin:

1. the alluvial aquifers along major creek lines

2. relatively shallow weathered/fractured rock aquifers
3. interburden units of very low permeability which form a thick succession of low permeability coal measures
4. the impermeable Alum Mountain Volcanics Formation that underlies these three hydrogeological units.

Findings of the studies (Australasian Groundwater and Environmental, 2013; Heritage Computing, 2009; 2012; Parsons Brinckerhoff, 2012a; 2012b; 2012c; 2013b) are summarised below:

- The alluvial aquifer (unconfined or semi-confined) (Quaternary deposits as shown in Figure 25) developed in close proximity to the river. It is composed of clay layers and highly permeable sediments (e.g. gravel) with a high range of hydraulic conductivity (K = 0.3 to 500 m/day). The alluvial thickness is 15 m or less in the northern part of the basin where most of AGL Energy Limited’s (AGL) groundwater investigation was undertaken (Parsons Brinckerhoff, 2012a)and an average of about 9 m at the Duralie Coal Mine (DCM) area, located in the southern part of the Gloucester Basin (Heritage Computing, 2009). The watertable is shallow and within the first metres of the area close to the river. The water levels are very responsive to rainfall and flooding events (see Figure 5 Parsons Brinckerhoff, 2013d, p. 6).
- The fractured rock aquifer, which underlies the alluvial systems but also extends to the entire area of the Gloucester Basin, is hosted by the top 150 m (see Figures B-16 and B-17 Heritage Computing, 2009, pp. B-68 to B-70) of the weathered profile across all shallow stratigraphic units (i.e. shallower than 150 metres below ground level (mbgl)) (Permian Formation as shown in Figure 25). This aquifer, confined locally, is of lower hydraulic conductivity (K = 0.01 to 20 m/day). There is a limited and delayed groundwater level response to rainfall seasons, however the groundwater response to the individual rainfall events is not commonly observed (see Figures A-6, A-7, A-9, A-10, A-13 to A-20, A-24 to A-26, A-29, A-30 Parsons Brinckerhoff, 2013d, p. 10 to 22). Parsons Brinckerhoff (2013b) reported that the shallow rock hydrogeological unit comprises inter-bedded sandstone, silt and claystone. This aquifer extends beneath the alluvium where present, and outcrops elsewhere in the Gloucester Basin. Also, the hydraulic properties are likely to be largely controlled by bedding plane fractures. The 150 mbgl zone of shallow rock is heterogeneous, with high and low hydraulic conductivity domains associated with fault zones and fracturing (Parsons Brinckerhoff, 2013b). The known aquifer zones occur to a maximum depth of 150 m but are mostly within less than 100 m.
- In addition to these two aquifer systems, SRK (2010) refer to deeper coal measures, including coal seams, as ‘water-bearing’ rather than ‘aquifers’, implying that they are low water yielding strata. However, Parsons Brinckerhoff (2012a) sometimes refer to coal seams as aquifers with hydraulic conductivity (K = 0.002 to 0.03 m/day). Changes in hydraulic conductivity of these formations with depth are characterised by a linear logarithmic decrease (see Figure 4-9 in Parsons Brinckerhoff, 2013b; SRK, 2010 or Figures 5.6 and 5.7 in Parsons Brinckerhoff) ~ 8.6×10^{2} m/day at 100 m; ~ 6.1×10^{2} to ~ 2.3×10^{3} m/day at 300 m, and ~ 4.8×10^{4} m/day at 500 m. Similar hydraulic conductivity values were also reported by Australian Groundwater and Environmental Consultants (AGE) for the DCM (see Tables B-4

(pp. B-19) and B-10 (pp. B-28) in Heritage Computing, 2009). It was also noticed that this relationship in the Gloucester Basin is similar to those in the Hunter Valley and Sydney Basin (see Figure 3.5 (pp. 22) in Ward and Kelly, 2013). No response to recharge events (rainfall) and very little fluctuation were observed in the bores in these strata. However changes in groundwater level (or heads) were identified in response to more general seasonal trends in rainfall (dry versus wet periods). The coal seams vary in thickness from 3 to 18 m, have relatively high permeability (as compared to the surrounding interburden) and hence are likely to form potential conduits for limited groundwater flow at depth.

- The Alum Mountain Volcanics Formation, which is considered to be impermeable, underlies the Permian Coal Measures. This formation outcrops in the east and west of the Gloucester Basin, forming the Gloucester River and Barrington Tops to the west, and the Mograni Range to the east. Parsons Brinckerhoff (2013b) suggested that there are springs along the margins of the basin, assumed to be associated with circulation of meteoric water through localised fractures in shallow parts of the Alum Mountain Volcanics Formation.

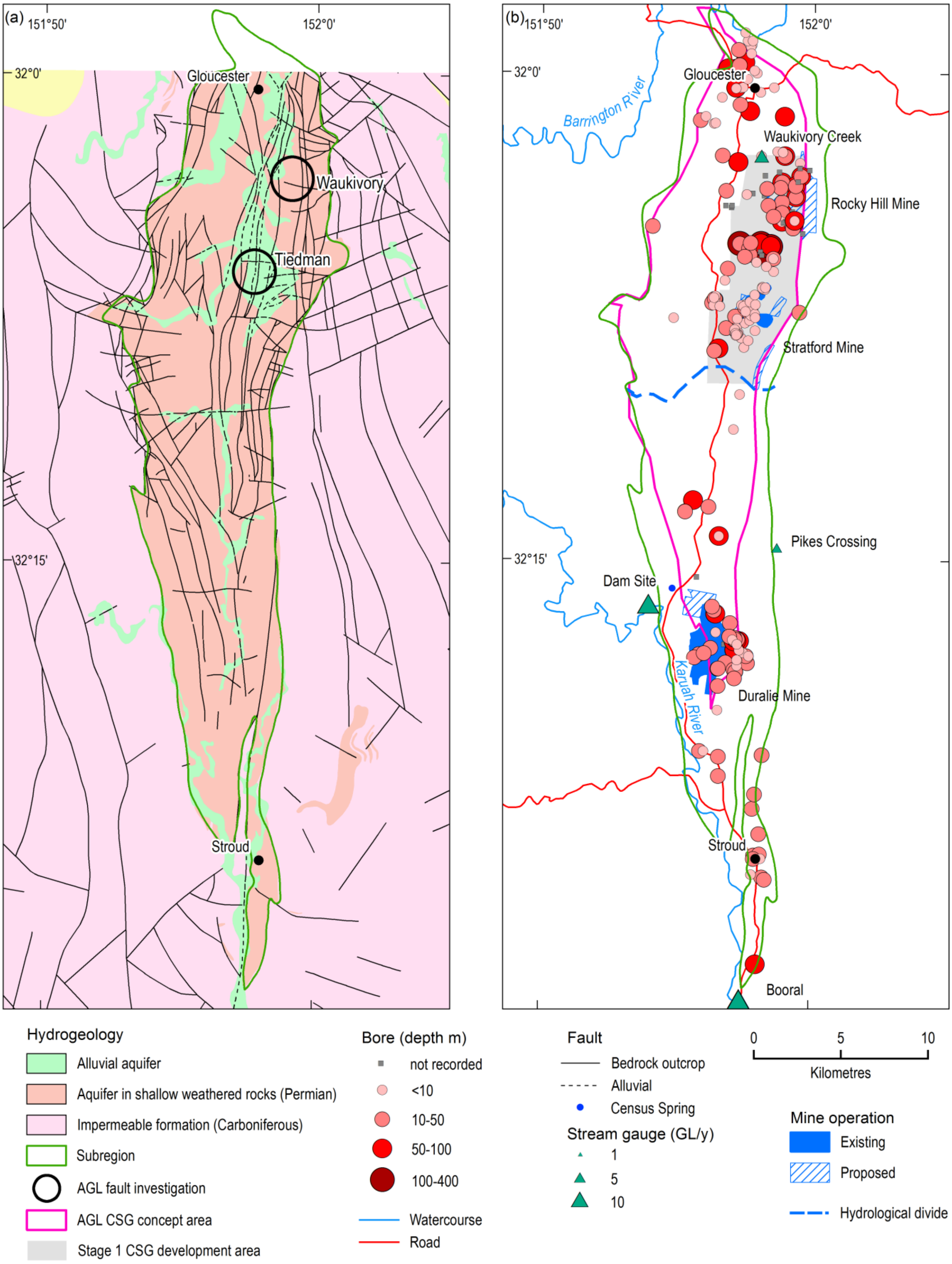


Figure 25 Hydrogeological information

1.1.4.1.2 Fault systems and their hydrogeological characteristics

A large number of faults are known or inferred to underlie the Gloucester Basin (Figure 25) (Roberts et al., 1991). However, the effect of faults on hydraulic properties of formations is not well known. Some evidence of the role of fault systems on hydraulic properties of the formations in the basin are summarised by Parsons Brinckerhoff (2012c; 2013b). Key findings are listed below:

- Pacific Power (1999, in SRK (2010)) reported that an inferred normal fault, intersected at 325 mbgl (the Bowens Road Coal Seam) showed hydraulic conductivity of approximately 5.8 x 10^{-2} m/day, approximately one order of magnitude higher than that estimated for coal seams at a similar depth (~ 8.6 x 10^{-3} to 1.2 x 10^{-2} m/day).
- Resource Strategies (2001) suggested that faulting caused compartmentalisation of groundwater flow (i.e. faults are of low permeability) (from URS, 2007, p. 14).
- Parsons Brinckerhoff (2012a) observed that groundwater monitoring data collected from bores near faults or which straddle fault zones do not indicate any effect of the faults on the natural groundwater flow characteristics of shallow rock aquifers, interburden confining units or coal seam water-bearing zones.
- The results of the site-specific investigations, field-based studies and geophysical methods summarised in Parsons Brinckerhoff (2013b) indicate that one of the strike-slip fault zones (the Tiedman property) forms a broad and heterogeneous zone of increased hydraulic conductivity within the shallow rock aquifer. This zone does not cause a strong preferred longitudinal flow along the faulting zone or form a barrier to groundwater flow. No clear evidence of enhanced connections between the deeper coal seams and shallow groundwater system was found. However distinct hydrochemistry and radiocarbon (older) ages within the fault zone were also reported, which may be indicative of some vertical (upward) migration of deeper groundwater under natural conditions.

AGL plans to conduct a further hydrogeological investigation into faulting in association with the proposed Waukivory flow testing program. The thrust fault in the Waukivory area is typical of many fault systems across the eastern portion of the Gloucester Basin (see Figure 3.7 in Parsons Brinckerhoff, 2013c, p. 16).

1.1.4.1.3 Groundwater use

According to the New South Wales Office of Water (NSW Office of Water), data for registered bores in the Gloucester Basin are categorised by use as: commercial or industrial; irrigation; mining; stock, domestic or farming; test or monitoring; and unknown.

Parsons Brinckerhoff (2013c) and Australasian Groundwater and Environmental (2013) provided a review of the NSW Office of Water groundwater database for the Gloucester Basin. Parsons Brinckerhoff (2013c) have identified registered bores: 24 used by stock and domestic supply; four used for irrigation; five used for commercial and industrial purposes; four for mining use; 121 for test and monitoring associated with mining in the area; and 30 are registered with unknown use.

Stock and domestic useThe 24 bores registered for stock and domestic use are between 4 m and 66 m deep and are likely to intersect the alluvium and shallow rock within the Gloucester Basin. Parsons Brinckerhoff (2013c) assumes that annual stock and domestic bore use is approximately 1

ML/bore. AGE (2013) has reported that a single groundwater facility exists in the Avon River management area with an annual entitlement of 20 ML/year from the alluvium.

Coal mining

There are 51 bores associated with Stratford Mine, Duralie Mine and the Rocky Hill Coal Project. Groundwater pit inflows to the Duralie Mine open cuts are expected to vary between approximately 0.2 and 1ML/day during mining operations (Heritage Computing, 2009, pp. B-5). Total pit inflows will range between approximately 0.7 ML/day and 1.3 ML/day during the Stratford Mine operation (Heritage Computing, 2012, p. A-47 and A-56). Pit inflows are predicted to be reduced by a maximum of 0.5 ML/day if CSG dewatering in the Stage 1 Gas Field Development Area is coincident with mining at the Stratford Mine (Heritage Computing, 2012, p. A-49 and A-54).

Coal seam gas

Over the last 10 years, AGL and Lucas Energy were the only organisations which conducted CSG exploration and relevant hydrogeological investigations in the Basin and the findings of those activities were summarised by Parsons Brinckerhoff (2013c). According to Parsons Brinckerhoff (2013c):

- Coal seam gas dewatering is deemed to be ‘industrial and irrigation use’ as water that is pumped as part of exploration (appraisal) and production programs is mostly reused (for drilling, fracture stimulation, industrial recycling and irrigation purposes).
- The long-term reuse of water produced as a result of CSG dewatering will mostly be for irrigation purposes. This would be conditional on water quality, which is likely to be brackish.
- The Gloucester Gas Project (GGP) will involve the dewatering of deep groundwater and the extraction of gas from multiple coal seams within the Gloucester Coal Measures. Target coal seam depths will vary from site to site but are expected to range between 200 and 1000 mbgl.
- The GGP includes the construction, operation and decommissioning of not more than 110 coal seam gas wells and associated infrastructure, including gas and water gathering lines, within the Stage 1 Gas Field Development Area.
- The volumetric rate of groundwater extraction will not exceed 2 ML/day (averaged over a 12 month period), as specified in the Commonwealth’s *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act; Part 3A Approval – condition 3.11; and EPBC Approval – condition 22). The effect of such abstraction on the basin water balance has not yet been fully assessed.

Planning and management of groundwater systems in the region is undertaken by the NSW Office of Water, through water sharing plans (WSP) and reviewed every 10 years from date of commencement. Currently there is no WSP for the sedimentary (porous) rocks of the Gloucester Basin. As per NSW Office of Water, Water Sharing Plan website development of Northern Fractured and Porous Rock Groundwater Sources WSP will be commenced in 2014 (DPI, 2014). The WSP for the Karuah River Water Source (DIPNR, 2004) indicated no plans for groundwater extraction. The unregulated Avon River as well as the Barrington and Gloucester rivers and the associated alluvial groundwater source are managed under the Lower North Coast Unregulated and Alluvial Water Sources Water Sharing Plan (DPI, 2009). As per this WSP there are 212 ML/year under groundwater extraction licences, authorising extraction for irrigation from these water sources, including the following:

- 20 ML/year in the Avon River Water Source
- 5 ML/year in the Lower Barrington/Gloucester Rivers Water Source
- 187 ML/year in the Manning Estuary Tributaries Water Source and
- 0 ML/year in all other water sources.

The licensed extraction is from the alluvial aquifer, and the purpose of use may not always be solely for irrigation, although licensed irrigation use would likely be a major component of usage in some water sources.

1.1.4.2 Groundwater quality

Groundwater salinity increases with the depth from fresh and brackish in alluvial aquifer (EC = 387 to 5810 µS/cm), brackish to saline in shallow bedrocks (EC = 3867 to 9371 µS/cm); inter-bedded sandstone-siltstone water-bearing zones (EC = 2395 to 6100 µS/cm) and coal seams (EC = 3014 to 4999 µS/cm) (Parsons Brinckerhoff, 2012a; 2012c; 2013a). Similar salinity patterns were also observed for the Stratford, Duralie and Rocky Hill coal mines located in the Gloucester Basin (Australasian Groundwater and Environmental, 2013; Heritage Computing, 2009; 2012).

The stable isotope values of groundwater, collected from all formations, indicated that all tested water samples are of meteoric (rainfall) origin and that no enrichment has occurred due to evaporation. In terms of the age, the oldest water was identified in the inter-bedded sandstone/siltstone water-bearing zone (mostly aquitard) and the youngest in alluvium. This corresponds with the EC/salinity trend. The stable isotopes, aging analysis and EC values are likely to indicate that high salinity in the older groundwater is likely to be related to in-situ water mineralisation.

In SRK (2010), iron (Fe), fluorine (F), phosphorus (P) and mercury (Hg) were identified as typical elements occurring in coal seams, which can potentially assist analysis of aquifer interactions. Only Fe and P were included in water quality monitoring, and P concentration was particularly elevated in all formations, which is not typical for groundwater. Total organic carbon levels increased with water age and methane concentrations were, on average, 10 µg/L, 140 µg/L, 12,789 µg/L and 21,931 µg/L in alluvial, shallow bedrock, inter-bedded sandstone-siltstone and coal seams respectively.

1.1.4.3 Groundwater flow

Groundwater monitoring undertaken by Parsons Brinckerhoff (2012a; 2012c; 2013b) within the Gloucester Basin provides some evidence for a topographical groundwater flow divide in the middle of the basin north of Wards River, approximately coincident with the surface water divide (Figure 25). This separates the Gloucester Basin into a northern sub-basin (where regional groundwater flow is predominantly from south to north) and a southern sub-basin (where regional groundwater flow is predominantly from north to south). The groundwater level (or heads) appears to be at less than 140 metres Australian Height Datum (mAHD) at the divide (60 to 160 mbgl), less than 60 mAHD at the outflow in the south and less than 100 mAHD at the outflow in the north – both outflows are practically at the surface elevation (see Figure 5.9 in Parsons Brinckerhoff, 2013b, p. 40). Based on limited observation data it appears that locally, groundwater flow can be east to west or west to east as groundwater may flow laterally from rock outcrop areas towards the centre of the basin.

Due to greater transmissivity of alluvial deposits, the greater rates of groundwater fluxes (and lesser residence time) are more likely to be associated with alluvial aquifers than in the underlying Permian deposits. This also is supported by groundwater age dating (Parsons Brinckerhoff, 2012a).

As the Gloucester Basin appears to be a closed system, groundwater recharge and discharge is confined to the syncline structure. Recharge associated with rainfall occurs at the outcropping aquifers, including the alluvial sediments along the valley floor, and shallow Permian fractured aquifers and deeper water-bearing zones (e.g. coal seams) around the flanks of the Gloucester Basin. It is not ruled out that upward fluxes can also occur through vertical leakage or faulting from deeper to shallower layers. Based on preliminary numerical modelling, vertical fluxes between hydrogeological units are generally low with a relatively higher upward flux from the fractured rock aquifer to the alluvial aquifer (Parsons Brinckerhoff, 2013c). However, there is no consistency in the groundwater level monitoring data in nested bores in terms of differences in the hydraulic heads and groundwater levels, as both upward and downward trends were reported (Parsons Brinckerhoff, 2012c).

Groundwater recharge was estimated as zero to 17% (under steady state conditions) and zero to 28% (under transient conditions) of rainfall on average with high values associated with alluvial aquifers (Australasian Groundwater and Environmental, 2013; Heritage Computing, 2009; 2012; Parsons Brinckerhoff, 2013c). It was also reported that rainfall in excess of 80 mm in a week and associated significant stream flow events greater than 3000 ML/day are required to recharge the alluvial groundwater system and sustain baseflow over the following months. Parsons Brinckerhoff (2013c) concluded that the alluvial system has limited storage and is rapidly depleted and replenished in response to rainfall variations.

Discharge occurs from all the hydrogeological units to rivers and streams (localised discharge) and, as evapotranspiration by deep-rooted vegetation, from the shallow watertable (diffuse discharge). Some limited groundwater outflow is likely along the most northern and southern edges of the Gloucester Basin. The elements of the basin water balance were estimated by Parsons Brinckerhoff (2013c) as 9.5 GL/year baseflow (or 2.9% rainfall), 0.2 GL/year seepage along the northern and southern boundaries (or 0.06% rainfall) and 1.7 GL/year diffuse discharge from the shallow watertable (or 0.5% rainfall on average).

A summary of the water balance estimation, based on groundwater modelling, is given in Table 5 for Duralie (see Tables B-7 (pp. B-25) and B-12 (pp. B-30) in Heritage Computing, 2009) and Stratford (see Table A-16 (pp. A-45) in Heritage Computing, 2012) coal mine and for the Rocky Hill Coal Project (see Table 18 (pp. 4-102) in Australasian Groundwater and Environmental, 2013). The locations of these mines are shown in Figure 25.The values of the water balance elements are site specific. A detailed numerical model is required to estimate reliable water balance values for the entire Gloucester Basin and to assess the cumulative impact of all proposed developments.

Table 5 Water balance estimation

	Duralie Coal Mine[1]	Stratford Coal Mine[2]	Rocky Hill Coal Project[3]
Steady state condition			
Recharge			
Diffuse (as % of rainfall)	76% of total recharge		100% of total recharge
• Alluvial aquifer	1.0%		1
• Weathered regolith	2.6%		0.1%
• Hills or slope wash zone	12%		5%
• Subcropping coal seams	1.0%		no data
Localised (from streams)	23% of total recharge		
• Discharge (as % of recharge)			
• Baseflow	23%		2.3%
• Evapotranspiration	64% (3 m – 750 mm)		97.3%
	13% suggested as a rejected recharge (?)		
Transient state condition			
Rainfall recharge			
Diffuse (as % of rainfall)	70% of total recharge	45% of total recharge	
• Alluvial aquifer	1.0%	8%	
• Weathered regolith	2.0%	1%	
• Hills or slope wash zone	23%	0.25%	
• Subcropping coal seams	0.5%		
Localised (from streams)	29% of total recharge	55% of total recharge	
• Discharge (as % of recharge)			
• Baseflow	31%	61%	
• Evapotranspiration	44%	35%	
	20% suggested as a rejected recharge (?), 3% and 2% to mining and boundaries	4% to mining	

Source data: [1]Tables B-7 and B-12 in Heritage Computing (2009), [2]Table A-16 in Heritage Computing (2012), [3]Table 18 in AGE (2013)

References

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

DIPNR (2004) Water sharing plan: Karuah River Water Source – guide. NSW Department of Infrastructure, Planning and Natural Resources, Taree.

DPI (2009) Water sharing plan: Lower North Coast Unregulated and Alluvial – guide. New South Wales Department of Primary Industries, Office of Water, Sydney.

DPI (2014) Water Sharing Plans under development. New South Wales Department of Primary Industries, Office of Water. Viewed 27 February 2014, <http://www.water.nsw.gov.au/Water-management/Water-sharing-plans/plans-under-development/default.aspx>.

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

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

Parsons Brinckerhoff (2012a) Phase 2 Groundwater Investigations – Stage 1 Gas Field Development Area: Gloucester Gas Project, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. *Parsons Brinckerhoff Australia Pty Limited*, Sydney. Viewed 12 Aug 2013, <http://agk.com.au/gloucester/assets/pdf/PB%20Gloucester%20Groundwater%20Report%20Phase%202%20Text.pdf>.

Parsons Brinckerhoff (2012b) Gloucester Resources Limited, Groundwater Investigation, Annual Monitoring Report, Technical report by Parsons Brinckerhoff Australia Pty Limited for Gloucester Coal Limited Pty Ltd. Parsons Brinckerhoff Australia Pty Limited, Sydney. Viewed 10 September 2013, <http://www.rockyhillproject.com.au/wp-content/uploads/2013/08/80604-Vol-2_Part-4-Groundwater_Appendices-3-to-6.pdf>.

Parsons Brinckerhoff (2012c) Gloucester Groundwater and Surface Water Monitoring – Annual Status Report, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. Parsons Brinckerhoff Australia Pty Limited, Sydney. Viewed 10 September 2013, <http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source

%20Energy/CSG%20and%20the%20Environment/Gloucester/Assessments%20and%20Reports/2012/September/Gloucester%202012%20Monitoring%20Report.pdf>.

Parsons Brinckerhoff (2013a) Gloucester Gas Project – Tiedman Irrigation Trial Baseline Water Monitoring Report, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. Parsons Brinckerhoff Australia Pty Limited, Sydney. <http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Gloucester/Plans%20and%20Proposals/2013/May/Gloucester%20Irrigation_PR.pdf>.

Parsons Brinckerhoff (2013b) Hydrogeological Conceptual Model of the Gloucester Basin, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. Parsons Brinckerhoff Australia Pty Limited, Sydney. Viewed 10 September 2013, <http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Gloucester/Assessments%20and%20Reports/2013/Conceptual%20model%20email%20version.pdf>.

Parsons Brinckerhoff (2013c) Water Balance for the Gloucester Basin, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. Parsons Brinckerhoff Australia Pty Limited, Sydney. Viewed 06 September 2013, <http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Gloucester/Assessments%20and%20Reports/2013/Water%20balance.pdf>.

Parsons Brinckerhoff (2013d) Gloucester Groundwater and Surface Water Monitoring – FY14 Q1 Monitoring Update, Technical report by Parsons Brinckerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. Parsons Brinckerhoff Australia Pty Limited, Sydney. Viewed 21 January 2014, <http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Gloucester/Assessments%20and%20Reports/2013/2162406E%20GGP%20FY%20Q1.pdf>.

Resource Strategies (2001) Bowens Road North Project - Environmental Impact Statement, Technical report by Resources Strategies Pty Limited for Stratford Coal Pty Ltd. Resources Strategies Pty Limited, Milton, Queensland. Viewed 10 September 2013, <http://www.gloucestercoal.com.au/documents/Enviro_EAD_SCM_BowensRoadNorthProjectEnvironmentalImpactStatement%282001%29.pdf>.

Roberts J, Engel B and Chapman J (1991) Geology of the Camberwell, Dungog and Bulahdelah 1:100,000 Sheets 9133, 9233, 9333. In: Energy NSWDoMa (ed.). New South Wales Geological Survey, Sydney.

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

URS (2007) Hydrogeological Review – Proposed Coal Seam Gas Exploration Area, Gloucester-Stroud Basin, New South Wales, Technical report by URS Australia Pty Limited for Lucas

Energy Pty limited. URS Australia Pty Limited, Sydney. Viewed 10 September 2013, <http://www.agl.com.au/~/media/AGL/About%20AGL/Documents/How%20We%20Source%20Energy/CSG%20and%20the%20Environment/Gloucester/Assessments%20and%20Reports/2007/August/URS%20Hydrogeological%20Review%20-%20Desk%20study%20Text.pdf>.

Ward CR and Kelly FB (2013) Background Paper on New South Wales Geology: With a focus on Basin Containing Coal Seam Gas Resources, Technical report for Office of the NSW Chief Scientist and Engineer. University of New South Wales, Sydney. Viewed 10 September 2013, <http://www.chiefscientist.nsw.gov.au/__data/assets/pdf_file/0009/31788/NSW-Geology-Background-Paper_Ward-and-Kelly_UNSW.pdf>.

1.1.5 Surface water hydrology and water quality

Summary

The Gloucester subregion contains rivers that flow into two separate river basins: the Manning and Karuah river basins. Observed river water quality in the subregion is good. The northern part of the Gloucester subregion sits within the catchment of a major tributary of the Manning River – the Gloucester River – and the southern part is located in the catchment of the Karuah River. The main surface water resources of the Gloucester subregion include the Avon, Gloucester, Barrington, Mammy Johnsons and Karuah rivers, most of which are unregulated. There are several small farm dams in the subregion that store water from new and existing coal seam gas (CSG) exploration wells, and supply water for agricultural irrigation. The average annual streamflow and baseflow indices are respectively 550 and 0.58 GL for the Gloucester River at Doon Ayre, and 270 and 0.50 GL for the Karuah River at Booral. There is no long-term, consistently applied water quality monitoring program in the Gloucester subregion. Water quality information about the northern part is mainly available for the Avon River where there is a large variation in salinity levels, with electricity conductivity (EC) varying from 100 to 1230 μS/cm and pH is near neutral (6.6 to 7.4). In the southern part, for the Karuah River, salinity is less than 400 μS/cm, and pH varies from 6.3 to 8.5.

1.1.5.1 Surface water systems

Major surface water systems in the Gloucester subregion are rivers, with some limited surface water infrastructure such as farm dams and fish farm dams. The rivers in the northern part of the subregion flow into the Manning River and those in the southern part flow into the Karuah River. The Gloucester River, a tributary of the Manning River, is the major river flowing through the northern part of the subregion, while the Karuah River flows through the southern part of the subregion.

1.1.5.1.1 Surface drainage networks

The Gloucester subregion contains rivers flowing into two separate river basins, the Manning River Basin and the Karuah River Basin (Figure 26 and Figure 27). The northern part of the subregion contributes 2.2% (181 km^2) of the catchment area of the Manning River Basin and the southern part contributes 11.4% (166 km^2) of the catchment area of the Karuah River Basin.

The main river flowing through the northern part of the subregion is the Gloucester River. It originates below the Gloucester Tops, outside the Gloucester subregion, before flowing through the subregion and then further downstream to its junction with the Manning River. The total length of the Gloucester River is 102 km, with about 43 km of its middle and lower reaches falling within the Gloucester subregion. The total catchment area of the Gloucester River (above its junction with the Manning River) is 1650 km^2, which represents 20% of the area of the Manning River Basin.

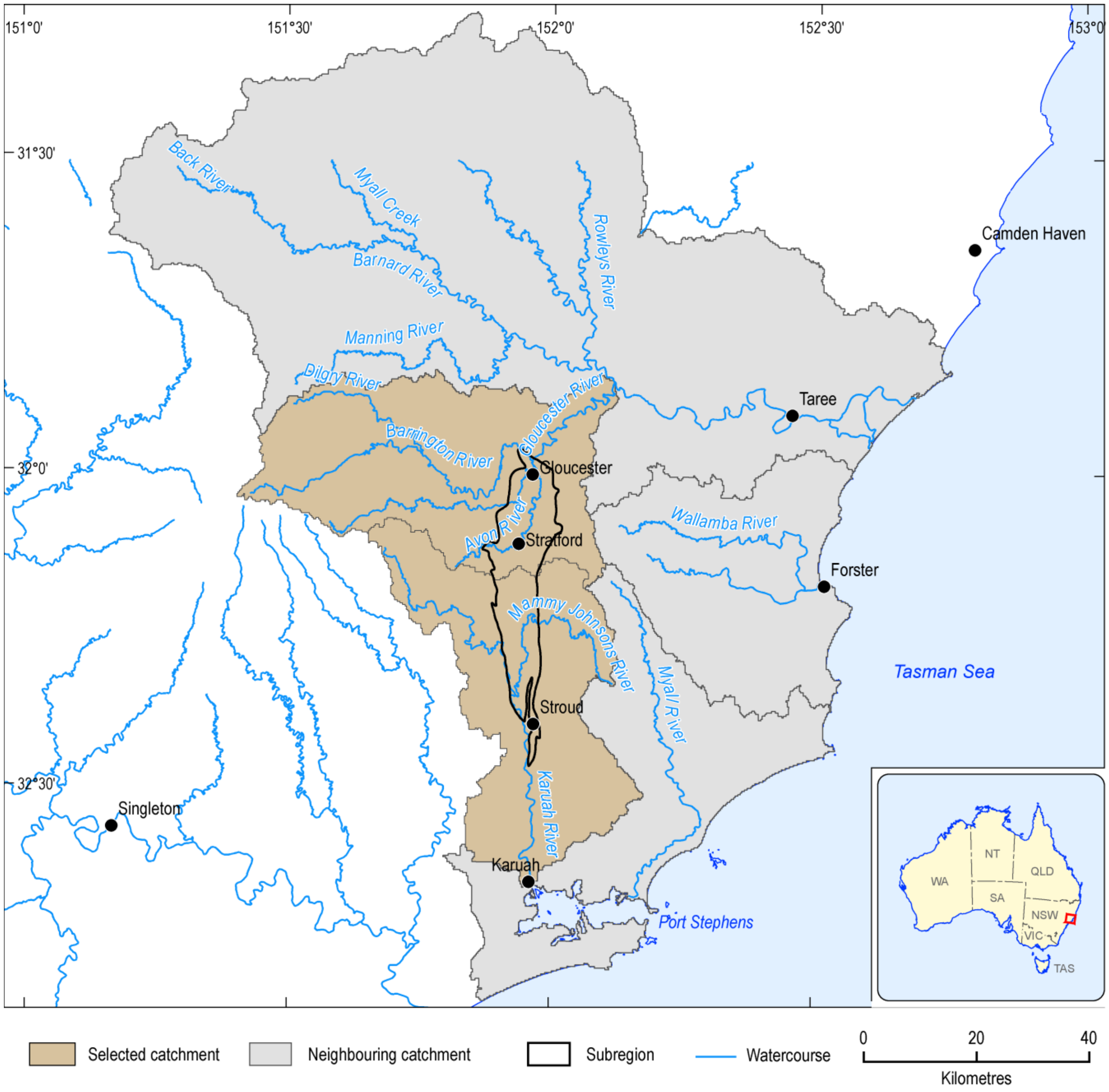


Figure 26 Location of the Gloucester subregion, towns, major watercourses, selected and neighbouring catchments

The main tributaries of the Gloucester River are the Avon, Barrington and Bowman rivers (Figure 27). The Avon River (catchment area 290 km^2) flows into the Gloucester River within the subregion just north of the Gloucester township and about 1 km upstream of the junction with the Barrington River. About 54% (158 km^2) of the catchment of the Avon River is located upstream of the subregion, both to the west and east of the subregion. About 46% (132 km^2) of the Avon River's catchment is located within the subregion, contributing 73% of the area of the northern part of the subregion (181 km^2) (Table 6). The Avon River descends 412 m over its 42 km course.

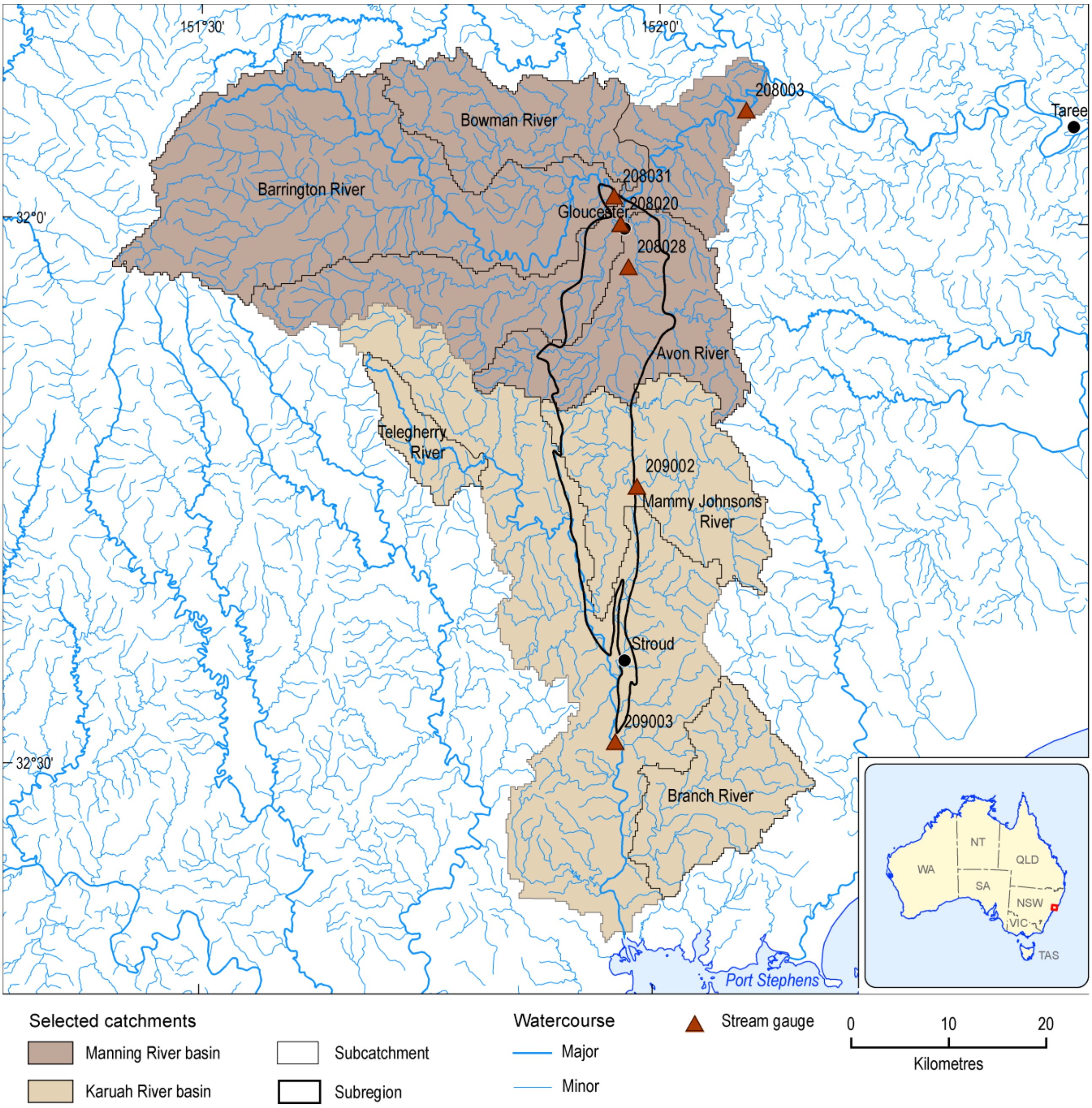


Figure 27 Surface drainage network and gauges for selected catchments and subcatchments

The Barrington River (catchment area 715 km^2) rises on the eastern slopes of the Mount Royal Range, within the Great Dividing Range, and flows generally east, before reaching its confluence with the Gloucester River near Gloucester. The Barrington River descends 1370 m over its 93 km course, and discharges approximately 435 GL per year at the Relf Rd streamflow gauge (208031) located about 1 km upstream from its confluence with the Gloucester River. The main tributaries of the Barrington River include the Kerripit, Cobark and Moppy rivers. Only about 0.59% (4 km^2) of the Barrington River's catchment is located within the subregion, contributing 2.0% of the area of the northern part of the subregion.

Table 6 Catchment area for the main rivers and their main tributaries flowing through the Gloucester subregion

Main rivers	Main tributaries	Catchment area (km^2)			
		Above subregion	Within subregion	Below subregion	Total
Gloucester		1081	181	392	1650
	Avon	158	132	0	290
	Barrington	711	4	0	715
	Bowman	0	0	231	231
Karuah		529	166	755	1450
	Mammy Johnsons	208	111	0	319
	Telegherry	74	0	0	74
	Branch	0	0	215	215

The Bowman River joins the Gloucester River downstream of the Gloucester subregion and about 2 km downstream of the junction of the Gloucester and Barrington rivers. As such, all of its catchment area (231 km^2) is below the subregion. The Bowman River descends around 635 m over its 54 km length.

The main river flowing through the southern part of the subregion is the Karuah River. It originates outside of the Gloucester subregion, before flowing through the subregion and then further downstream before discharging into Port Stephens near the township of Karuah. The total length of the Karuah River is 100 km, with about 40 km of its middle and lower reaches falling within the southern Gloucester subregion. The total catchment area of the Karuah River (above Port Stephens) is 1450 km^2.

The main tributaries of the Karuah River are the Mammy Johnsons, Telegherry and Branch rivers (Figure 27). The Telegherry River joins the Karuah River upstream of the Gloucester subregion and its entire catchment area (74 km^2) is outside the subregion. The Telegherry River descends around 771 m over its 28 km length.

The Mammy Johnsons River originates in the Myall River State Forest, outside the Gloucester subregion, before flowing into the subregion and joining the Karuah River, still within the subregion, near Stroud. The catchment area of the Mammy Johnsons River is 319 km^2, about 67% (111 km^2) of which is in the subregion (Table 6). The catchment of the Mammy Johnsons River thus contributes about two-thirds of the area of the southern part of the subregion. The main tributary of the Mammy Johnsons River is the Wards River, which occupies the northernmost part of the catchment of the Mammy Johnsons River. The Mammy Johnsons River descends 371 m over its 55 km course, and discharges approximately 59 GL per year at the Crossing streamflow gauge (gauge 209002), which is located just over half way along its length and is upstream of the junction with the Wards River.

The Branch River joins the Karuah River below the Gloucester subregion. All of its catchment area (215.3 km^2) is below the subregion. The Branch River is 27 km long and has an elevation drop of 62 m.

1.1.5.1.2 Surface water infrastructure

There is some limited surface water infrastructure, such as farm dams and fish farm dams, within the Gloucester subregion. There is currently approximately combined storage capacity of 50 ML on the Tiedman property with 20 ML, 20ML, and 10 ML coming from the Tiedman North, South, and East dams respectively. These dams lie within the Avon River catchment, 10 km south of Gloucester and approximately 3 km north-east of Stratford (Figure 26). The two dams store water from new and existing CSG exploration wells, and supply water for agricultural irrigation. The two dams consist of a completely enclosed, above ground embankment, and are located on a ridgeline so can only be filled by reticulation. Therefore, they have very little impact on surface runoff water and total catchment flows (AGL Energy Limited, 2012).

There is a fish farm, the Pioneer Fish Farm, in the Gloucester subregion. It is 3 km to the south of Gloucester town. This fish farm consists of 20 ponds covering 5.8 ha plus three dedicated water storage reservoirs. The farm’s water supply is sourced from surface runoff, bore water and river water. The 28 ML headwater dam collects surface runoff. There are two settling ponds holding 21 ML and 48 ML respectively. The fish farm holds a licence that allows up to 390 ML of water per year to be pumped from the Gloucester River.

1.1.5.1.3 Flooding history

The largest reported flood for the Gloucester River occurred in 1929 (Gloucester Shire Council, 2004). The largest recorded flood for the Gloucester River occurred on 20 March 1978, with a maximum gauged level of 12.05 m and a maximum daily discharge of 227 GL at gauge 208003. The largest flood in the last 20 years occurred on 16 June 2011, with a maximum gauged level of 8.7 m and a maximum daily discharge of 92 GL at gauge 208003.

The largest recorded flood for the Karuah River occurred on 21 January 1971, with a maximum gauged level of 8.53 m and a maximum daily discharge of 144 GL at the gauge 209003. The largest flood in the last 20 years occurred on 8 May 2001, with a maximum gauged level of 7.32 m and a maximum daily discharge of 101 GL at the gauge 209003.

1.1.5.2 Surface water quality

There is no long-term, consistently applied water quality monitoring program in the Gloucester subregion. Therefore there is limited capacity to fully understand what baseline water quality should be for the subregion. The data provided in the text has limited capacity to be used with confidence to indicate the baseline water quality for the river systems mentioned.

Surface water quality measurements in the northern part of Gloucester subregion have been mainly conducted in the Avon River and its tributaries. The salinity (electrical conductivity; EC) and acidity (pH) of the Avon River, Avondale Creek and Dog Trap Creek were intermittently measured between 1993 and 2009 (SRK, 2010). Measured ECs vary from 100 to 500 µS/cm and pH is near neutral to slightly alkaline. The EC is also well related with rainfall, with a reduction in EC following rainfall and an increase in EC when flow reduces and baseflow increases.

Another surface water sampling program was undertaken in April 2011 at three monitoring locations on the Avon River (Parsons Brinckerhoff, 2012). Salinity at the time of sampling was fresh with EC varying from 161 to 324 µS/cm and showing a slight increase in a downstream direction. The pH for the three sampling locations is near neutral, with a pH value varying from 6.6 to 7.4. It is noted that there were regular flows in April 2011 which would have kept the conductivity readings down.

Surface water samplings for the southern part of Gloucester subregion were intermittently undertaken by Gloucester Coal Ltd on Karuah River and Mammy Johnsons Rivers in 2002 to 2009 (Gilbert and Associates, 2010). Measured salinity is less than 600 µS/cm for the Mammy Johnsons River, and is less than 400 µS/cm for the Karuah River; pH for both rivers shows large variation, varying from 6.3 to 8.5.

The pH and EC readings for gauge 209003 on the Karuah River at Booral were also kept by NSW Office of Water. Between 2007 and 2013, pH ranged from 6.3 to 7.6 and EC ranged from 96 to 346 µS/cm.

1.1.5.3 Surface water flow

1.1.5.3.1 Monthly and annual flow characteristics

Four available streamflow gauges in the Gloucester River Basin are Avon River at Waukivory (208028), Gloucester River at Gloucester (gauge 208020), Barrington River at Relfs Road (gauge 208031), and Gloucester River at Doon Ayre (gauge 208003). Two available gauges in the Karuah River Basin are Mammy Johnsons River at Crossing (gauge 209002) and Karuah at Booral (gauge 209003). The locations of these gauging stations are shown in Figure 27. Out of the six gauges, gauge 208031 has the least data length (less than three years), while others have data lengths ranging from around ten years for gauges 208020 and 208028, to more than 45 years for gauges 208003, 209002 and 209003.

Figure 28 shows monthly flow distribution for the four gauges in the Gloucester River Basin. The monthly flow for each gauge is distributed unevenly. The maximum flows occur in February for gauges 208028, 208020 and 208031, and in March for the downstream gauge 208003. The minimum flow, however, occurs in different months. The driest month is January for the Avon River (gauge 208028), and September for the Gloucester River (gauges 208020 and 208003). The low flow occurs in April, May, and September for the gauge 208031 in the Barrington River.

Figure 29 shows monthly flow distribution for the two gauges in the Karuah River Basin. The maximum flow occurs in March, followed by a second peak in June. The minimum flow occurs in September, the same month as for the Gloucester River Basin.

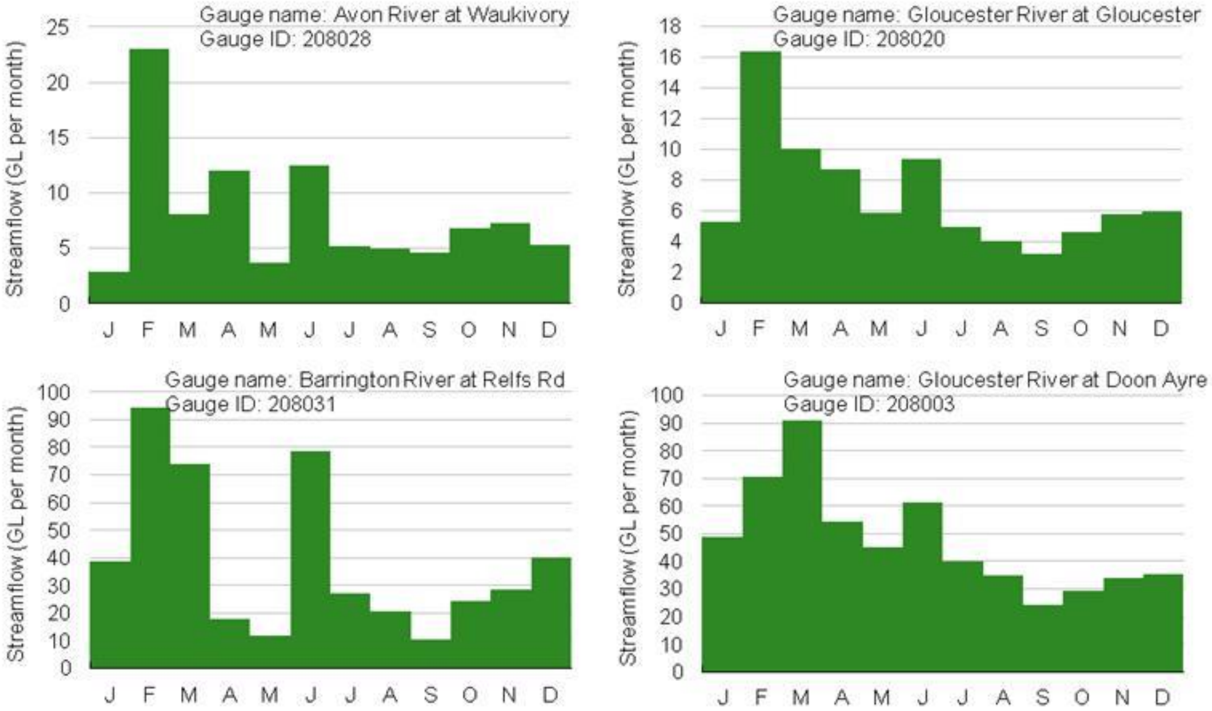


Figure 28 Monthly flow distribution for four streamflow gauges in the Gloucester River Basin

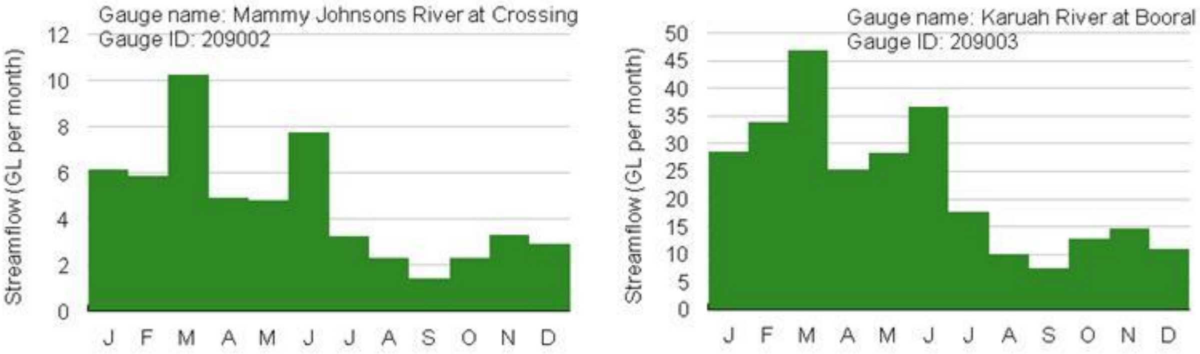


Figure 29 Monthly flow distribution for two streamflow gauges in the Karuah River Basin

Figure 30 shows annual flow variation for the four streamflow gauges in the Gloucester River Basin. Note that annual flow data in Figure 30 (and Figure 31) are missing for some years because of missing daily flow data. However, there are no years with zero flow, so all gaps in the figures represent years with missing data. Furthermore, there is no missing data in any of the remaining annual totals. Among the four gauges, only the lower reach gauge 208003 has more than 50 years of observed data, while the rest have fewer than ten years of data (Table 7). For the last 20 years, the annual flow for the Gloucester River is much less than that for the pre-1980 period. The mean annual flow at gauge 208003 is about 550 GL/year, more than 70% of which is contributed by the Barrington River.

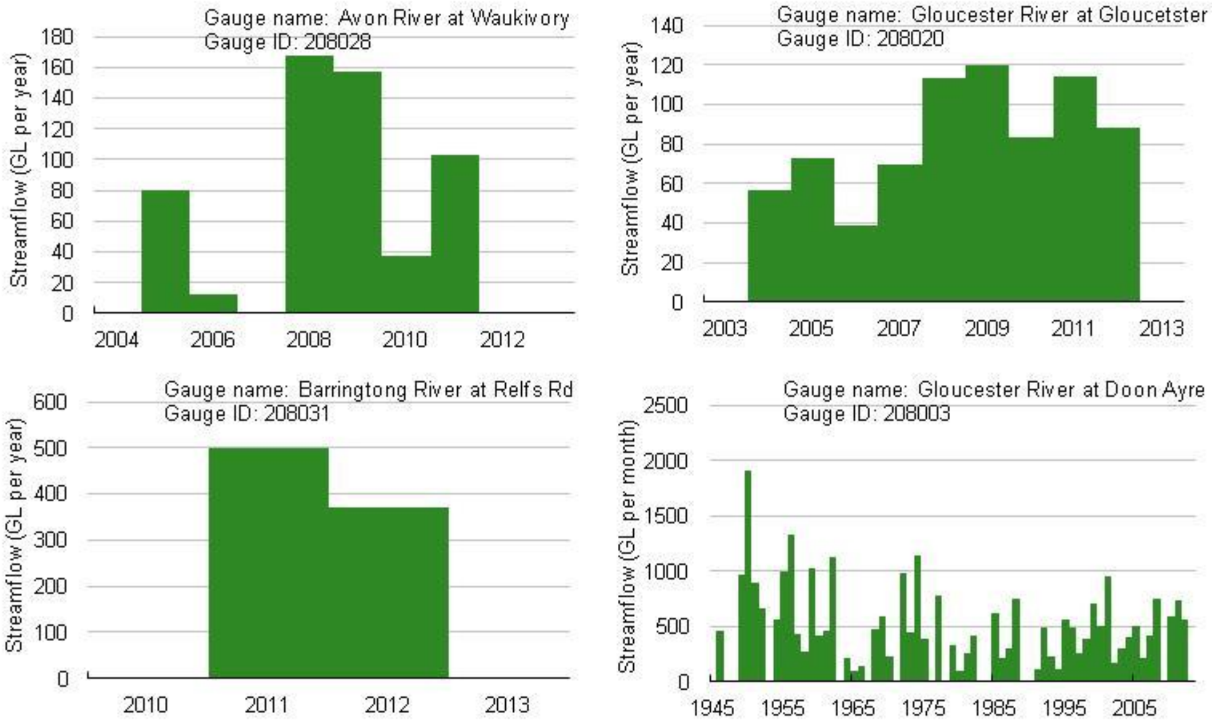


Figure 30 Annual flow time series for the four streamflow gauges in the Gloucester River Basin

Gaps represent missing annual flow data.

Table 7 Streamflow data length and climatology for the six streamflow gauging stations in the Gloucester subregion

Gauge ID	Catchment Area (km^2)	Total length (days)	Start date	End date	Mean annual flow (GL)
208020	253	3,789	5 April 2003	18 August 2013	84
208028	225	3,267	8 September 2004	18 August 2013	93
208031	711	1,081	3 September 2010	18 August 2013	435
208003	1631	24,916	1 June 1945	18 August 2013	550
209002	158	16,680	19 December 1967	18 August 2013	59
209003	974	16,367	27 October 1968	18 August 2013	270

Figure 31 shows annual flow variation for the two gauges in the Karuah River Basin. Both have long-term annual flow data, and show large interannual variability. For the Mammy Johnsons River, higher annual flows often occurred in the 1970s and 1980s, while relatively lower annual flows occurred from 1990 onwards, with only three such years (2001, 2008 and 2011) being above the long-term average. For the Karuah River, the annual flow was significantly greater than average in five years since 1990 to 1999, 2001, 2008, 2009, and 2011.

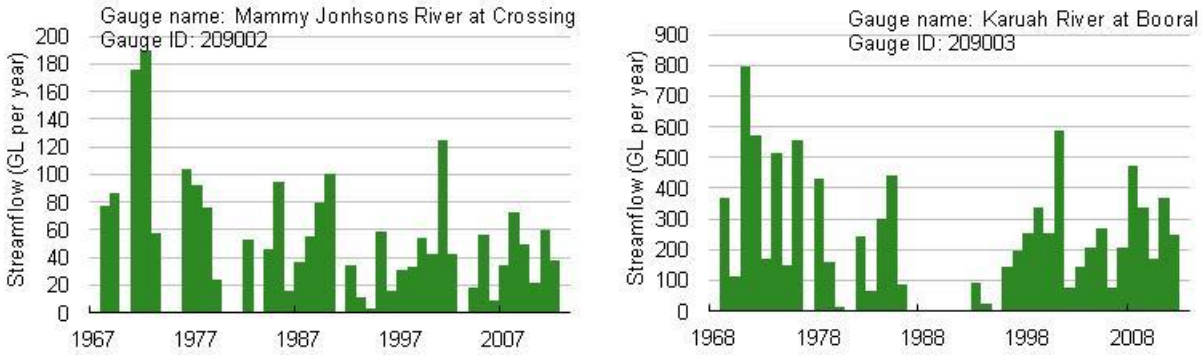


Figure 31 Annual flow time series for the two streamflow gauges in the Karuah River Basin

Gaps represent missing annual flow data.

1.1.5.3.2 Baseflow index characteristics

Streamflow includes two components, quick flow and baseflow. Quick flow 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 quick flow using a one-parameter filtering separation equation (Lyne and Hollick, 1979) that is expressed as:

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

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

Baseflow index (BFI) is defined as the ratio of annual Q_b to annual Q_t. The BFI for the Avon River at Waukivory is only 0.27, while those for the other three gauges in the Gloucester River Basin are similar with BFI values of 0.57 to 0.58 (Figure 32). This means that 43% of the total flow for the Gloucester River at Gloucester is contributed by quick flow and 57% is contributed by baseflow, while for the Avon River 73% of total flow is contributed by quick flow and 27% is contributed by baseflow. For the two gauges in the Karuah River, the BFI value is 0.34 for the Mammy Johnsons River at Crossing, and is 0.40 for the Karuah River at Booral (Figure 33), which is lower than that for the Gloucester River.

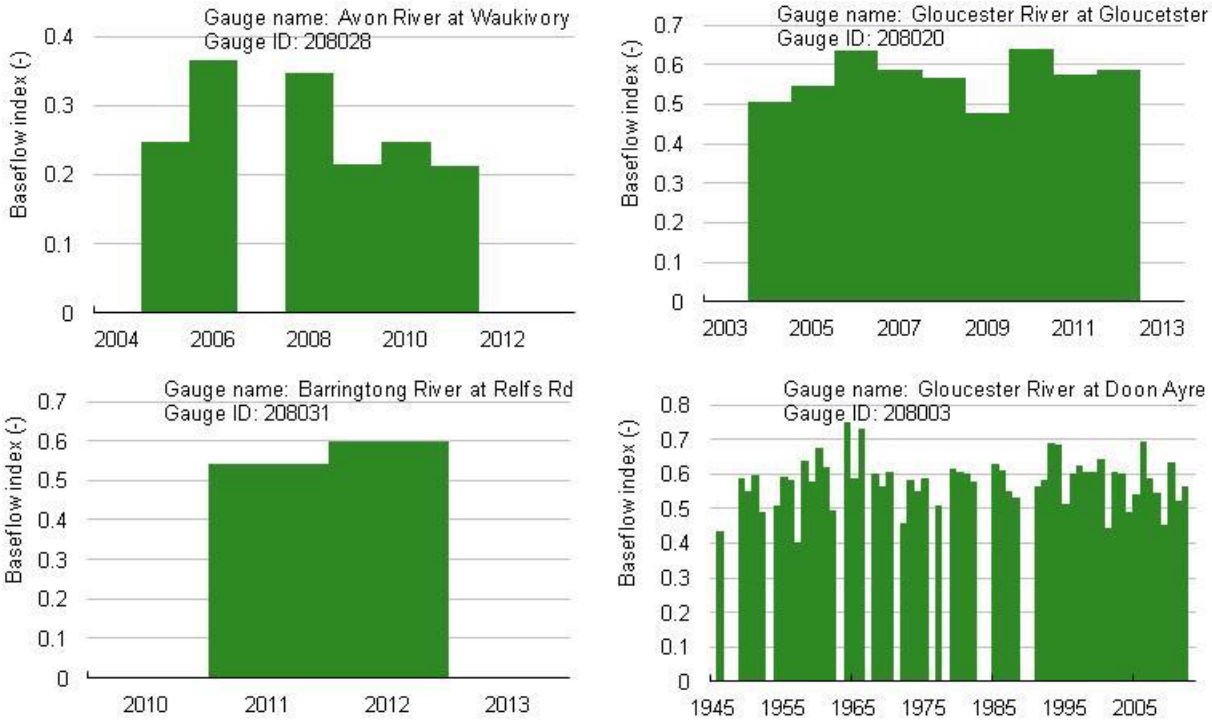


Figure 32 Baseflow index (annual baseflow divided by annual total flow) time series for the four gauges in the Gloucester River

Gaps represent missing annual flow data.

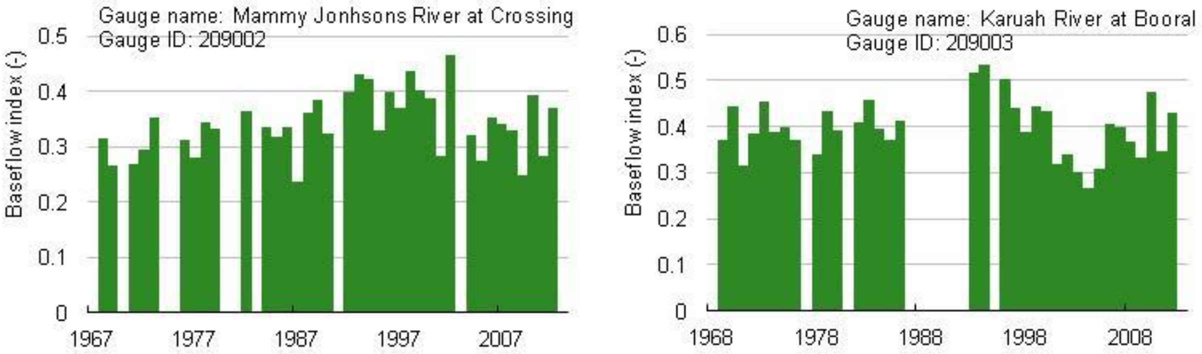


Figure 33 Baseflow index time series for the two gauges in the Karuah River

Gaps represent missing annual flow data.

1.1.5.4 *Water sharing plans*

To maintain and protect low flows for environmental and ecological purposes, the New South Wales government established water sharing plans (WSPs) for the state-unregulated rivers under *the New South Wales Water Management Act 2000*. These WSPs are reviewed every ten years. The Avon River, Gloucester River and Barrington River are protected by the *Lower north coast unregulated and alluvial plan for 2009 to 2019* (DPI, 2009). It requires water to be available to meet all competing environmental and extractive needs, based on climate conditions and river flows, and also requires the entire Lower North Coast WSP area meeting the long-term average annual extraction limit. The rules in the plan determine when licence holders can and cannot pump on a daily basis. The plan also determines where trade of water licences can occurs within the WSP area. As one of the 20 first-stage implemented WSPs, the Karuah River WSP has been applied to the Karuah River and its tributaries since 1 July 2004, and will expire on 30 June 2014 (DIPNR, 2004). After expiring it will be merged into the *Lower north coast unregulated and alluvial plan*. Currently, the Karuah River WSP area is divided into five management zones. At the start of the plan, 3.36 GL/year was accessed by 64 licences, of which, about 3.0 GL/year was for irrigation, 320 ML/year for towns, 25 ML per year for stock and 100 ML/year for domestic and farming purposes (DIPNR, 2004). However, the extremely dry conditions since the WSP commenced have meant that water use has been well below the extraction limit set in the plan (DWE, 2009). Furthermore, there had been a less than 4% increase in access licences for the Karuah River in 2004 to 2008.

References

AGL Energy Limited (2012) Gloucester coal seam gas project irrigation project: Ecological assessment.

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

DIPNR (2004) A Guide to the Water Sharing Plan for the Karuah River Water Source. NSW Department of Infrastructure, Planning and Natural Resources, Taree.

DPI (2009) Water sharing plan: Lower North Coast Unregulated and Alluvial – guide. New South Wales Department of Primary Industries, Office of Water, Sydney.

DWE (2009) Water sharing in unregulated rivers: progress report 2004 to 2008. NSE Department of Water & Energy, Sydney

Gilbert and Associates (2010) Duralie Extension Project: Environmental Assessment – Appendix A (Surface Water Assessment). Consultants report for Duralie Coal Pty Ltd, Duralie Extension Project Environmental Assessment (EPBC Act Referral 2010/5396). Viewed 4 February 2014, <www.gloucestercoal.com.au/documents/Enviro_EAD_DCM_2010_Appendix_A_Surface%20Water%20Assessment.pdf>.

Gloucester Shire Council (2004) Gloucester flood study - supplementary report.

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

Lyne V and Hollick M (1979) Stochastic time-variable rainfall-runoff modelling. Institute of Engineers Australia National Conference, 89-93.

Parsons Brinckerhoff (2012) Phase 2 Groundwater Investigations – Stage 1 Gas Field Development Area: Gloucester Gas Project, Technical report by Parsons Brinkerhoff Australia Pty Limited for AGL Upstream Investments Pty Ltd. *Parsons Brinckerhoff Australia Pty Limited*, Sydney. Viewed 12 Aug 2013, <agk.com.au/gloucester/assets/pdf/PB%20Gloucester%20Groundwater%20Report%20Phase%202%20Text.pdf>.

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

1.1.6 Surface water – groundwater interactions

Summary

Surface water – groundwater interactions in the Gloucester subregion are considered to be relatively minor. Interactions occur primarily within shallow sandy and clayey surface deposits adjacent to existing streams and rivers. Stream gauging data and groundwater modelling indicate that Avon River and Dog Trap Creek are gaining streams under most conditions.

1.1.6.1 Connectivity mapping

The majority of surface water – groundwater interactions in the Gloucester subregion are considered to occur within the alluvial deposits adjacent to major creeks and rivers (Parsons Brinckerhoff, 2013a). The alluvium typically comprises a layer of clay 3 to 4 m thick, overlying 8 to 12 m of coarse sands and poorly mixed gravels, and is not expected to exceed 15 m total depth. The system as a whole is an unconfined to semi-confined aquifer. It is heterogeneous with highly variable conductivity, but is overall quite permeable with rapid recharge, throughflow and discharge. The average hydraulic conductivity is 10 m/d, with a range of 0.3 to 100 m/d (Parsons Brinckerhoff, 2013b).

Hydrographs from bores drilled and screened in the alluvium show a response to high rainfall and streamflow events, and the ponding associated with these events. Some observations of the vertical head gradients indicate that recharge to the alluvium is highest at the margins of the geological basin (Parsons Brinckerhoff, 2013a). This is due to surface runoff from the elevated and rocky areas there. Due to the heterogeneous nature of the alluvium, bore hydrograph responses can be divided into two broad groups. In the relatively more permeable areas there is a rapid rise in response to recharge and a steep recession to previous levels occurs within one or two months. In the less permeable areas that have greater clay content and semi-confined conditions, hydrographs respond rapidly when recharge passes a threshold, then recede slowly over several months, sometimes not fully recovering before the next major event (Parsons Brinckerhoff, 2013a).

Stream gauging data, when compared with nearby groundwater level data, indicate that the Avon River and Dog Trap Creek are gaining streams under most conditions. Adjacent bore water levels are consistently one to two metres above the stream level indicating the streams are discharge features for shallow groundwater in the local alluvium (Parsons Brinckerhoff, 2013b). Both upward and downward gradients were observed in nested bores in the Stratford area, indicating the possibility of both upward and downward leakage between the alluvium and the shallow weathered rock aquifer. Due to the low permeability of the shallow rock aquifer, any contribution to surface water was considered to be only a minor component (Parsons Brinckerhoff, 2013a). Using a five-layer MODFLOW model, Parsons Brinckerhoff (2013a) estimated a net upward flux from the shallow rock aquifer to the alluvium in the Gloucester subregion of 1.7 GL/yr.

References

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

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

1.1.7 Ecology

Summary

The Gloucester subregion lies within the Hunter Local Land Services (LLS) region and within the Karuah-Manning subregion of the NSW North Coast bioregion designated by the Interim Biogeographic Regionalisation for Australia (IBRA; SEWPaC, 2012). The Karuah-Manning is largely comprised of coastal barrier sands, estuarine plains and alluvial deposits, and supports significant wetlands and World Heritage areas. Of particular note are the Barrington Tops National Park from which many of the rivers that run through the subregion originate and the Port Stephens estuary into which the Karuah River feeds. Very little of the subregion lies within conservation reserves and the subregion has been extensively cleared for agricultural, horticultural and urban use. A significant nature conservation area lies south of the Gloucester subregion along the eastern edge of the Karuah National Park. There are twelve endangered communities and four endangered species listed under various state and Commonwealth Acts that may be present within the Karuah-Manning subregion and therefore within the Gloucester subregion. Much of the remnant vegetation in the Gloucester subregion lies within areas classified as ‘Other minimal use’ or ‘Water’, and is mainly distributed along the margins of the Gloucester subregion, on or adjacent to hill slopes or along watercourses. No groundwater dependent ecosystems have been identified within the Gloucester subregion.

1.1.7.1 Ecological systems

The Gloucester subregion lies within the Hunter Local Land Services (LLS) region, which evolved from the Hunter-Central Rivers Catchment Management Authority (CMA) on 1 January 2014. At the time of writing, LLS region boundaries were not available so the CMA boundary and following description (DECCW, 2010a) was used. The CMA covers an area of approximately 3.7 million hectares on the east coast of NSW, and extends 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 major ‘natural bioregions’ of the CMA – as classified by the Interim Biogeographic Regionalisation of Australia (IBRA), (Environment Australia, 2000) – are NSW North Coast (47.4%), Sydney Basin (39.8%) and Brigalow Belt South (9.4%). Smaller areas of the CMA lie within the New England Tableland, NSW South Western Slopes and Nandewar IBRA bioregions (Somerville, 2009, p. 3). 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. Intact native vegetation covers over 50% of the CMA and 658 species of terrestrial vertebrate have been recorded in the region. There are one critically endangered, one vulnerable and 24 endangered ecological communities, and 276 threatened species in the CMA.

The CMA contains two World Heritage-listed areas – the Greater Blue Mountains and the Barrington Tops – as well as internationally significant wetlands listed by 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, 2010c) reported 126 species of flora and 152 species of fauna (including two fish species) within the Hunter-Central Rivers CMA that are listed under either NSW's *Threatened Species Conservation Act 1995* (the TSC Act) or *Fisheries Management Act 1994.* However, a search with the *Threatened and Protected Species Record Viewer* (DPI, 2013) revealed no threatened or protected aquatic species within the Hunter-Central Rivers CMA. It is possible that 56 threatened fauna species and twelve threatened flora species listed under the TSC Act occur in the Gloucester subregion (Table 8). Table 8 also includes 18 threatened fauna species and eight threatened flora species listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*.

Table 8 Potentially threatened species within the Gloucester subregion

Number of species listed under the *Threatened Species Conservation Act 1995* or *Environment Protection and Biodiversity Conservation Act* 1999 that have been recorded or have the potential to occur in the Gloucester subregion in New South Wales

	Vulnerable	Endangered	Critically endangered	Total
Threatened Species Conservation Act 1995				
Fauna				
Mammals	22	1	0	23
Birds	21	6	1	28
Amphibians	0	3	0	3
Reptiles	1	1	0	2
Flora				
Plants	7	5	0	12
Total	51	16	1	68
Environment Protection and Biodiversity Conservation Act 1999				
Fauna				
Mammals	6	2	0	8
Birds	2	4	0	6
Amphibians	2	1	0	3
Reptiles	1	0	0	1
Flora				
Plants	6	2	0	8
Total	17	9	0	26

1.1.7.2 Terrestrial species and communities

The Gloucester subregion lies almost entirely within the IBRA Karuah-Manning subregion within the IBRA NSW North Coast (NNC) bioregion and also within the North Coast botanical region described by Harden (1990). The vegetation of the IBRA NNC is briefly described as: humid; hills, coastal plains and sand dunes; *Eucalyptus – Lophostemon confertus* tall open forests, *Eucalyptus* open forests and woodlands, subtropical rainforest (often with *Araucaria cunninghamii* and *Melaleuca quinquenervia)*, wetlands and heaths (Environment Australia, 2000).

The IBRA Karuah-Manning subregion is located in the south of the IBRA NNC bioregion and is largely comprised of coastal barrier sands, estuarine plains and alluvial deposits (DECCW, 2009). Over half of this IBRA subregion has been cleared but it still supports significant wetlands, coastal sand heaths and woodlands from Fullerton Cove north to Port Stephens. The following description of the vegetation in the IBRA Karuah-Manning subregion is based on NSW National Parks and Wildlife Service (NPWS, 2003). In the south of the IBRA NNC bioregion on the Barrington Plateau, cool temperate species are common and the fertile basaltic soils support rainforest including Antarctic beech (*Nothofagus moorei*) which forms a two tiered forest structure. Here it occurs as the only overstorey species with a fern understorey. Rainforests are also sometimes found inhabiting protected pockets where plant nutrients have accumulated in litter. In contrast, eucalypt vegetation communities mainly occur on granitic soils; dominant species include blackbutt (*Eucalyptus pilularis*), Sydney blue gum (*Eucalyptus saligna*), spotted gum (*Eucalyptus maculata*), grey gum (*Eucalyptus punctata*), forest red gum (*Eucalyptus tereticornis*), red bloodwood (*Corymbia gummifera*), brush box (*Tristania conferta*) and white mahogany (*Eucalyptus acmenoides).*

In the coastal dunes, coastal tea tree (*Leptospermum laevigatum*) and coastal wattle (*Acacia longifolia*) occur near the beach, with some areas of beach she-oak (*Casuarina equisetifolia*), snappy gum (*Eucalyptus racemosa*), blackbutt, dwarf red bloodwood and bastard mahogany (*Eucalyptus umbra*). Banksia and bangalow palms are found in the dunes and heath and paperbark swamps occur behind the dunes and near the lagoons. Where sufficient nutrients have accumulated, rare patches of rainforest species may also be found.

Almost none of the Gloucester subregion lies within conservation reserves compared to 16% of the IBRA Karuah-Manning subregion. The majority of the Gloucester subregion is cleared (see Section 1.1.2). The major land uses are grazing on modified pastures, intensive urban use or other commercial uses. Much of the remnant vegetation in the Gloucester subregion lies within areas classified as ‘Other minimal use’ or ‘Water’, which are mainly distributed along the margins of the subregion, on or adjacent to hill slopes, or along watercourses. A significant nature conservation area lies south of the subregion along the eastern edge of the Karuah National Park. Much of the vegetation is eucalypt forest (see Section 1.1.2), with open eucalypt forest and grassy understorey being the single most common natural vegetation type within the subregion (Table 9). Much of the riparian zone has been cleared from the banks of the Gloucester River north of Gloucester along the Manning River. In contrast, the banks of the Karuah River from Stroud to Karuah are well-vegetated. The section of Karuah National Park within the subregion contains eucalypt forest with a broadleaf/fern or woody understorey and substantial areas of mangroves.

Table 9 Vegetation of the Gloucester subregion

Comparative areas of vegetation within the Gloucester subregion and the IBRA* Karuah-Manning subregion of the IBRA NSW North Coast bioregion.

	Gloucester subregion % area	Gloucester subregion area (ha)	IBRA* Karuah-Manning subregion % area	IBRA* Karuah-Manning subregion area (ha)
Tropical or subtropical rainforest	0.0		1.1	4935
Eucalyptus (tall) open forest with a dense broad-leaved and/or tree-fern understorey (Eucalyptus open forests with a shrubby wet sclerophyll understorey)	3.6	1659	15.7	68,158
Eucalyptus open forests with a shrubby understorey	2.0	936	6.4	27,732
Eucalyptus open forests with a grassy understorey	11.7	5389	27.2	117,907
Eucalyptus woodlands with a shrubby understorey	1.8	849	3.2	13,889
Melaleuca open forests and woodlands	0.0	5	0.8	3273
Casuarina and Allocasuarina forests and woodlands	0.0		0.2	632
Heath	0.0		1.4	6188
Other shrublands	0.0		0.1	486
Mangroves	0.4	203	0.2	826
Naturally bare, sand, rock, claypan, mudflat	0.0		0.2	802
Freshwater, dams, lakes, lagoons or aquatic plants	1.1	484	5.3	22,772
Eucalyptus tall open forest with a fine-leaved shrubby understorey	1.7	794	9.7	42,195
Eucalyptus tall open forests and open forests with ferns, herbs, sedges, rushes or wet tussock grasses	0.0	4	0.1	368
Sedgelands, rushes or reeds	0.0		0.4	1605
Unclassified native vegetation	0.0		0.5	1987
Cleared, non-native vegetation, buildings	77.5	35,836	27.2	117,824
Unknown/No data	0.2	103	0.5	2291
Total	100.0	46,262	100.0	433,870

* Interim Biogeographic Regionalisation of Australia

Sixteen threatened ecological communities are listed under the TSC Act. One is listed as critically endangered and four are endangered (Table 10), and may be present within the IBRA Karuah-Manning subregion. This includes twelve vegetation and two animal threatened ecological communities. Five of the vegetation and one of the animal threatened ecological communities are also listed under the EPBC Act, including three listed as critically endangered (Table 10).

Table 10 Conservation status of threatened ecological communities found in the IBRA* Karuah-Manning subregion

As listed under NSW's *Threatened Species Conservation Act 1995* (the TSC Act) or the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act).

Community name	TSC Act	EPBC Act
Coastal Saltmarsh in the New South Wales North Coast, Sydney Basin and South East Corner Bioregions / Subtropical and Temperate Coastal Saltmarsh	endangered	vulnerable
Eucalyptus seeana population in the Greater Taree local government area	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
Hunter Lowland Redgum Forest in the Sydney Basin and New South Wales North Coast Bioregions	endangered	not listed
Littoral Rainforest in the New South Wales North Coast, Sydney Basin and South East Corner Bioregions / Littoral Rainforest and Coastal Vine Thickets of Eastern Australia	endangered	critically endangered
Lowland Rainforest in the NSW North Coast and Sydney Basin Bioregions / Lowland Rainforest of Subtropical Australia	endangered	critically endangered
Lowland Rainforest on Floodplain in the New South Wales North Coast Bioregion / Lowland Rainforest of Subtropical Australia	endangered	critically endangered
Rhizanthella slateri (Rupp) M.A. Clem. & Cribb in the Great Lakes local government area / *Rhizanthella slateri* — Eastern Underground Orchid	endangered	endangered
River-Flat Eucalypt Forest on Coastal Floodplains of the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	endangered	not listed
Subtropical Coastal Floodplain Forest of the New South Wales North Coast Bioregion	endangered	not listed
Swamp Oak Floodplain Forest of the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	endangered	not listed
Swamp Sclerophyll Forest on Coastal Floodplains of the New South Wales North Coast, Sydney Basin and South East Corner Bioregions	endangered	not listed
Sydney Freshwater Wetlands in the Sydney Basin Bioregion	endangered	not listed
Themeda grassland on seacliffs and coastal headlands in the NSW North Coast, Sydney Basin and South East Corner Bioregions	endangered	not listed
Emu (Dromaius novaehollandiae) population in the New South Wales North Coast Bioregion and Port Stephens local government area	endangered	not listed
Koala, Hawks Nest and Tea Gardens population / Koala (combined populations of Queensland, New South Wales and the Australian Capital Territory)	endangered	vulnerable

* Interim Biogeographic Regionalisation of Australia.

Source data: <http://www.environment.nsw.gov.au/threatenedSpeciesApp/AreaHabitatSearch.aspx?cmaname=Hunter-Central+Rivers>.

There are 56 threatened fauna and twelve threatened flora species listed under the TCS Act that may occur within the Gloucester subregion (Table 11). This includes 18 threatened fauna and eight threatened flora species that are listed as vulnerable or endangered under the EPBC Act.

Table 11 Conservation status of threatened flora and fauna species recorded in the Gloucester bioregion

As listed under NSW's Threatened Species Conservation Act 1995 (the TSC Act) or the Commonwealth's Environment Protection and Biodiversity Conservation Act 1999 (the EPBC Act) that have been recorded in or that may occur in the Gloucester subregion. Source data: <http://www.bionet.nsw.gov.au/>.

Common name	Species name	TSC Act	EPBC Act
Broad-headed Snake	*Hoplocephalus bungaroides*	Endangered	Vulnerable
Stephens' Banded Snake	*Hoplocephalus stephensii*	Vulnerable	Not listed
Green and Golden Bell Frog	*Litoria aurea*	Endangered	Vulnerable
Stuttering Frog	*Mixophyes balbus*	Endangered	Vulnerable
Giant Barred Frog	*Mixophyes iteratus*	Endangered	Endangered
Magpie Goose	*Anseranas semipalmata*	Vulnerable	Marine
Australasian Bittern	*Botaurus poiciloptilus*	Vulnerable	Endangered
Bush Stone-curlew	*Burhinus grallarius*	Endangered	Not listed
Gang-gang Cockatoo	*Callocephalon fimbriatum*	Vulnerable	Not listed
Glossy Black-Cockatoo	*Calyptorhynchus lathami*	Vulnerable	Not listed
Spotted harrier	*Circus assimilis*	Vulnerable	Not listed
Brown Treecreeper	*Climacteris picumnus*	Vulnerable	Not listed
Barred Cuckoo-shrike	*Coracina lineata*	Vulnerable	Not listed
Eastern Bristlebird	*Dasyornis brachypterus*	Endangered	Endangered
Black-necked Stork	*Ephippiorhynchus asiaticus*	Endangered	Not listed
Red Goshawk	*Erythrotriorchis radiatus*	Critically Endangered	Vulnerable
White-throated Needletail	*Hirundapus caudacutus*	Not listed	Marine, Migratory
Comb-crested Jacana	*Irediparra gallinacea*	Vulnerable	Not listed
Black Bittern	*Ixobrychus flavicollis*	Vulnerable	Not listed
Swift Parrot	*Lathamus discolor*	Endangered	Endangered
Square-tailed Kite	*Lophoictinia isura*	Vulnerable	Not listed
Black-chinned Honeyeater	*Melithreptus gularis*	Vulnerable	Not listed
Rainbow Bee-eater	*Merops ornatus*	Not listed	Marine, Migratory
Black-faced Monarch	*Monarcha melanopsis*	Not listed	Marine, Migratory
Turquoise Parrot	*Neophema pulchella*	Vulnerable	Not listed
Barking Owl	*Ninox connivens*	Vulnerable	Not listed
Powerful Owl	*Ninox strenua*	Vulnerable	Not listed
Grey-crowned Babbler	*Pomatostomus temporalis*	Vulnerable	Not listed
Wompoo Fruit-Dove	*Ptilinopus magnificus*	Vulnerable	Not listed
Rose-crowned Fruit-Dove	*Ptilinopus regina*	Vulnerable	Not listed

Common name	Species name	TSC Act	EPBC Act
Superb Fruit-Dove	*Ptilinopus superbus*	Vulnerable	Marine
Speckled Warbler	*Pyrrholaemus saggitatus*	Vulnerable	Not listed
Rufous Fantail	*Rhipidura rufifrons*	Not listed	Marine, Migratory
Painted Snipe	*Rostratula benghalensis*	Endangered	Vulnerable
Masked Owl	*Tyto novaehollandiae*	Vulnerable	Not listed
Sooty Owl	*Tyto tenebricosa*	Vulnerable	Not listed
Regent Honeyeater	*Xanthomyza phrygia*	Endangered	Endangered
Large-eared Pied Bat	*Chalinolobus dwyeri*	Vulnerable	Vulnerable
Spotted-tailed Quoll	*Dasyurus maculatus*	Vulnerable	Endangered
Eastern False Pipistrelle	*Falsistrellus tasmaniensis*	Vulnerable	Not listed
Golden-tipped Bat	*Kerivoula papuensis*	Vulnerable	Not listed
Parma Wallaby	*Macropus parma*	Vulnerable	Not listed
Little Bent-wing Bat	*Miniopterus australis*	Vulnerable	Not listed
Eastern Bentwing-bat	*Miniopterus schreibersii oceanensis*	Vulnerable	Not listed
Eastern Free-tail Bat	*Mormopterus norfolkensis*	Vulnerable	Not listed
Large-footed Myotis (or Southern Myotis)	*Myotis macropus*	Vulnerable	Not listed
Yellow-bellied Glider	*Petaurus australis*	Vulnerable	Not listed
Squirrel Glider	*Petaurus norfolcensis*	Vulnerable	Not listed
Brush-tailed Rock-wallaby	*Petrogale penicillata*	Vulnerable	Vulnerable
Brush-tailed Phascogale	*Phascogale tapoatafa*	Vulnerable	Not listed
Koala	*Phascolarctos cinereus*	Vulnerable	Vulnerable
Common Planigale	*Planigale maculata*	Vulnerable	Not listed
Long-nosed Potoroo	*Potorous tridactylus*	Vulnerable	Vulnerable
New Holland Mouse, Pookila	*Pseudomys novaehollandiae*	Vulnerable	Endangered
Hastings River Mouse, Koontoo	*Pseudomys oralis*	Endangered	Vulnerable
Grey-headed Flying-fox	*Pteropus poliocephalus*	Vulnerable	Vulnerable
Yellow-bellied Sheath-tail Bat	*Saccolaimus flaviventris*	Vulnerable	Not listed
Greater Broad-nosed Bat	*Scoteanax rueppellii*	Vulnerable	Not listed
Red legged pademelon	*Thylogale stigmatica*	Vulnerable	Not listed
Eastern Cave Bat	*Vespadelus troughtoni*	Vulnerable	Not listed
Charmhaven Apple	*Angophora inopina*	Vulnerable	Vulnerable

Common name	Species name	TSC Act	EPBC Act
Trailing Woodruff	*Asperula asthenes*	Vulnerable	Vulnerable
Netted Bottle Brush	*Callistemon linearifolius*	Vulnerable	Not listed
Leafless Tongue-orchid	*Cryptostylis hunteriana*	Vulnerable	Vulnerable
White-flowered Wax Plant	*Cynanchum elegans*	Endangered	Endangered
Slaty Red Gum	*Eucalyptus glaucina*	Vulnerable	Vulnerable
Guthrie's Grevillea	*Grevillea guthrieana*	Endangered	Endangered
Small-flower grevillea	*Grevillea parviflora subsp. parviflora*	Vulnerable	Vulnerable
Scant Pomaderris	*Pomaderris queenslandica*	Endangered	Not listed
Black-eyed Susan	*Tetratheca juncea*	Vulnerable	Vulnerable
Zannichellia palustris	*Zannichellia palustris*	Endangered	Not listed

1.1.7.3 *Aquatic species and communities*

The IBRA Karuah-Manning and adjacent subregions support large areas of significant wetlands, coastal sand heaths and woodlands (DECCW, 2009). Major rivers in the IBRA Karuah-Manning subregion include the Manning, Gloucester and Karuah rivers (see Section 1.1.5). The tributaries of the Manning River rise immediately north of the Barrington Tops at an altitude of more than 1400 m above sea level. It is fed from the south by the Barrington, Gloucester and Avon rivers which flow through and drain the northern parts of the Gloucester subregion.

The Karuah River drains south from the lower slopes (600 m above sea level) of the Barrington Tops, past the Karuah National Park and into the north-western corner of the Port Stephens estuary (DECCW, 2010b). The Karuah River is also fed by the Wards and Mammy Johnsons rivers which also flow through the subregion. Together these rivers drain the southern parts of the subregion. The Port Stephens estuary supports 22 migratory and ten breeding shorebird species. Two endangered and eight vulnerable shorebird species listed under the TSC Act have been recorded at Port Stephens. The estuary, together with rivers, creeks and tributaries under tidal influence, are included in the Port Stephens-Great Lakes Marine Park. The estuaries of the NNC are dominated by mangrove communities composed of *Avicennia marina*, *Aegiceras coniculatum*, *Exoecaria agallocha* and saltmarsh species. Vegetation on freshwater margins consists of swamp oak (*Casuarina glauca*) and paperbark (*Melaleuca quinquenervia*) and flooded gum (*Eucalyptus grandis*) is prevalent on alluvial river flats.

The NSW Office of Water and the NSW Office of Environment and Heritage have used a risk analysis framework (Serov et al., 2012) to identify groundwater-dependent ecosystems overlying New South Wales coastal groundwater sources. The conceptual framework classifies groundwater-dependent ecosystems based on the degree on which they depend on groundwater access and their priority for management actions. It allows potential and actual impacts of proposed activities on groundwater dependent ecosystems to be assessed in accordance with the *Water Management Act 2000 (NSW)* and other relevant legislation. The Gloucester subregion contains no groundwater dependent ecosystems identified within this framework. One wetland has been identified in proximity to the subregion (Figure 34) (Wallaroo wetlands about 4 km north-west by west of Karuah) along with several karst wetlands.

The water sharing plan (WSP) for the Lower North Coast area covers the Manning Extraction Management Unit (State of NSW through the Department of Water and Energy, 2009). Within this Unit, the Upper Gloucester River Management Zone lies within the section of the Gloucester subregion north of Craven, and covers the Avon and Upper Gloucester rivers, amongst others. The section of the subregion south of Craven is covered by a separate WSP for the Karuah River Water Source (DIPNR, 2004), which covers the Karuah, Mammy Johnsons and Wards rivers, amongst others. The WSP for the Lower North Coast area identifies six species of endangered frogs and two species of endangered birds in the Lower Barrington/Gloucester and Gloucester Water Sources; four species of endangered frog and one species of endangered bird in the Avon Water Source; and four species of endangered frog and two species of endangered birds in the Central and Lower Karuah Water Sources.

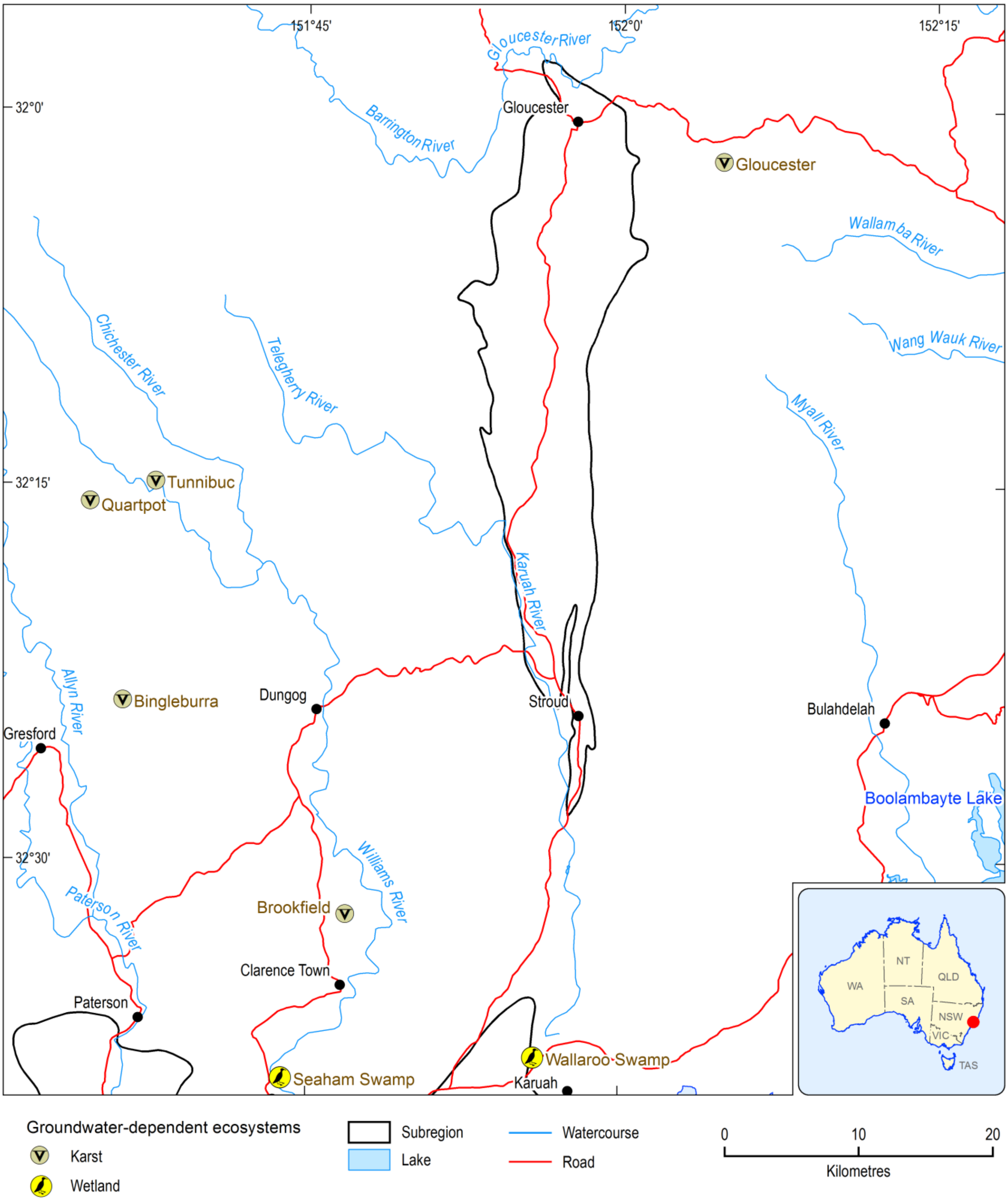


Figure 34 Distribution of groundwater-dependent ecosystems adjacent to the Gloucester subregion

References

Burbidge NT (1960) Phytogeography of the Australian Region. Australian Journal of Botany 8(2), 75-211.

DECCW (2009) Lower Hunter Regional Conservation Plan. Department of Environment, Climate Change and Water NSW, Sydney.

DECCW (2010a) State of the Catchments 2010: Overview Hunter-Central Rivers region. Department of Environment, Climate Change and Water, Sydney South.

DECCW (2010b) State of the Catchments 2010: Riverine ecosystems Hunter-Central Rivers region. Department of Environment, Climate Change and Water, Sydney South.

DECCW (2010c) State of the Catchments 2010: Threatened species Hunter-Central Rivers region. Department of Environment, Climate Change and Water, Sydney South.

DIPNR (2004) A Guide to the Water Sharing Plan for the Karuah River Water Source. NSW Department of Infrastructure, Planning and Natural Resources, Taree.

DPI (2013) Threatened and protected species – records viewer. Viewed 6 March 2014, <http://www.dpi.nsw.gov.au/fisheries/species-protection/records/viewer>. NSW Department of Primary Industries, Sydney.

Environment Australia (2000) Revisions of the Interim Biogeographic Regionalisation Australia (IBRA) and development of version 5.1:summary report. Environment Australia, ACT.

Harden GJ (1990) Flora of New South Wales. Revised Edition Volume 1. Royal Botanic Gardens and Domain Trust, Sydney., University of New South Wales Press.

McCauley A (2006) Vegetation Survey and Mapping of the Hunter, Central and Lower North Coast Region of NSW. A report prepared for the Hunter-Central Rivers Catchment Management Authority by the HCCREMS team at the Environment Division of Hunter Councils Inc., NSW. Viewed 18 September 2013, <http://www.hccrems.com.au/RESOURCES/HCCREMS-Publications.aspx>.

NPWS (2003) The Bioregions of New South Wales: their biodiversity, conservation and history. NSW National Parks and Wildlife Service, Hurtsville.

Serov P, Kuginis L and Williams J (2012) Risk Assessment Guidelines for Groundwater Dependent Ecosystems, Volume 1. The Conceptual Framework. NSW Office of Water (Department of Primary Industries) and Office of Environment and Heritage (Department of Premiers and Cabinet), Sydney, Australia. Viewed 3 October 2013, <http://www.water.nsw.gov.au/Water-management/Water-availability/Risk-assessment/Groundwater-dependent-ecosystems/Risk-assessment-guidelines-for-groundwater-dependent-ecosystems>.

SEWPaC (2012) Interim Biogeographic Regionalisation for Australia (IBRA), Version 7. Australian Government Department of Sustainability Environment Water Population and Communities, Canberra.

Somerville M (2009) Hunter, Central and Lower North Coast Vegetation Classification and Mapping Project Volume 1. Vegetation classification technical report. report prepared by HCCREMS / Hunter Councils Environment Division for Hunter-Central Rivers Catchment Management Authority, Tocal, NSW.

State of NSW through the Department of Water and Energy (2009) Water sharing plan - Lower North Coast unregulated and alluvial water sources. <http://www.water.nsw.gov.au/ArticleDocuments/34/wsp_lower_north_coast_guide.pdf.aspx>.

www.bioregionalassessments.gov.au

Australian Government
Department of the Environment
Bureau of Meteorology
Geoscience Australia

CSIRO