Australian Government

BIOREGIONAL ASSESSMENTS

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

Context statement for the Clarence-Moreton bioregion

Product 1.1 from the Clarence-Moreton 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/>.

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Authorship is listed in relative order of contribution.

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Rainforest waterfall in Border Ranges National Park, NSW, 2008.

Credit: Liese Coulter, CSIRO.

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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.

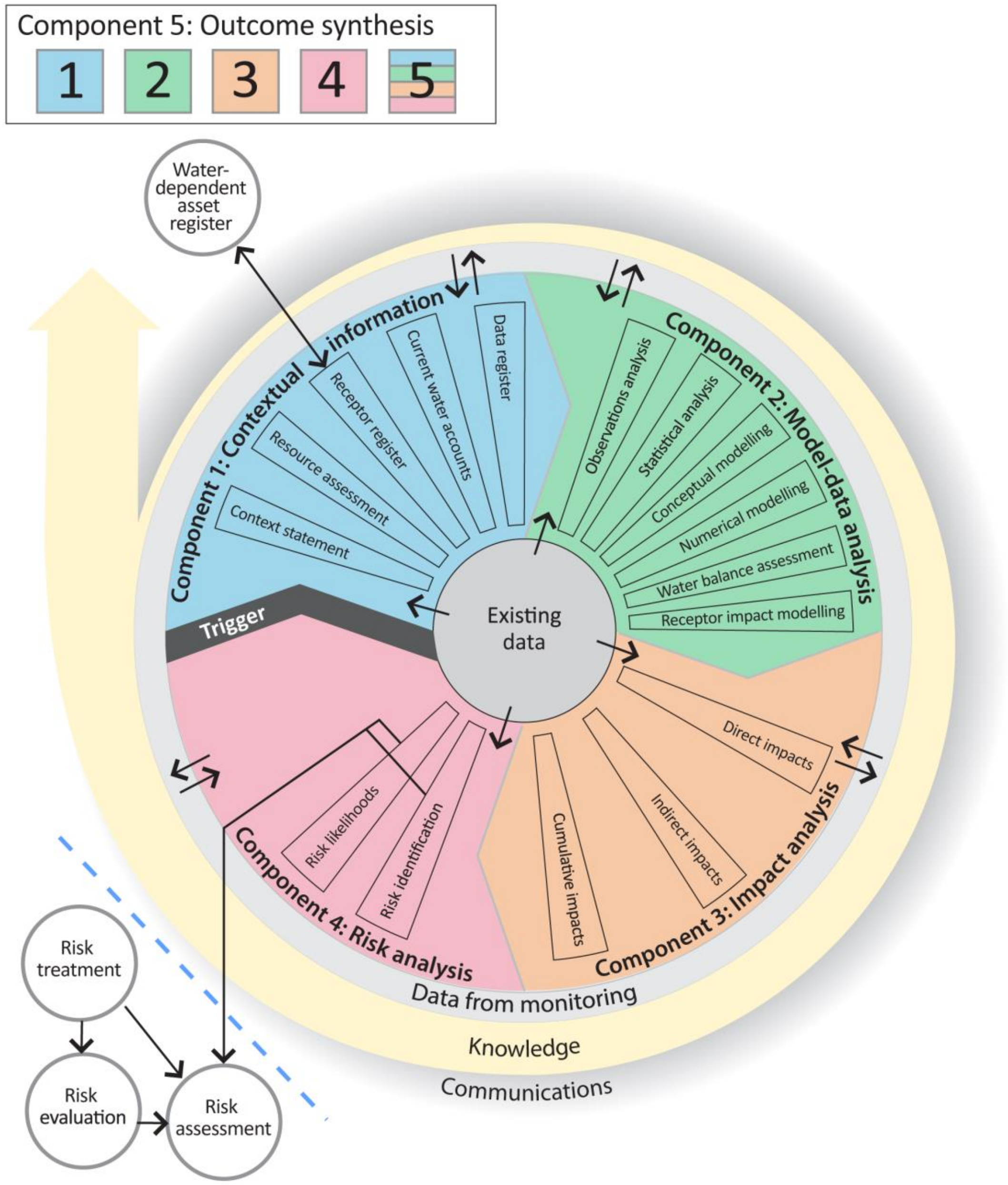

Figure 1 Schematic diagram of the bioregional assessment methodology

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 20. 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 Clarence-Moreton bioregion and two standard parallels of –18.0° and –36.0°.

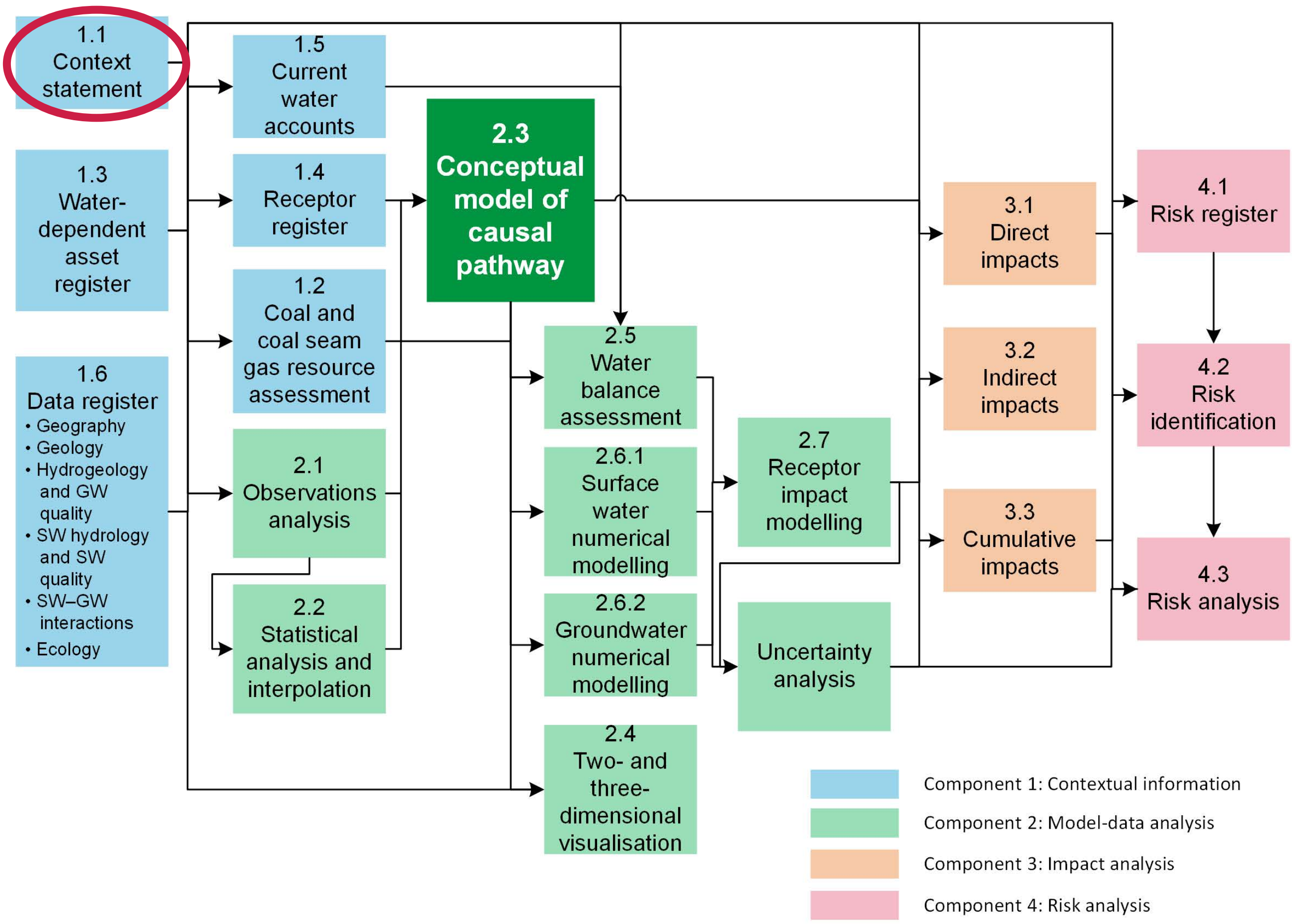

Figure 2 The simple decision tree indicates the flow of information through a bioregional assessment

The red oval indicates the information covered in this report.

Table 1 Technical reports being delivered as part of the Clarence-Moreton Bioregional Assessment

For each subregion in the Clarence-Moreton 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 Clarence-Moreton	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 Clarence-Moreton	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 Clarence-Moreton	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 Clarence-Moreton	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 Clarence-Moreton	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 Clarence-Moreton bioregion

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 and feel is not consistent with those produced in the Assessment. Likewise, results from different sources may use different methods or inconsistent units.

1.1.1 Bioregion

The Clarence-Moreton bioregion is located in north-east New South Wales and south-east Queensland (Figure 3). It covers an area of approximately 24,292 km^2 and adjoins the Northern Inland Catchments bioregion in the north-west.

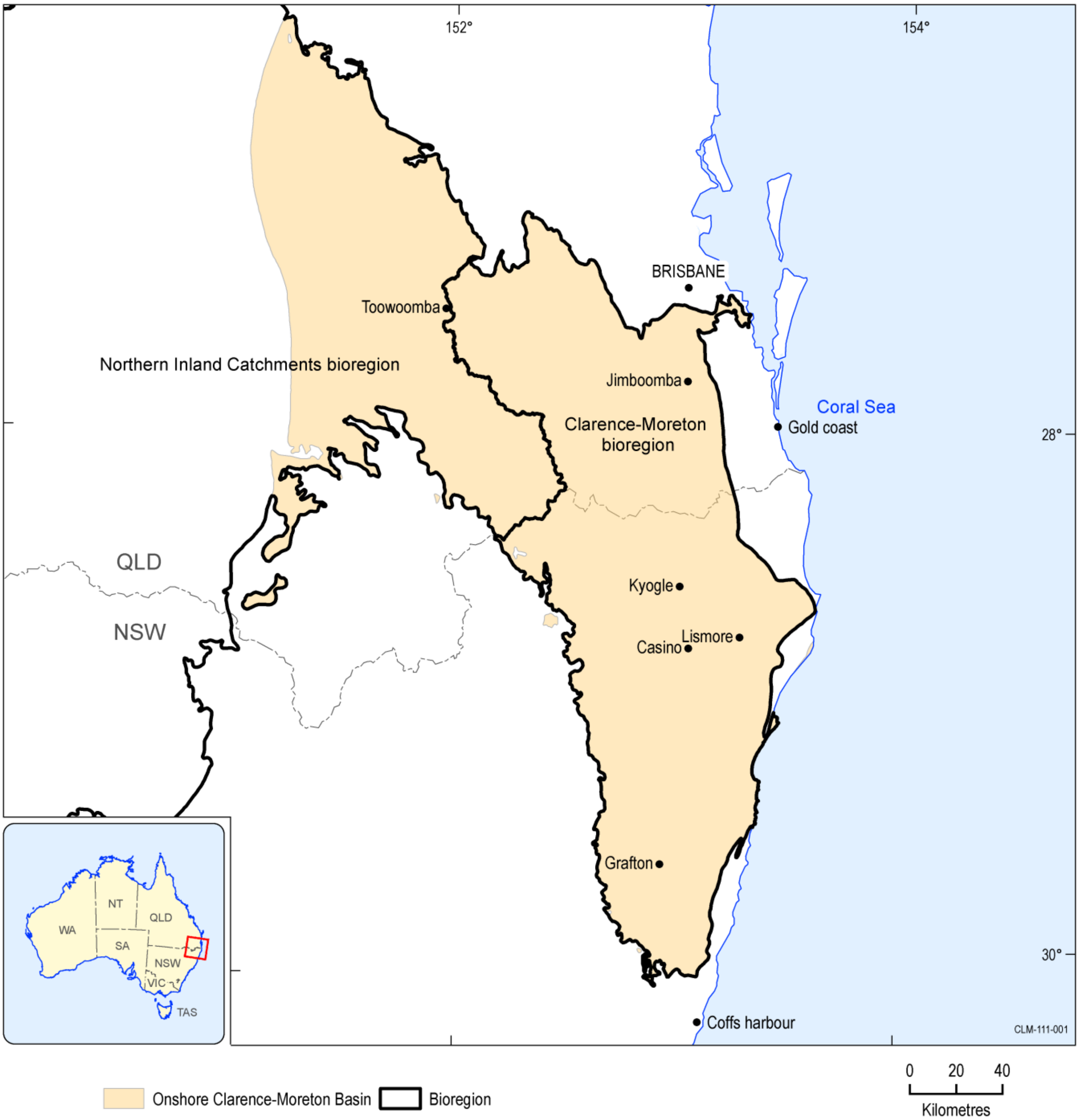

Figure 3 Clarence-Moreton Basin, Clarence-Moreton bioregion and Northern Inland Catchments bioregion

Prominent river basins in the Clarence-Moreton bioregion include the Brisbane river basin (which includes the Lockyer Valley and Bremer river basins) and the Logan-Albert river basin in Queensland, and the Richmond and Clarence river basins in New South Wales.

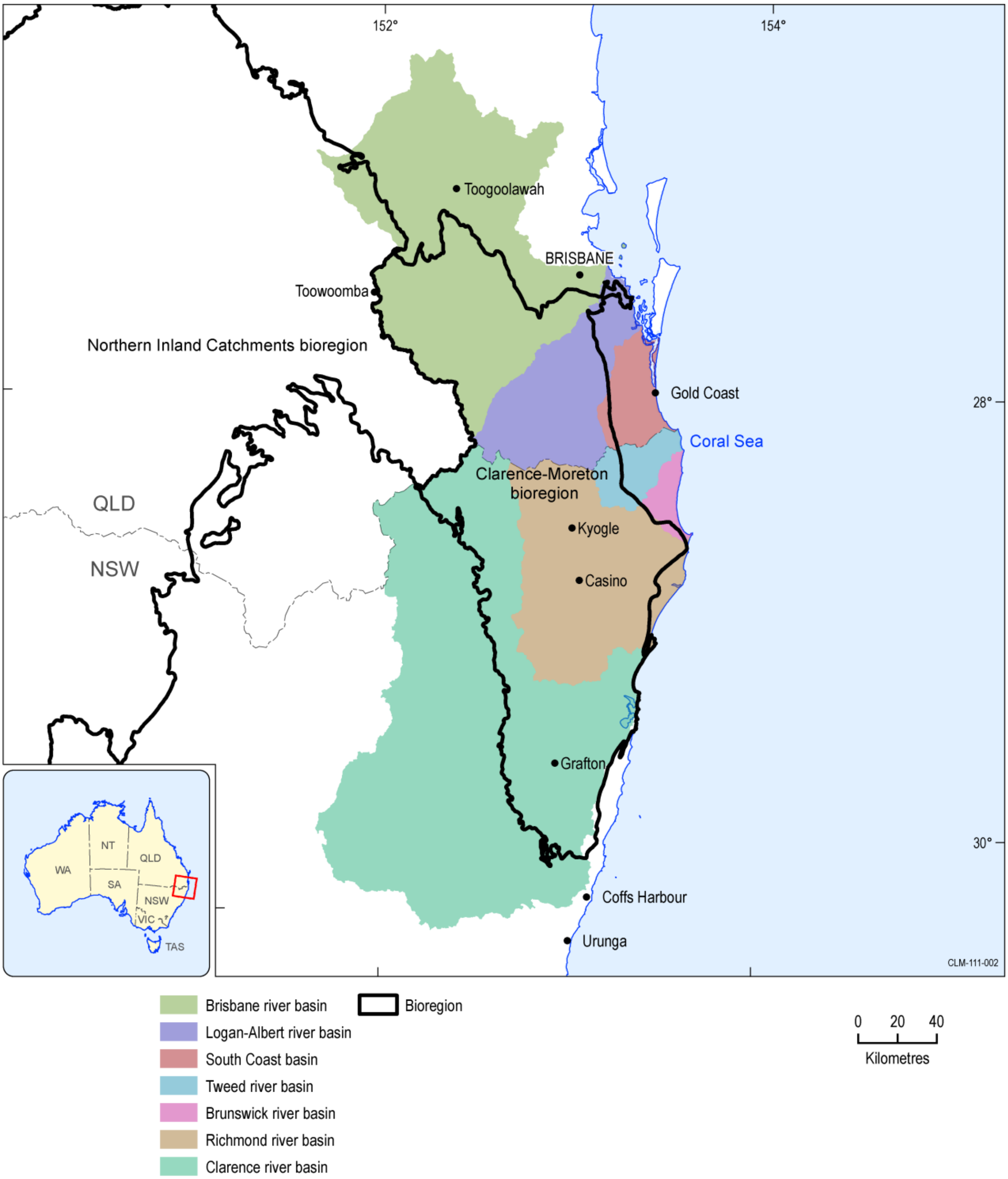

Figure 4 Clarence-Moreton bioregion and river basins

1.1.1.1 Definitions used

The Clarence-Moreton bioregion only includes the eastwards draining part of the Clarence-Moreton Basin (based on surface water flow delineation), comprising the area east of the Great Dividing Range in eastern Australia. The section of the Clarence-Moreton Basin west of the Great Dividing Range forms part of the Northern Inland Catchments bioregion (Figure 3). The Clarence-Moreton Basin contains substantial coal resources. The major stratigraphic units that have in the past been targeted for coal mining are the Walloon Coal Measures, which extends over most of the basin, and to a lesser extent the Ipswich and Nymboida coal measures (more detail in Section

1.1.3). The Walloon Coal Measures also are the major target in the Clarence-Moreton Basin for coal seam gas exploration.

The boundary between the Clarence-Moreton bioregion and the Northern Inland Catchments bioregion is defined on the basis of an assessment of river basins, coal basins and natural resource boundaries, as outlined in the *Methodology for bioregional assessments of coal seam gas and coal mining development on water resources* (Barrett et al., 2013).

Only those sections of the Clarence river basin and Brisbane river basin which overlap with the Clarence-Moreton Basin are part of the Clarence-Moreton bioregion (Figure 4).

The Clarence-Moreton bioregion includes parts of two natural resource management regions: South East Queensland Catchments and North Coast Local Land Services (Section 1.1.6 and Section 1.1.7).

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 17 December 2013, <www.environment.gov.au/coal-seam-gas-mining/pubs/methodology-bioregional-assessments.pdf>.

1.1.2 Geography

Summary

The Clarence-Moreton bioregion spans across north-east New South Wales and south-east Queensland, covering an area of about 24,292 km^2, approximately 9,500 km^2 of which is in Queensland. In New South Wales it contains much of the Clarence and Richmond river basins, while in south-east Queensland it covers the mid and upper parts of the Logan-Albert river basin, Bremer river basin, Lockyer Valley basin, and parts of the Brisbane river basin.

The population within the boundaries of the bioregion is estimated to be around 500,000. The Clarence-Moreton bioregion includes areas of Bundjalung and Yuggera nations.

The Clarence-Moreton bioregion is economically diverse, with agriculture, forestry and fishing being the main employer in the Lockyer Valley and Kyogle regions whereas retail trade, health care and social assistance represent some of the more typical industries elsewhere.

The largest component of the bioregion is used as grazing of modified pastures and native vegetation. There are extensive areas of wetlands, with 31,000 ha in the Richmond river basin, and 43,000 ha mapped in the Clarence river basin (DLWC, 2000). Soil types in the New South Wales part include the Clarence Sodic Soils, Alstonville Plateau, Casino Alluvials along the Richmond Valley, and North Coast Acid Sulfate Soils mainly in the lower parts of the Clarence and Richmond floodplains. The Queensland part includes large areas of alluvial plains with surrounding undulating hills (Lockyer, Bremer, Warrill Creeks).

The climate of the Clarence-Moreton bioregion falls within the temperate and subtropical climate groupings. The mean annual rainfall varies from 800 to 2716 mm. Rainfall is highest during the warmer months of January to March and lowest during the colder months of July to September.

The largest water supply reservoir in the Clarence-Moreton bioregion is Lake Wivenhoe on the Brisbane River, which is a major water supply reservoir for Brisbane and south-east Queensland. The other storages in the Queensland part of the bioregion are an order of magnitude smaller than Lake Wivenhoe, and include Lake Wyaralong in the Logan river basin, Lake Maroon, Lake Moogerah, Lake Clarendon and Lake Atkinson. The New South Wales part of the bioregion has only small dams such as Toonumbar Dam in the upper Richmond river basin.

1.1.2.1 Physical geography

The Clarence-Moreton bioregion spans several coastal river basins in north-east New South Wales, and south-east Queensland, and forms an area of about 24,292 km^2, approximately 9500 km^2 of which is in Queensland. In New South Wales it contains much of the Clarence and Richmond river basins, while in south-east Queensland it covers the mid and upper parts of the Logan-Albert Rivers, Bremer River, Lockyer Valley, and parts of the Brisbane river basin (Figure 21).

The bioregion covers a large area, and spans multiple climate zones. The climate of the bioregion falls within the temperate and subtropical climate groupings (ABARES, 2013). It contains large areas of steep ranges and forests. The bioregion contains large river systems (e.g. Clarence and Richmond Rivers in New South Wales), and there are extensive river valley flats, floodplain swamps and wetlands in these areas. Grazing and cropping is undertaken in the large valley floor areas. There are also smaller areas of intense horticulture in locations such as the Alstonville plateau near Byron Bay in New South Wales. The Lockyer Valley in south-east Queensland supports a large irrigated cropping and vegetable industry.

There are extensive areas of wetlands, with 31,000 ha in the Richmond river basin, and 43,000 ha mapped in the Clarence river basin (DLWC, 2000). The extensive wetlands in the lower Clarence valley are supplied by groundwater and local runoff (except during large flood events) (Auld, 1998: cited by DLWC, 2000).

Figure 5 Surface elevation, major rivers and wetlands of the Clarence-Moreton bioregion

1.1.2.1.1 Physiographic regions

Physiographic regions are defined in terms of landform characteristics and geology, and are the basic geomorphological subdivisions for Australia (Pain et al., 2011). The mapping criteria relate to landform attributes, and the resultant mapped units can be described in terms of landform, underlying geology, regolith and soils (Pain et al., 2011).

The bioregion is part of the New England-Moreton Uplands Province, within the broader Eastern Uplands Division. This diverse area covers parts of the six physiographic regions, which are listed in Table 2 (Pain et al., 2011), and shown in Figure 6.

Table 2 Physiographic regions within the Clarence-Moreton bioregion

Region	Region name	Region description
10503	Moreton Lowland	Lowland on weak sedimentary rocks, with prominent volcanic plugs, includes dune islands
10504	Toowoomba Plateau	Basaltic plateau terminating southeast in dissected volcanic pile (Mount Warning)
10507	Clarence Fall	Dissected plateau margin on granite and metamorphic rocks
10508	Clarence Lowlands	Coastal lowlands on weak sedimentary rocks, with littoral and alluvial plains
10513	Bunya-Burnett Ranges	Mountain ranges, rugged and dissected on granitic and metamorphic rocks in east, broader uplands and upland basins, partly on sedimentary rocks, in west
20205	Condamine Lowlands	Undulating clay lowlands on siltstone and low sandstone hills; floodplains

Source data: Pain et al. (2011)

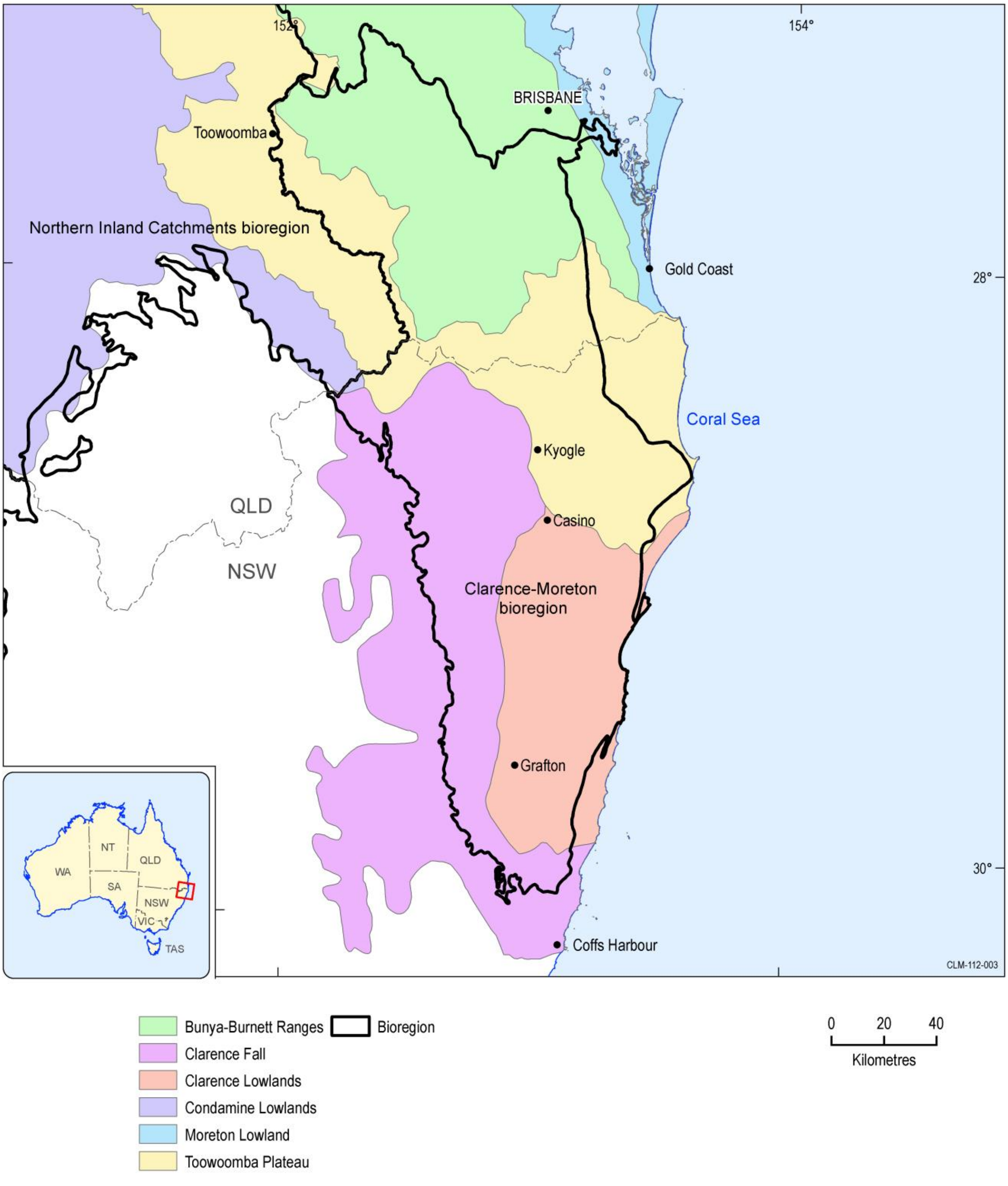

Figure 6 Physiographic regions in the Clarence-Moreton bioregion

Source data: ASRIS (2013)

1.1.2.1.2 Soils and land capabilities

As expected in such a diverse area containing steep mountains, river valleys and coastal areas, there is wide variability in soil type across the Clarence-Moreton bioregion. Soil Orders (Australian Soil Classification: ASRIS (2013)) are shown in Figure 7.

In New South Wales there are several large soil monitoring units (SMUs) in the bioregion (DECCW, 2010a). These include Clarence Sodic Soils around Grafton (Kurosols), Alstonville Plateau

(Ferrosols), Casino Alluvials along the Richmond Valley (Vertosols), and North Coast Acid Sulfate Soils (Hydrosols) mainly in the lower parts of the Clarence and Richmond floodplain. In Queensland, the Lockyer, Bremer and Warrill valleys have large areas of alluvial plains (Vertosols) with surrounding undulating hills (Sodosols).

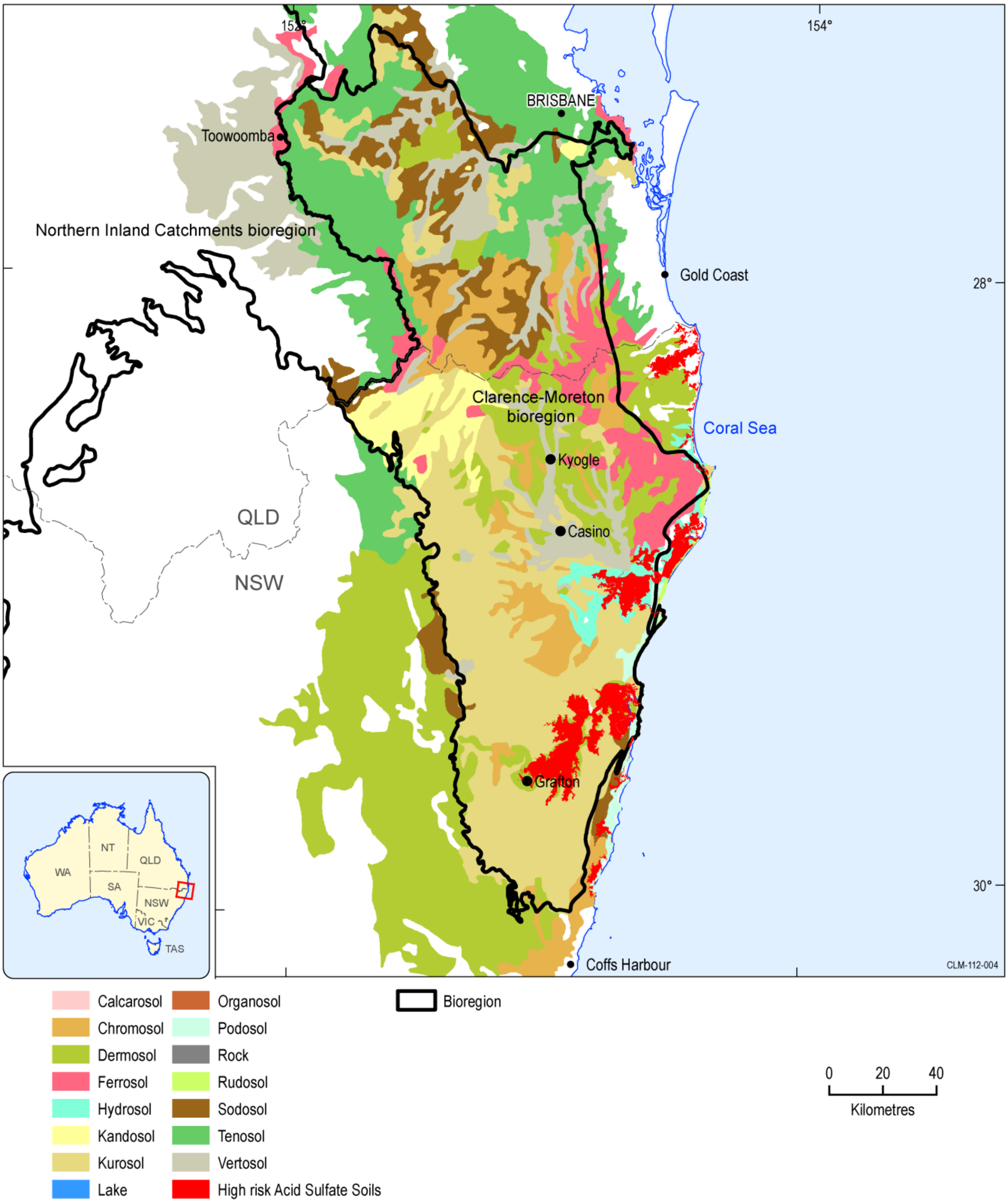

Figure 7 Australian Soil Classification (ASC) Soil Orders and Acid Sulfate Susceptible Soils of the Clarence-Moreton bioregion

Source data: ASRIS (2013) and DECCW (2010a)

There are extensive areas of acid sulfate soils scattered across the southern (New South Wales) parts of the bioregion (see Figure 7). Acid sulfate soils are typically low-lying coastal soils which were formed in a marine environment. The drainage of these soils can lead to their exposure and can produce sulfuric acid which reduces pH of the soil, associated water bodies and result in damage to ecosystems (DECCW, 2010a). Table 3 shows the distribution of acid sulfate soils in the Upper North Coast of New South Wales. The Queensland part of the bioregion is mostly away from these coastal areas, although there are small scattered areas of acid sulfate soils in this part. The largest area of acid sulfate soils in the bioregion is in New South Wales in the Clarence Valley downstream of Grafton, and there are also large areas in the lower Richmond Valley (Figure 7). These New South Wales SMU 'North Coast Acid Sulfate Soils' is assessed as being in fair (declining) condition (DECCW, 2010a) and with only a poor rating for 'Land management with capability' (DECCW, 2010b).

Table 3 Distribution of acid sulfate soils in the Upper North Coast of New South Wales

River basin	Estimated area with underlying acid sulfate soils
Tweed	9700 ha high risk 2000 ha low risk
Brunswick	3193 ha high risk 10,000 ha low risk
Richmond	34,000 ha high risk 34,000 ha low risk
Clarence	53,000 ha high risk

Source data: DLWC (2000)

1.1.2.1.3 Land cover

The Clarence-Moreton bioregion has large areas of woody vegetation (both closed and open) (Figure 8). These dominate the landscape in the steeper and upland parts of the bioregion, but are also widespread throughout the bioregion. The Clarence-Moreton bioregion also contains large areas of cropping and grazing land, which tend to be focused along the flatter river valley areas. The northern part of the Clarence-Moreton bioregion has a greater amount of scattered woody vegetation than the southern part, and also has a lower rainfall.

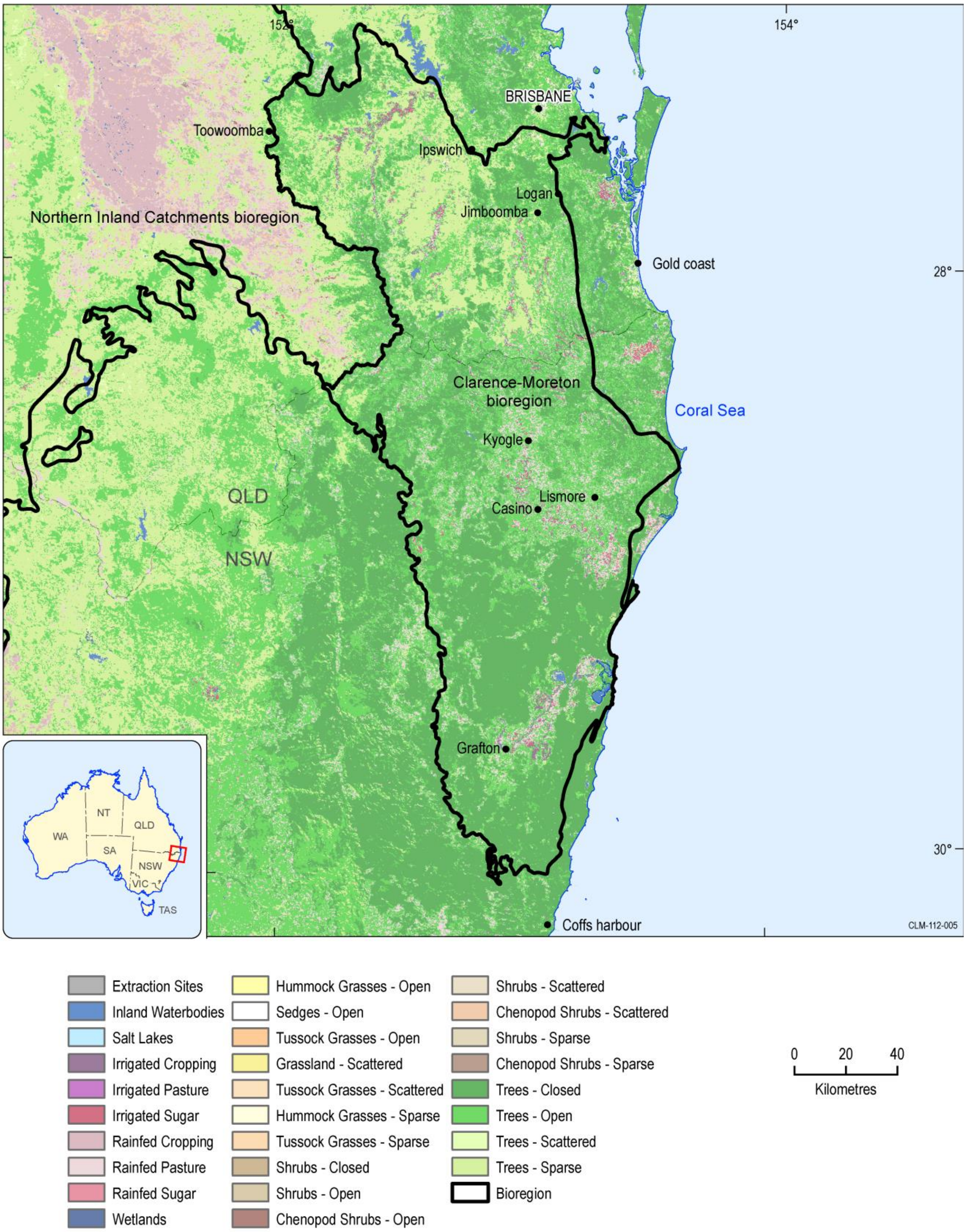

Figure 8 Land cover in the Clarence-Moreton bioregion

Source data: Geoscience Australia (2013)

1.1.2.2 Human geography

1.1.2.2.1 Population

The Clarence-Moreton bioregion population is difficult to estimate accurately, as it contains the fringes of major Queensland population centres of Brisbane, Ipswich, Logan and Toowoomba. Outside of these heavily populated fringes, the largest urban centres are Jimboomba (20,596 people), Grafton (19,070 people) and Lismore (16,156 people). The bioregion covers parts of at least ten local government areas, which in total have a total population of 713,000 (ABS, 2013a). The population within the boundaries of the Clarence-Moreton bioregion itself is estimated to be around 500,000 although this is not precise.

1.1.2.2.2 Economic activity

The Clarence-Moreton bioregion is economically diverse, with a mixture of industries in each local government area. ‘Agriculture, forestry and fishing’ is the main employer in two of the local government areas (Lockyer Valley and Kyogle). The other local government areas in the bioregion have a mix of industries, with ‘health care and social assistance’ and ‘retail trade’ representing some of the more typical industries elsewhere (ABS, 2013b).

1.1.2.2.3 Land use

The Australian Land Use and Management classification v7 (ABARES, 2010) identifies six primary classes of land use. Figure 9 shows the relative proportions of these in the Clarence-Moreton bioregion. This breakdown highlights that more than half of the bioregion is either natural or relatively natural environments. Dryland agriculture and plantations is almost one third of the bioregion, while irrigation is a much smaller area, although it is far more intensive. Table 4 provides a finer level of breakdown of these primary classes, and is presented in the numbered order of the ABARES classification. The largest component of the Clarence-Moreton bioregion is used as grazing of modified pastures and native vegetation.

In the New South Wales part of the Clarence-Moreton bioregion, the area can be divided into three broad types of region (DECCW, 2010c), which is helpful in conceptualisation of river basin structure in this state:

1. upper catchment zone: being the upland areas and steeper country, with mixed broad-acre and forestry
2. lower flood zone: being the areas along the lower Clarence and Richmond valleys, with highly productive sugarcane and dairy industries
3. middle zone: being the coastal areas between the major river valleys, with small-scale operations on poor soils.

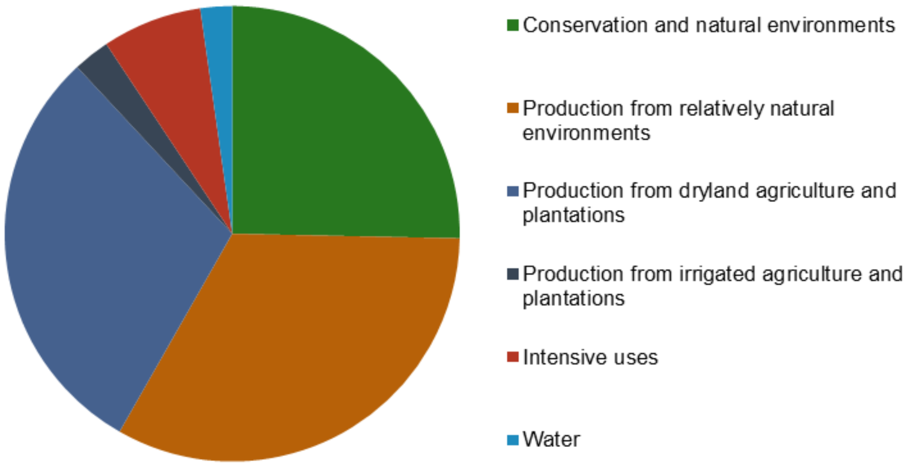

Figure 9 Primary classes of land use in the Clarence-Moreton bioregion

Source data: Australian Land Use and Management classification (ABARES, 2010)

Table 4 Australian Land Use and Management classification for the Clarence-Moreton bioregion

Land use	Area (percentage of total)	Area (km^2)
1.1 Nature conservation	11%	2,556.47
1.2 Managed resource protection	<1%	17.07
1.3 Other minimal use	15%	3,576.91
2.1 Grazing natural vegetation	26%	6,249.59
2.2 Production forestry	7%	1,747.30
3.1 Plantation forestry	1%	268.78
3.2 Grazing modified pastures	26%	6,280.72
3.3 Cropping	2%	379.85
3.4 Perennial horticulture	1%	168.95
3.5 Seasonal horticulture	<1%	2.60
3.6 Land in transition	1%	145.39
4.2 Grazing irrigated modified pastures	<1%	61.14
4.3 Irrigated cropping	1%	293.75
4.4 Irrigated perennial horticulture	<1%	48.78
4.5 Irrigated seasonal horticulture	1%	227.71
5.1 Intensive horticulture	<1%	5.85
5.2 Intensive animal husbandry	1%	285.62
5.3 Manufacturing and industrial	<1%	42.93
5.4 Residential and farm infrastructure	4%	1,067.61
5.5 Services	1%	155.23
5.6 Utilities	<1%	9.58

Land use	Area (percentage of total)	Area (km^2)
5.7 Transport and communication	<1%	93.87
5.8 Mining	<1%	51.90
5.9 Waste treatment and disposal	<1%	9.31
6.1 Lake	<1%	0.69
6.2 Reservoir/dam	<1%	67.41
6.3 River	1%	287.41
6.4 Channel/aqueduct	<1%	4.96
6.5 Marsh/wetland	1%	180.85
6.6 Estuary/coastal waters	<1%	4.14

Source data: ABARES (2010)

1.1.2.2.4 Water storages

Water resource accounts for the Moreton Basin (Queensland Department of Environment and Resource Management, 2011a) show levels of abstraction of between 1.88 and 2.2% (not including Pine Rivers as this is outside the bioregion). In the Logan Basin (Queensland Department of Environment and Resource Management, 2011b), abstractions in the 2009–2011 period ranged between 0.34 and 4.07% of inflows.

The New South Wales part of the Clarence-Moreton bioregion has no large dams. The largest reservoir is Toonumbar Dam in the upper Richmond river basin, which is a minor ungated dam, with a storage of 11,000 ML. Surface water balance reporting is available for the Richmond River, which shows levels of water diversions (net water diverted under basic rights and under access licences) of between 0.02 and 0.33% of inflows in this river basin during 2010–2013 period (Statewater, 2013).

The largest water supply reservoir in the Clarence-Moreton bioregion is Lake Wivenhoe on the Brisbane River. Wivenhoe has a full supply capacity of 1,165,238 ML. This is a major water supply reservoir for Brisbane and south-east Queensland. The other storages in the Queensland part of the bioregion are around an order of magnitude smaller than Lake Wivenhoe, and include the recently constructed Wyaralong Dam in the Logan river basin (101,323 ML storage). The smaller dammed storages in the Queensland part of the bioregion include Lake Maroon (Logan river basin: 44,319 ML capacity), Lake Moogerah (Bremer river basin, 83,765 ML capacity), Lake Clarendon (Lockyer river basin, 24,276 ML capacity), and Lake Atkinson (Lockyer river basin, 30,401 ML capacity) (Seqwater, 2013). The locations of these storages are given in Section 1.1.5.

1.1.2.2.5 Sites of Aboriginal significance

The Clarence-Moreton bioregion includes areas of Bundjalung and Yuggera nations. The New South Wales part of the Clarence-Moreton bioregion includes areas of the North Coast Aboriginal Land Council Region, which includes parts of the Grafton-Ngerrie, Yaegl, Baryulgil, Bogal, Jana

Ngalee, Jubullum, Casino, Ngulingah, Jali, Gugin Gudduba, Tweed Byron, and Muli Muli Local Aboriginal Land Councils (New South Wales Aboriginal Land Council, 2013).

As the Native Title Report 2008 (Aboriginal and Torres Strait Islander Social Justice Commissioner, 2009) highlights, sites of Aboriginal significance exist across Australia and include a range of ecosystems (e.g. wetlands) and animal and plant species – some of which have been formally recognised through legislation or legal claims. Even so, as a Traditional Owner and Indigenous Engagement Support Officer from SEQ catchments asserts, it is important to note that 'Aboriginal cultural heritage is evidence of Aboriginal occupation of an area, both pre- and post-European settlement – and can be found anywhere in the landscape in both cities and regional areas' (Hounsell, no date).

Some sites of Aboriginal significance that have been formally listed in the bioregion include a combination of contact sites, earthen and stone arrangements, engravings and paintings, stone artefact scatters, story places and cultural sites (DATSIMA, 2013). These include five 'declared Aboriginal Places' in the New South Wales Atlas of Aboriginal Places: Miimiga Gaungan – St Marys Waterhole (sacred site), Casino Bora Ground (sacred site), Parrots Nest (sacred site), Cubawee (settlement), Ti Tree (Taylor's) Lake (sacred site) (New South Wales Department of Environment and Heritage, 2013). In the Queensland part of the Clarence-Moreton bioregion, the Cultural Heritage Database is not publicly available.

From his efforts to map Aboriginal cultural landscapes in the Locker valley, Strong (2009, p. 14) notes that the Queensland *Aboriginal Cultural Heritage Act 2003* recognises that archaeologically unsupported places may, in fact, have considerably more significance to Aboriginal people than more visible sites. He reports creation places, initiation places, camping places, gathering places, good food places and historical incident places as examples of significant places present in this area.

Sites of Aboriginal significance have also been the focus of regional natural resource management (NRM) group activities and partnerships. This includes efforts to rehabilitate important bio-cultural landscapes and ecological systems as well as mapping Aboriginal cultural landscapes and values in the region (e.g. NSW DNR, 2005a; 2005b, 2005c; Strong, 2009).

1.1.2.3 Climate

The climate of the Clarence-Moreton bioregion falls within the temperate and subtropical climate groupings (ABARES, 2013). The mean annual rainfall varies from 800 to 2716 mm (BOM, 2013a). The highest mean annual rainfall zone is in the east of the bioregion around the State border north-east of Kyogle (Figure 10). The northern part of the bioregion around the Lockyer Valley has the lowest mean annual rainfall (Figure 10). Rainfall is highest in the warmer months (January, February, March) and lowest in the colder months (July, August, September) (Figure 11). Climate statistics are given for four selected stations across the bioregion (Table 5).

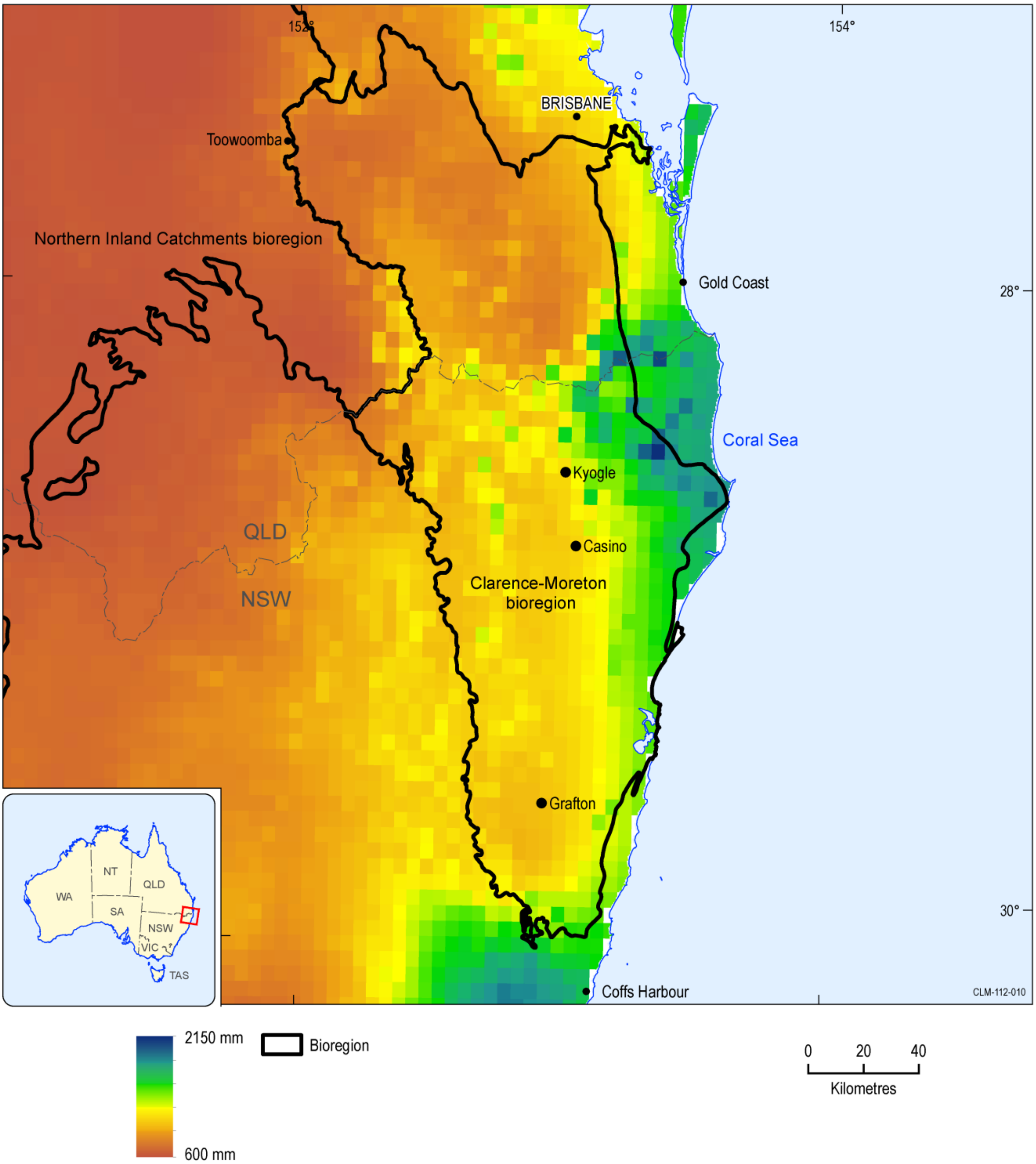

Figure 10 Mean annual rainfall (mm) across the Clarence-Moreton bioregion

Source data: BOM (2013b)

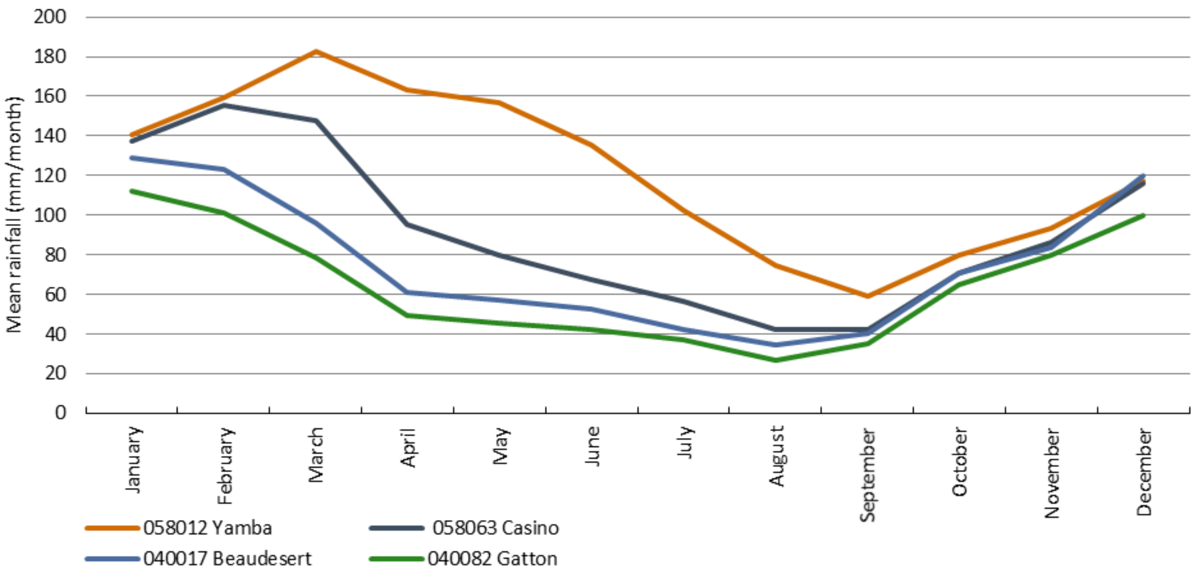

Figure 11 Mean monthly rainfall for four selected stations across the Clarence-Moreton bioregion

Source data: BOM (2013a)

Table 5 Climate statistics for selected climate stations in the Clarence-Moreton bioregion

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
040082 University of Queensland Gatton (89 m elevation)														
1897–2013	**Mean rainfall (mm)**	112.2	101.0	78.4	49.6	45.7	42.5	37.4	26.9	35.3	65.0	79.5	100.1	772.8
1913–2013	**Mean max. temp. (°C)**	31.5	30.7	29.5	27.1	23.7	21.1	20.7	22.4	25.5	28.1	30.1	31.3	26.8
	Mean min. temp. (°C)	19.1	19.0	17.3	13.7	10.1	7.6	6.2	6.7	9.5	13.2	16.0	18.1	13.0
058063 Casino Airport (26 m elevation)														
1858–2012	**Mean rainfall (mm)**	137.6	155.2	147.9	95.3	79.8	67.8	56.3	42.4	42.2	70.5	86.6	116.0	1097.8
1908–2012	**Mean max. temp. (°C)**	31.3	30.4	29.0	26.8	23.7	21.4	21.1	22.8	25.6	27.8	29.7	31.1	26.7
	Mean min. temp. (°C)	18.9	18.8	17.3	14.1	10.6	8.0	6.7	7.3	10.2	13.2	15.9	17.8	13.2

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
058012 Yamba Pilot Station (27 m elevation)														
1877–2013	**Mean rainfall (mm)**	140.7	159.4	182.9	163.3	156.6	135.3	102.2	74.8	59.2	79.7	93.1	117.0	1464.8
1877–2012	**Mean max. temp. (°C)**	26.7	26.7	26.0	24.3	21.7	19.6	19.0	20.1	22.0	23.3	24.6	25.9	23.3
	Mean min. temp. (°C)	20.2	20.3	19.2	16.5	13.3	10.8	9.7	10.5	13.0	15.4	17.4	19.1	15.5
040017 Beaudesert Cryna (106 m elevation)														
1887–2012	**Mean rainfall (mm)**	129.1	123.3	95.9	61.3	57.4	52.9	42.2	34.5	40.1	70.5	83.4	119.9	906.6
1967–1979	**Mean max. temp (°C)**	30.8	30.0	29.2	27.6	23.8	21.5	21.2	22.4	24.6	27.1	29.4	31.0	26.5
	Mean min. temp. (°C)	19.2	18.6	17.3	13.5	9.8	6.4	5.1	6.2	9.1	12.9	15.9	17.8	12.6

Source data: BOM (2013a)

Mean annual point potential evapotranspiration varies from 1400 to 2014 mm (BOM, 2013c), with the distribution shown in Figure 12.

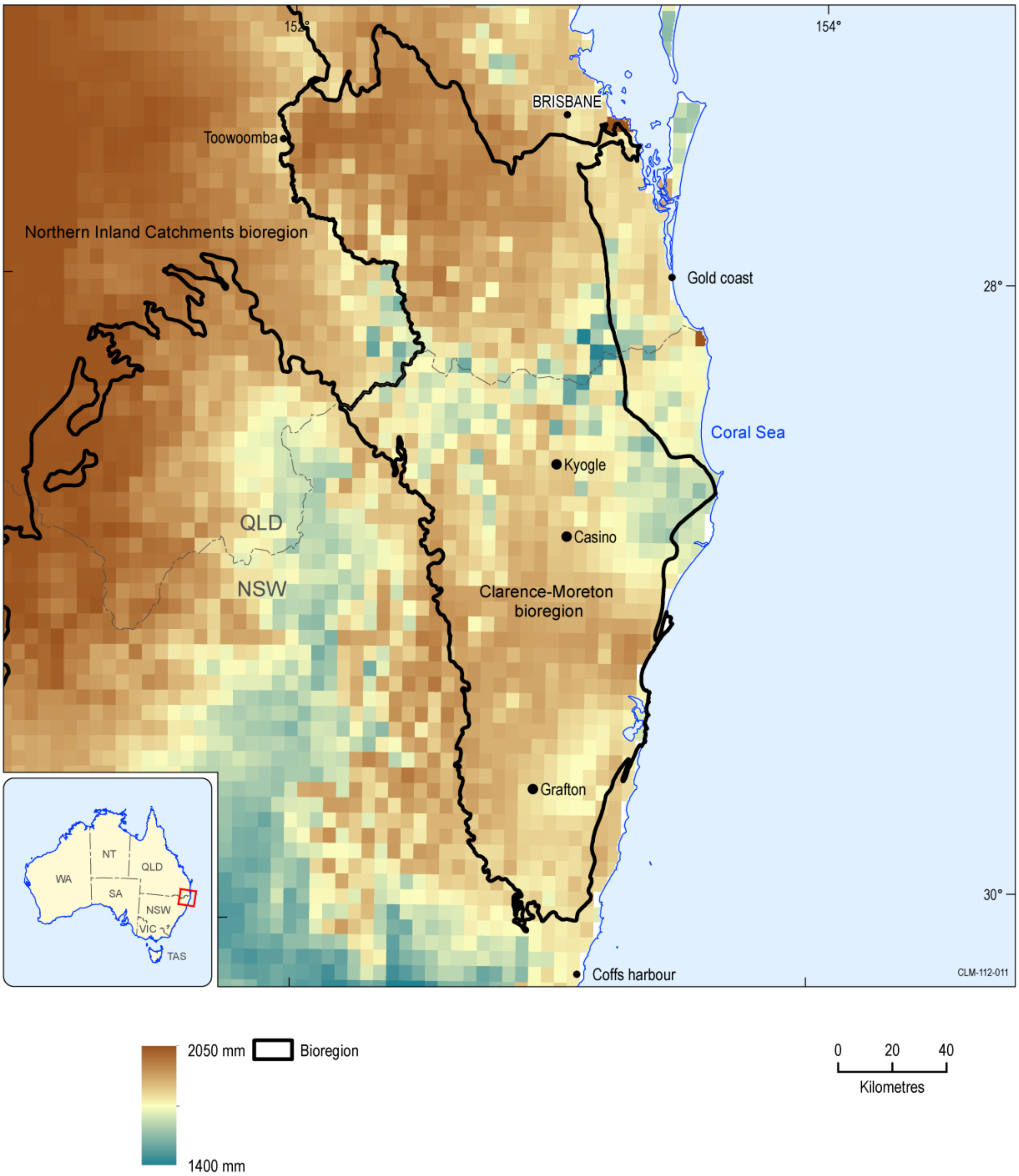

Figure 12 Mean annual point potential evapotranspiration in the Clarence-Moreton bioregion

Source data: BOM (2013c)

Climate statistics are presented here for the entire Clarence-Moreton bioregion. Figure 13a presents the annual rainfall series averaged over the entire bioregion, together with a smoothed moving average. Figure 13b presents the annual divergence from the long-term mean for the entire bioregion. Figure 14 presents the average monthly precipitation, potential evapotranspiration (PET) and aridity index for the Clarence-Moreton bioregion. The black line indicates an aridity index of 1 (i.e. where precipitation is equal to PET). Atmosphere evaporative demand is energy-limited below the black line and water-limited above (assuming no soil moisture storage). Values were calculated over the years 1981 to 2012 (inclusive).

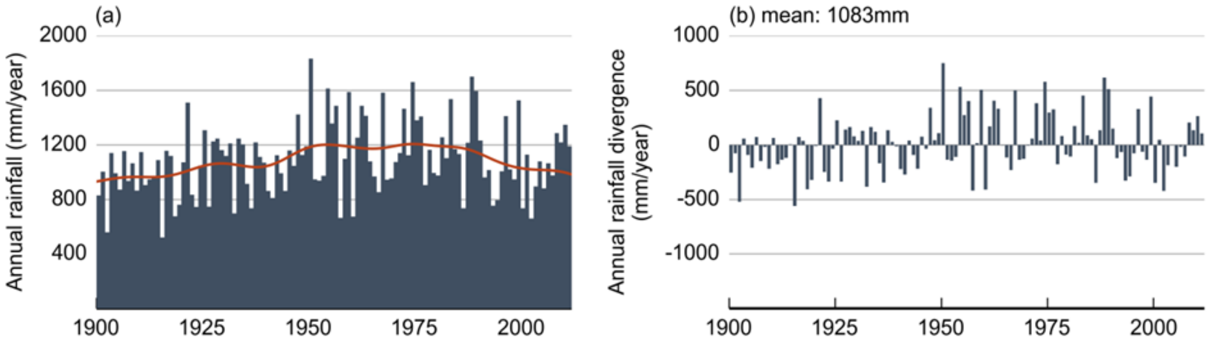

Figure 13 (a) Annual rainfall with smoothed rolling average and (b) annual rainfall divergence from the long-term mean for the Clarence-Moreton bioregion

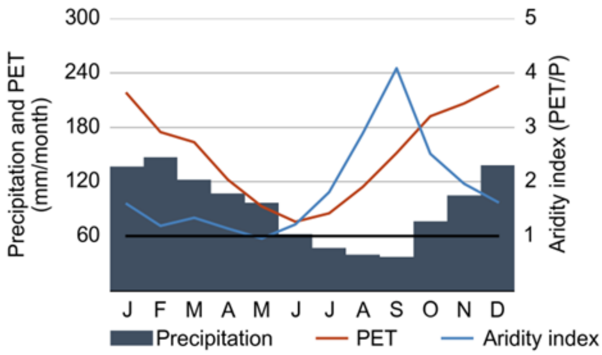

Figure 14 Average monthly precipitation, potential evapotranspiration (PET) and aridity index for the Clarence-Moreton bioregion

Figure 15 shows monthly average values of precipitation, potential evapotranspiration, temperature, vapour pressure deficit, radiation and wind speed for the Clarence-Moreton bioregion. The trend (line), ±1 standard error (blue shaded area) and trend significance (dashed markers) are shown. Values were calculated over the years 1981 to 2012 (inclusive).

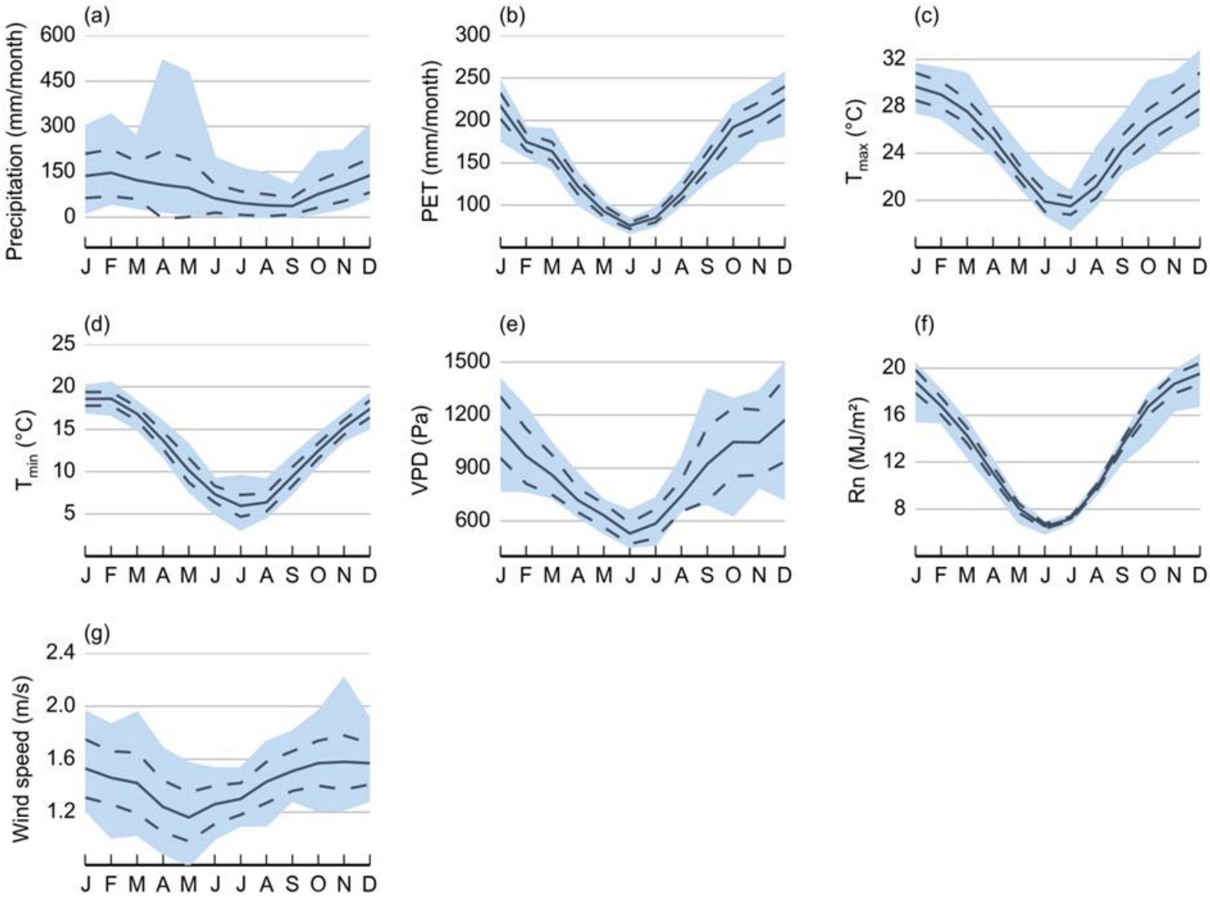

Figure 15 Monthly average values of (a) precipitation,(b) potential evapotranspiration (PET), (c) maximum temperature (T_{max}), (d) minimum temperature (T_{min}), (e) vapour pressure deficit (VPD), (f) net radiation (Rn) and (g) wind speed for the Clarence-Moreton bioregion

Figure 16 shows the annual trend by month of precipitation, potential evapotranspiration, temperature, vapour pressure deficit, radiation and wind speed for the Clarence-Moreton bioregion. The trend (line), ± 1 standard error (blue shaded area) and trend significance (markers) are shown. Values were calculated over the years 1981 to 2012 (inclusive).

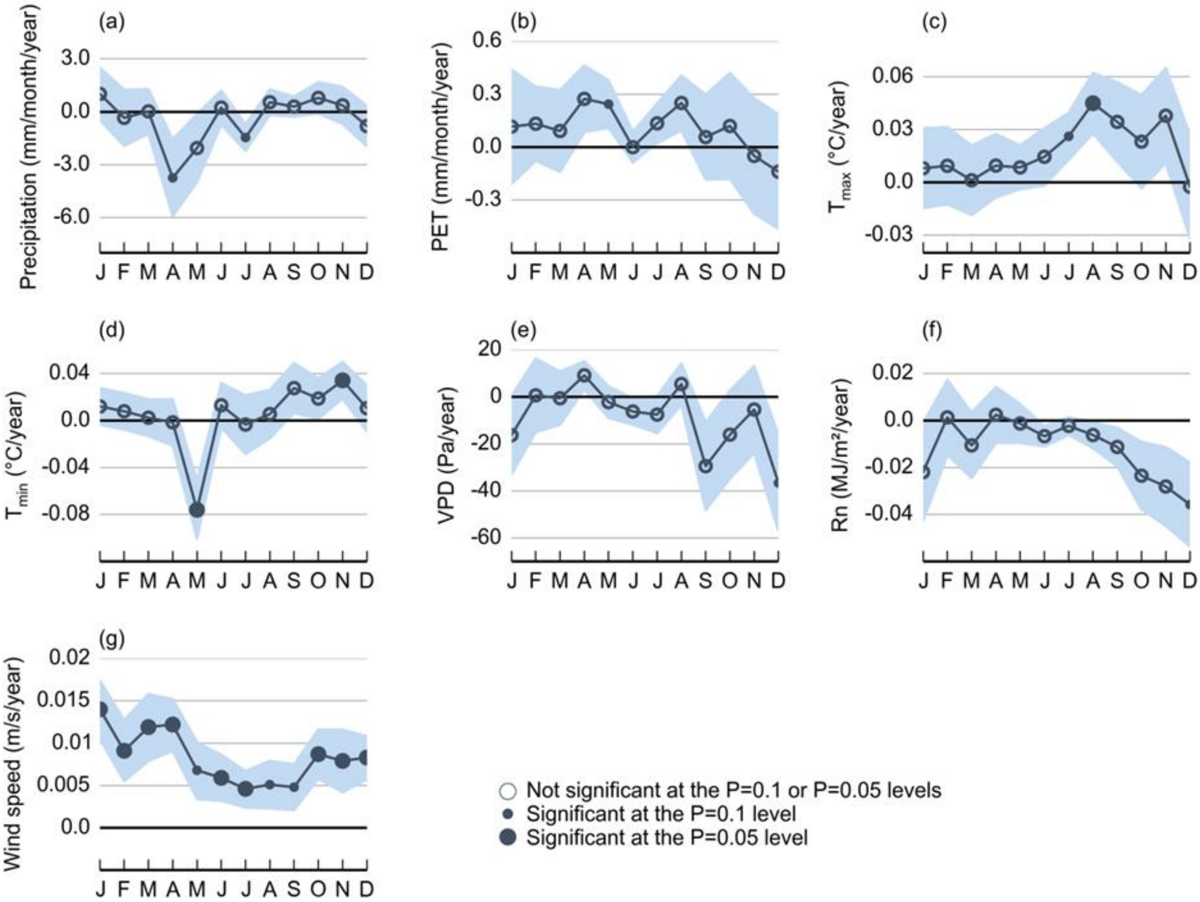

Figure 16 Annual trend by month of (a) precipitation,(b) potential evapotranspiration (PET), (c) maximum temperature (T_{max}), (d) minimum temperature (T_{min}), (e) vapour pressure deficit (VPD), (f) net radiation (Rn) and (g) wind speed for the Clarence-Moreton bioregion

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1.1.3 Geology

Summary

The Clarence-Moreton Basin covers approximately 38,000 km^2 on-shore in south-eastern Queensland and north-eastern New South Wales, and extends off-shore over an area of at least 1,000 km^2 in New South Wales. The basin is bounded on three sides by Paleozoic basement blocks, which are part of the New England Orogen.

Following the initiation of the Clarence-Moreton Basin and associated precursor basins by tectonic extension during the Middle Triassic, a period of thermal cooling continued from the Late Triassic probably into the Cretaceous. Thermal relaxation was also the dominant driving force for subsidence in the Clarence-Moreton Basin. The Clarence-Moreton Basin has three sub-basins separated by basement highs. These discrete depositional centres, which are bounded by transtension-related strike-slip faults, are from north-west to south-east: the Cecil Plains sub-basin, the Laidley sub-basin and the Logan sub-basin. Both the Laidley and Logan sub-basins form part of the Clarence-Moreton bioregion, whereas only the eastern Cecil Plains sub-basin is included (the western Cecil Plains sub-basin is part of the Northern Inland Catchments bioregion). In Queensland, the north-western Clarence-Moreton Basin is connected to the Surat Basin across the Kumbarilla Ridge, a shallow basement high. However, only four stratigraphic units are common to both basins.

The Clarence-Moreton Basin contains sedimentary sequences of Late Triassic to Lower Cretaceous age, with a combined estimated thickness of approximately 3 to 4 km. The sediments were originally deposited in non-marine depositional environments by northwards flowing rivers in a humid climate. The mixed nature of the sedimentary facies indicates that there were frequent environmental changes, mostly associated with tectonic processes. This resulted in the deposition of interbedded sequences of fluvial, paludal (swamp) and lacustrine deposits.

The oldest coal-bearing units of the Clarence-Moreton Basin sedimentary succession are the Middle Triassic Nymboida Coal Measures and the Late Triassic Ipswich Coal Measures, which are separated from each other by an angular unconformity. Deposition of the overlying Bundamba Group (including the Woogaroo Subgroup, the Gatton Sandstone and the Koukandowie Formation) occurred during the Late Triassic to Early Jurassic. These lithostratigraphic units comprise mixed facies dominated by sandstone, siltstone, mudstone and conglomerate, with minor coal also reported, particularly from the Koukandowie Formation. Deposition of the Walloon Coal Measures followed the Bundamba Group during the Middle Jurassic. This formed the major coal-bearing stratigraphic unit in the Clarence-Moreton Basin and the primary target for coal and coal seam gas exploration. Its deposition marked a change towards lower energy depositional environments characterised by sinuous rivers meandering across a wide floodplain. During the Late Jurassic to Cretaceous, the Orara Formation and the Grafton Formation were deposited. As a result of widespread erosion, these youngest stratigraphic units are restricted to the New South Wales part of the Clarence-Moreton Basin.

Throughout the Clarence-Moreton bioregion, there are only two currently operating coal mines (both in south-east Queensland), but the basin has a long history of coal mining dating back to the 1870s. The Clarence-Moreton Basin has also been explored for conventional hydrocarbon (oil and gas) in the past and more recently for unconventional gas resources (coal seam gas), primarily targeting the Walloon Coal Measures.

1.1.3.1 Geological structural framework

1.1.3.1.1 Definition of the basin, basin extent and regional geological context

The Clarence-Moreton Basin is an elongated intracratonic sag basin which overlies the mid to late Paleozoic rocks of the New England Orogen in south-east Queensland and north-east New South Wales (Korsch et al., 1989). It covers approximately 38,000 km^2 on-shore, and contains sedimentary sequences of Middle and Late Triassic to Lower Cretaceous age with a combined thickness of up to approximately 3500 to 4000 m. The basin extends from the Kumbarilla Ridge in the west to the coast in south-east Queensland and into northern New South Wales (Figure 15). It is the youngest of a series of linked Mesozoic basins in the region (Johnstone et al., 1985). The formation of the Clarence-Moreton Basin and adjoining Mesozoic basins is closely related to large-scale tectonic processes associated with the development of the New England Orogen and the reorganisation of tectonic plates which began in the Late Carboniferous (Korsch et al., 1989).

Basin geometry and sub-basins

The Clarence-Moreton Basin has three sub-basins (Martin and Saxby, 1982) which, from north-west to south-east, are the Cecil Plains, Laidley and Logan sub-basins (Figure 17). Within these sub-basins and especially within the Logan sub-basin, multiple subsidiary structural features have been identified based primarily on seismic interpretation (O'Brien et al., 1994a; Ingram and Robertson, 1996).

The Cecil Plains sub-basin is linked to the Surat Basin across the Kumbarilla Ridge (Figure 17), a broad structural basement high which separates sedimentary rocks of the Woogaroo Subgroup (and the Precipice Sandstone, its equivalent in the Surat Basin) in the Cecil Plains sub-basin and the Surat Basin (O'Brien et al., 1994a). Only the eastern part of the Cecil Plains sub-basin is included in the Clarence-Moreton bioregion, whereas the Northern Inland Catchments bioregion covers the western part of the Cecil Plains sub-basin.

More recently, Day et al. (2008) suggested that the boundary between the Clarence-Moreton and Surat basins may be located further to the east at the Toowoomba Strait (Figure 17). This would mean that much of the Cecil Plains sub-basin forms part of the Surat Basin (Jell, 2013).

The Laidley sub-basin is separated from the Cecil Plains sub-basin to the west through the Gatton Arch, and from the Logan sub-basin to the south by a structurally complex basement high (South Moreton Anticline). The West Ipswich and East Richmond faults form the western and eastern boundaries of the South Moreton Anticline, respectively. The Logan sub-basin consists of several basement highs and troughs, including the Casino Trough and the Grafton Trough (Ingram and Robinson, 1996) and the offshore Yamba Trough (Wells and O'Brien, 1994). In addition, the Logan sub-basin is also partly divided along the Queensland – New South Wales border by a group of intermediate intrusions of Cenozoic age.

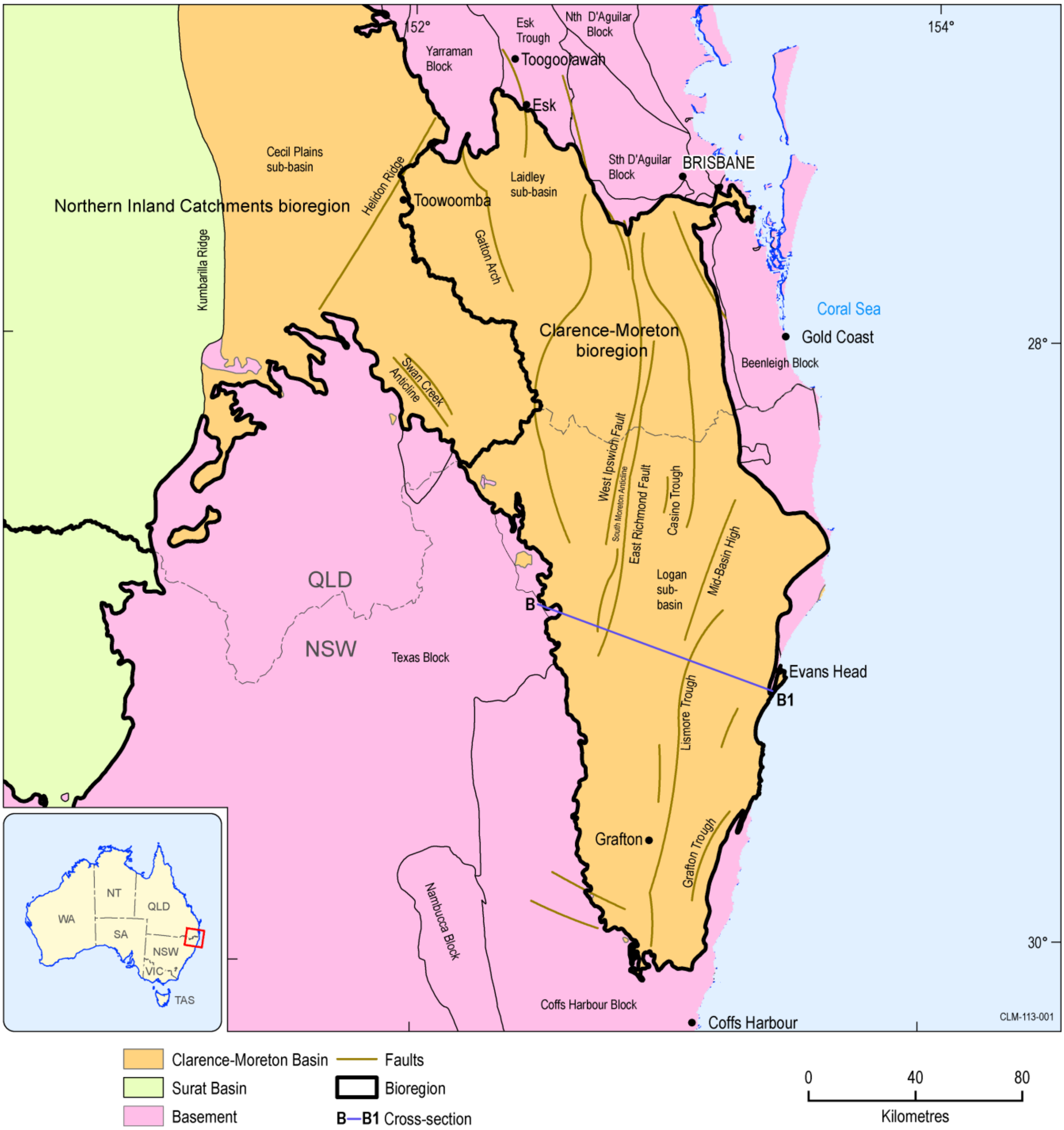

Figure 17 Regional geological setting, major structural elements and sub-basins of the Clarence-Moreton Basin

a. The B – B1 Cross-section is shown in Figure 20.
Source data: derived from data presented in Wells and O'Brien (1994a)

1.1.3.1.2 Basin thickness

The maximum thickness of sedimentary rocks intersected in drill holes in the Clarence-Moreton Basin is approximately 2500 m in the Logan sub-basin (conventional petroleum exploration well

Kyogle-1, Wells and O'Brien, 1994b). However, a sedimentary thickness of approximately 3500 to 4000 m is inferred from seismic interpretations (e.g. Wells and O'Brien, 1994b; Ingram and Robinson, 1996; Doig and Stanmore, 2012). In the Laidley and Cecil Plains sub-basins, the sedimentary thickness is poorly constrained due to the lack of wells penetrating the complete sequence of the basal stratigraphic units in the deepest part of the depositional centre. However, a 500 m thick sequence of the Walloon Coal Measures was intersected in a coal seam gas exploration well in the Laidley sub-basin (Silverdale 3; Pinder, 2008). This is comparable to the thickness of the Walloon Coal Measures in the Logan sub-basin.

1.1.3.1.3 Basin basement

The Paleozoic basement to the Clarence-Moreton Basin and older Mesozoic basins in south-east Queensland and north-east New South Wales consists of several fault-bounded blocks and exotic terranes of Paleozoic age. These basement blocks, which are part of the New England Orogen, restricted the deposition of sediments in the Clarence-Moreton Basin. The basement terranes are interpreted as part of an accretionary wedge (Korsch and Harrington, 1981; Day et al., 1983) composed of metasedimentary and metavolcanic rocks of Early Paleozoic to Permian, as well as granitoids that were emplaced in the region from the Late Permian to the Early Triassic (Donchak et al., 2007; Sommacal et al., 2008). They include the Yarraman and D'Aquiliar blocks (north), Texas Block (west), Coffs Harbour Block (south) and Beenleigh Block (east) (Figure 15).

1.1.3.1.4 Structure

Distribution of major faults and folds

The understanding on the nature of the tectonic setting and structural elements in the Clarence-Moreton Basin is still evolving. Recent seismic surveys as well as re-interpretation of older seismic surveys and new records from explorations bores will provide an opportunity to re-examine the tectonic processes that have led to the formation of the Clarence-Moreton Basin.

Murray et al. (1997) suggested that a strike-slip fault regime was initiated in the Late Carboniferous during a major tectonic plate reorganisation. Jell et al. (2013) indicate that oblique extension along major, dextral strike-slip basement faults was followed by thermal relaxation and subsidence over the transtensional rifts identified by Korsch et al. (1989). Strike-slip movement occurred along several major faults, controlling the magnitude of extension during the evolution of the Clarence-Moreton Basin, as well as older extensional Mesozoic basins such as the Esk Trough and the Ipswich Basin (Korsch et al., 1989).

Some of the most prominent structural features in the Clarence-Moreton Basin (Figure 15) which had a major influence on the development of depositional centres are:

- West Ipswich Fault: Cranfield et al. (1976) suggested that the West Ipswich Fault forms part of the Great Moreton Fault System, and is composed of a network of braided and intersecting near-vertical, west-dipping normal faults. These occur near Ipswich (Korsch et al., 1989) and form the western limit of the Ipswich Basin and the eastern limit of the Laidley sub-basin in south-east Queensland. This fault was active until the time of deposition of the Gatton Sandstone, and was locally reactivated during the mid Cretaceous (Ingram and Robinson, 1996).

- Gatton Arch: the Gatton Arch is a broad basement ridge across which the sedimentary rocks of the Clarence-Moreton Basin are folded and relatively thin (Day et al., 1974; Korsch et. al, 1989, O'Brien et al., 1994a). It is interpreted as a peripheral bulge, resulting from isostatic adjustment of the crust and lithosphere in response to loading of the basin fill (Korsch et al., 1989). The rocks of the Middle Triassic Esk Trough wedge-out against the Gatton Arch, with the Clarence-Moreton Basin strata directly overlying the Esk Trough in this vicinity. The Gatton Arch remained a relative structural high area during the transtensional and thermal relaxation phase in the west.
- South Moreton Anticline: the structural style and exact timing of the South Moreton Anticline is still uncertain (Pinder, 2001). The South Moreton Anticline is a broad structural basement high, over which the Clarence-Moreton Basin strata thin and are folded. Korsch et al. (1989) and Gleadow and O'Brien (1994) described it as a flower structure which has developed over a major dextral strike-slip fault at depth. In contrast to the Gatton Arch, the South Moreton Anticline was probably not a peripheral bulge but formed part of the footwall block of the West Ipswich Fault (O'Brien et al., 1994a). The eastern margin of this basement high is formed by the East Richmond Fault (Figure 17) and the western margin by the West Ipswich Fault. Both faults are believed to have components of strike-slip and high-angle reverse movement (Ingram and Robinson, 1996). A comprehensive study by Pinder (2001) which focused on the characteristics of the South Moreton Anticline questioned some of the earlier interpretations; Pinder (2001) found no evidence for flower structures in the area from Beaudesert to Rathdowney (located approximately 100 km south-west of Brisbane), and described the lack of en-echelon structures as evidence against a major strike-slip motion. However, more evidence for strike-slip movement may be in NSW (BJ Pinder, 2013, pers. comm.).

1.1.3.2 Stratigraphy and rock type

1.1.3.2.1 Lithostratigraphic units

A detailed review of the lithostratigraphy of the Clarence-Moreton Basin and underlying basins is for example given by Wells and O'Brien (1994b), Ingram and Robinson (1996), and Doig and Stanmore (2012). Wells and O'Brien (1994b) did not consider the Ipswich Coal Measures and the Nymboida Coal Measures as part of the Clarence-Moreton Basin stratigraphic succession, whereas other authors (e.g. Ingram and Robinson, 1996; Doig and Stanmore, 2012) have included these older coal measures as part of the Clarence-Moreton Basin. The generalised stratigraphic sub-division of the Clarence-Moreton Basin is shown in Figure 18 (based on Wells and O'Brien, 1994b; Doig and Stanmore, 2012). Except where noted and discussed otherwise, the stratigraphic classification in this report adopts the formal stratigraphic nomenclature of the Australian Stratigraphic Units Database (Geoscience Australia, 2013).

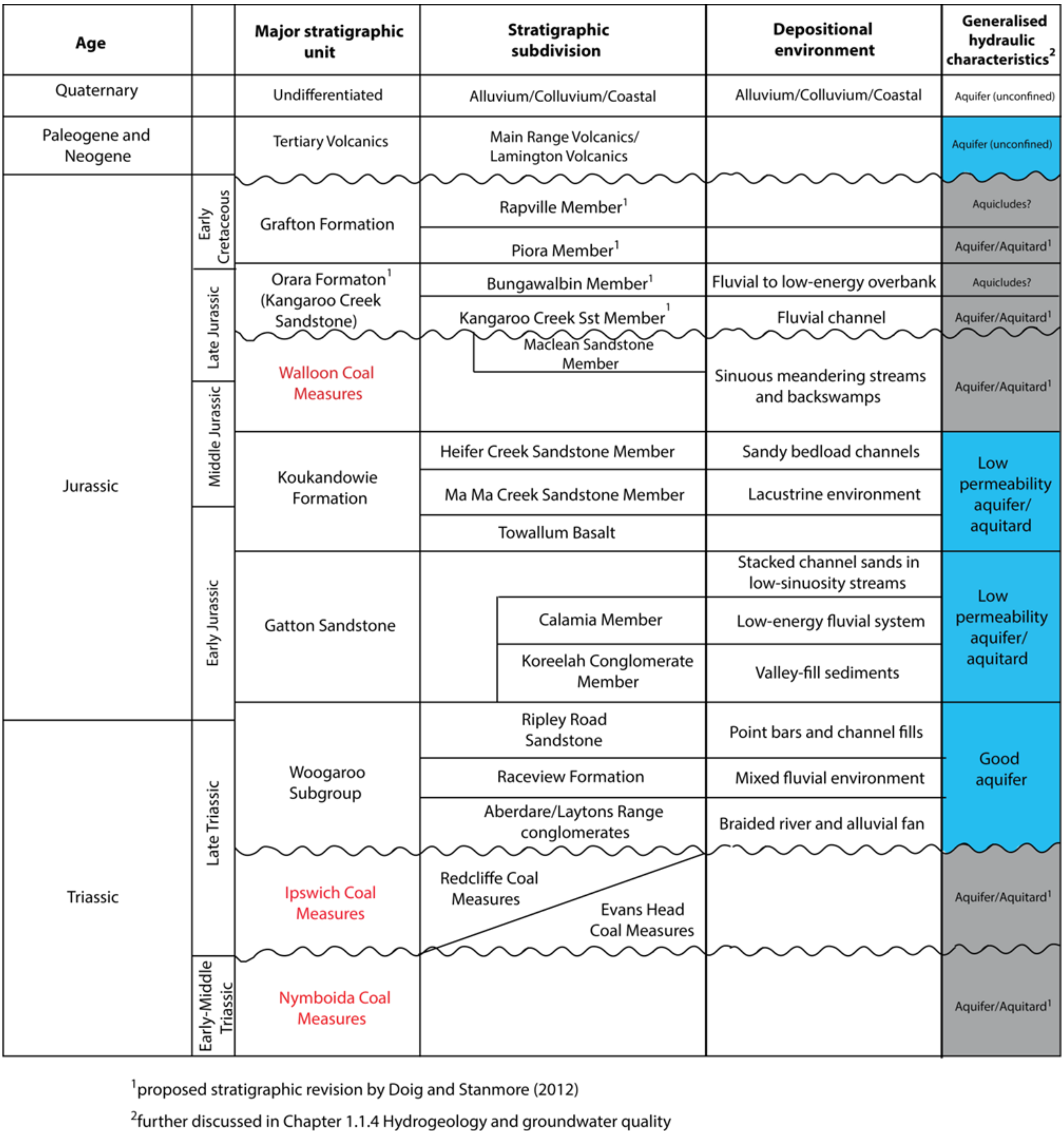

Figure 18 Stratigraphic column for the Clarence-Moreton Basin

Note: major coal-bearing stratigraphic units are highlighted in red
Source data: Wells and O'Brien (1994b) and Doig and Stanmore (2012)

Nymboida Coal Measures

The Middle Triassic Nymboida Coal Measures outcrop in the southern part of the basin in New South Wales, comprising sequences of sandstone, shale, polymictic conglomerate, felsic tuff, basalt and coal with a thickness of up to 1000 m. The unit is thickest in the south-east but thins towards the west where only minor outcrops are known (Stewart and Adler, 1995).

Ipswich Coal Measures, Red Cliff Measures and Evans Head Coal Measures

The Late Triassic Ipswich Coal Measures have been defined in Queensland, where they outcrop along the eastern margin of the Clarence-Moreton Basin but are absent west of the West Ipswich Fault (Korsch et al., 1989; Chern, 2004). The unit consists of variable sequences of sandstone, claystone and coal as well as volcanic rocks. The thickness of the Ipswich Coal Measures in Queensland is poorly constrained due to poor well control, but locally probably reaches 1000 m. Its time-equivalents in New South Wales are the Red Cliff and the Evans Head Coal Measures (Stewart and Adler, 1995). The Evans Head Coal Measures comprise a maximum stratigraphic thickness of approximately 300 m of sandstone, lesser conglomerate, mudstone and coal. The Red Cliff Coal Measures have a maximum stratigraphic thickness of approximately 600 m, comprised of conglomerate, lithic sandstone, siltstone, mudstone and coal. The Ipswich Coal Measures are separated from the older Nymboida Coal Measures by an angular unconformity attributed to a structural deformation event in the Middle Triassic (Doig and Stanmore, 2012).

Woogaroo Subgroup

The Late Triassic Woogaroo Subgroup is the oldest stratigraphic unit of the Bundamba Group in the Clarence-Moreton Basin with a maximum stratigraphic thickness of 1000 to 1200 m. The Laytons Range Conglomerate and Aberdare Conglomerate, the basal units of the Woogaroo Subgroup, consist of conglomerate beds with a thickness of up to 15 m, thin beds of sandstone, mudstones, siltstone and minor coal (O’Brien and Wells, 1994). These units also contain a large volume of quartz-rich sand grains derived from erosion of the uplifted granitic basement to the west of the Clarence-Moreton Basin (Rosenbaum, 2012) and deposited by braided rivers feeding stream-dominated alluvial fans and broad plains (O’Brien and Wells, 1994). The Raceview Formation is characterised by mudstone and siltstone and lesser sandstone (O’Brien and Wells, 1994). This unit formed in a mixed fluvial environment with channel fill sands deposited on the flanks of the Clarence-Moreton Basin, and overbank and accreting sand bodies deposited in intermediate areas, and fine-grained floodplain, swamp and lacustrine deposits accumulated in the most basinal positions. In the Cecil Plains and Laidley sub-basins, the Raceview Formation is comparatively thin and restricted to the deeper parts of the depocentres. The uppermost unit of the Woogaroo Subgroup, the Ripley Road Sandstone, has a maximum thickness of 150 m, and is dominated by coarse-grained and clean quartz-rich sandstone as well as quartz-rich granule conglomerate, with minor mudstone and coal. These were probably deposited as point bars and channel fills in a regional drainage system (Wells and O’Brien, 1994b; Ingram and Robinson, 1996). This upper unit of the Woogaroo Subgroup is a lithostratigraphic equivalent to the Precipice Sandstone of the Surat Basin (Wells and O’Brien, 1994b).

Gatton Sandstone

The Early Jurassic Gatton Sandstone is the basal unit of the Marburg Subgroup and the middle unit of the Bundamba Group. It is dominated by thick-bedded, medium- to coarse-grained quartz-lithic and feldspathic sandstone (Ingram and Robinson, 1996), primarily derived from uplifted and eroded Paleozoic basement rocks of the Woolomin Province as well as Permian-Triassic granite of the New England Batholith (Donchak et al., 2007). It was deposited as stacked channel sands in low sinuosity streams with high avulsion rates (O’Brien and Wells, 1994; Donchak et al., 2007). The Gatton Sandstone consists of two members (Koreelah Conglomerate and Calamia Member) with a maximum thickness of approximately 900 m intersected at the Kyogle 1 well in the Logan sub-basin (Wells and O'Brien, 1994b). It is mostly conformable with the Ripley Road Sandstone, or rests unconformably on basement rocks where the Ripley Road Sandstone is absent (O'Brien and Wells, 1994). The Calamia Member is generally only a few tens of metres thick and comprises thinly bedded mudstone, siltstone and cross-bedded sandstone (O'Brien and Wells, 1994; Ingram and Robinson, 1996). It was deposited by a lower gradient fluvial system compared to the rest of the Gatton Sandstone (O'Brien and Wells, 1994). The Koreelah Conglomerate Member occurs along the western margin of the basin and grades into the Gatton Sandstone towards the east. It consists of massive, clast-supported, polymictic pebble to cobble conglomerate, as well as massive matrix-supported sandy conglomerate and thick bedded coarse-grained sandstone (Wells and O'Brien, 1994b), deposited as valley-fill sediments (O'Brien and Wells, 1994). The Gatton Sandstone is correlated with the lower part of the Evergreen Formation of the Surat Basin (Donchak et al., 2007).

Koukandowie Formation

The Lower Jurassic Koukandowie Formation is the upper unit of the Marburg Subgroup and the Bundamba Group. It was described by Willis (1994) as a mixed-facies sequence consisting of sheets of interbedded quartzose-feldspathic-lithic sandstone, siltstone, claystone and minor coal with thickness of 250 to 500 m. It is conformably overlain by the Walloon Coal Measures and conformably rests on the Gatton Sandstone. It has three members: the Heifer Creek Sandstone Member, the Ma Ma Creek Member and the Towallum Basalt. The middle member of the Koukandowie Formation, the Ma Ma Creek Member, is composed primarily of finer-grained facies including shale, siltstone and interbedded sandstone with minor fossil woods and conglomerate bands. The deposition of the Ma Ma Creek Member occurred during interruption of fluvial conditions by a lacustrine environment in the Early Jurassic (Wells and O'Brien, 1994b). A widespread isochronous ferruginous oolite marker bed occurs at the base of the Ma Ma Creek Member in the Clarence-Moreton Basin, as well as in correlative stratigraphic horizons in other basins. It covers more than 350,000 km^2, and has also been attributed to deposition in a large lake system, controlled probably by sea level or climatic changes that occurred during the Early Jurassic (Cranfield et al., 1994; O'Brien and Wells, 1994). The Heifer Creek Sandstone Member is a major regional unit composed of resistant medium- to coarse-grained and cross-bedded quartzose sandstone, with conglomeratic sandstone towards the top. Some fining upwards sequences near the top of the Heifer Creek Sandstone Member have characteristics of sandy bedload channel and point bar sands (Powell et al., 1993; Ingram and Robinson, 1996). The classification of the Towallum Basalt has long been unclear, but Bradshaw et al. (1994) suggested that the Towallum Basalt occurs at the base of the Koukandowie Formation, between the Ma Ma Creek Sandstone Member and the Gatton Sandstone.

Walloon Coal Measures

The Middle Jurassic Walloon Coal Measures are composed of volcaniclastic, lithic and silty sandstone with interbedded mudstone and siltstone (Wells and O'Brien, 1994b). Ash-fall tuff is also present throughout the sequence (Doig and Stanmore, 2012). The Walloon Coal Measures were deposited in low energy depositional environments by highly sinuous streams meandering across a wide floodplain, as well as in shallow water backswamps (Donchak et al., 2007), possibly during a Middle Jurassic phase of high sea levels (Burger, 1994b). Volcanic ash falls were common, and avulsion rates were high during this period, leading to discontinuous deposition of coal seams. Near the edges of the basin, deposition of channel sands was more common (Ingram and Robinson, 1996). Numerous coal seams and carbonaceous coal shales with a maximum combined thickness of approximately 120 m have been intersected in the centre of the Logan sub-basin near Casino (Ingram and Robinson, 1996). The Maclean Sandstone, which occurs on the eastern basin margin and thickens towards the south at the top of the Walloon Coal Measures sequence in New South Wales, consists of massive to medium bedded, cross-bedded, labile, feldspathic and lesser quartzose sandstone. In Queensland, the Walloon Coal Measures are unconformably overlain by the volcanic and sedimentary rocks of the Main Range Volcanics. In New South Wales, the Orara Formation conformably overlies the Walloon Coal Measures.

Orara Formation (Kangaroo Creek Sandstone)

A revision of the stratigraphy of the post-Walloon Coal Measures sequence has been proposed by Doig and Stanmore (2012) based on lithological records from new exploration wells in New South Wales. This pending stratigraphic revision is currently under review by the Geological Survey of New South Wales (J Greenfield (Geological Survey of New South Wales), 2013, pers. comm.). In the current formal stratigraphic nomenclature (e.g. Wells and O'Brien, 1994b; Geoscience Australia, 2013), the Kangaroo Creek Sandstone is classified as a separate stratigraphic unit overlying the Walloon Coal Measures in New South Wales (e.g. McElroy, 1969, Wells and O'Brien, 1994b). The proposed revision assigns member status to the Kangaroo Creek Sandstone, and if adopted, it will become the lower member within the newly created Orara Formation together with the upper Bungawalbin Member. The Kangaroo Creek Sandstone Member, as defined by Doig and Stanmore (2012), is composed of massive, quartzose, medium- to coarse-grained sandstone, interbedded with layers of siltstone and carbonaceous mudstone and finer-grained sandstone. The Kangaroo Creek Sandstone Member is a fluvial channel sandstone with small to large planar cross-bedding.

The upper member of the newly proposed stratigraphy, the Bungawalbin Member, has been defined in the type well Bungwalbin Creek 2 (Doig and Stanmore, 2012) and is characterised by mudstone and carbonaceous mudstone interbedded with thin layers of fine-grained sandstone from 45 to 115 m thick. Ripple cross-laminations throughout the Bungawalbin Member suggests that this unit was deposited in a fluvial to low-energy overbank environment (Doig and Stanmore, 2012). It conformably overlies the Kangaroo Creek Sandstone Member.

Grafton Formation

The Late Jurassic to Early Cretaceous Grafton Formation has been described by Wells and O'Brien (1994b) and Burger (1994b) as a green-grey sandstone, siltstone and mudstone with minor coal and carbonaceous plant fragments. Within the proposed stratigraphic revision of the Grafton Formation (Doig and Stanmore, 2012), the Grafton Formation has two members, the Piora Member and the Rappville Member. The proposed Piora Member, a thick sandstone unit previously assigned to the Kangaroo Creek Sandstone (Doig and Stanmore, 2012), consists of massive to well-sorted medium- to coarse-grained quartzose sandstone with extensive clay matrix and minor coal clasts. The upper member is the Rappville Member, which is composed of interbedded sandstone, siltstone and mudstone and is restricted to the axial part of the basin. The contact of the Orara Formation with the Grafton Formation marked the return to fluvial sandstone deposition (Doig and Stanmore, 2012).

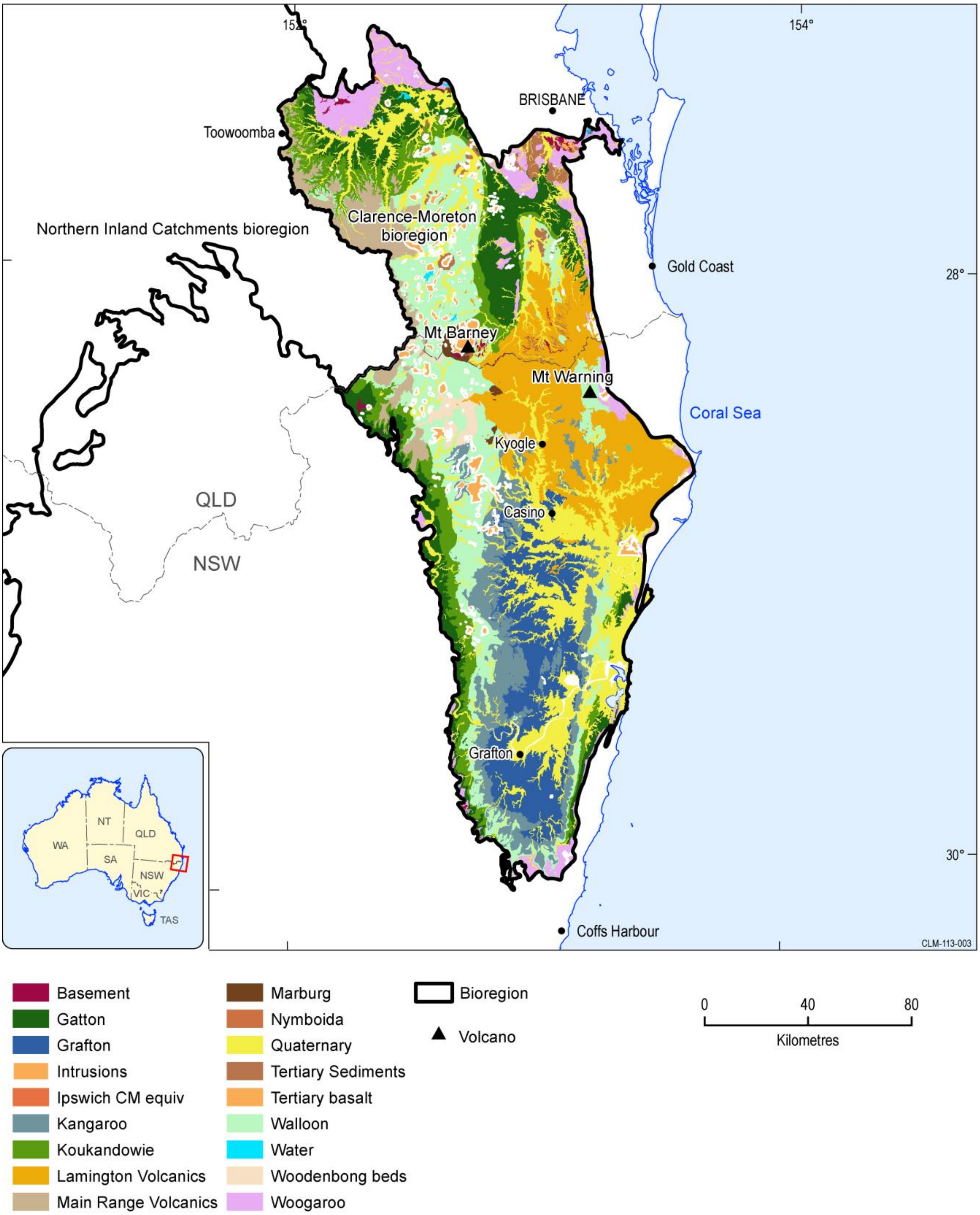

Figure 19 Simplified surface geology of the Clarence-Moreton bioregion

1.1.3.3 Basin history

1.1.3.3.1 Paleogeography

The distribution, internal sedimentary structures and thickness of sedimentary facies in the Clarence-Moreton Basin indicate that environmental changes occurred commonly during deposition across the Clarence-Moreton Basin (O'Brien and Wells, 1994). There is no fossil evidence of significant marine incursions during the latest Triassic and Jurassic (Burger, 1994a), and non-marine conditions prevailed without any significant hiatus from deposition of the Raceview Formation to the Grafton Formation. Paleocurrent measurements show that the sediments of the Bundamba Group were supplied by streams flowing northward from the highlands to the west, south and south-east of the Logan sub-basin (Ingram and Robinson, 1996), and draining the basin via the northern margin along the Esk Trough (O'Brien and Wells, 1994; Korsch et al., 1989). The climate during deposition of the Clarence-Moreton Basin strata was probably humid, as indicated by the presence of plant fragments, locally abundant thin coal and coaly mudstone as well as the absence of typical markers of arid or semi-arid floodplain deposition, such as red oxidised horizons and carbonate nodules (O'Brien and Wells, 1994).

Depositional and tectonic history

The Clarence-Moreton Basin is the youngest of a number of Mesozoic basins in the region that developed on basement rocks of the New England and Yarrol orogens (Korsch and Harrington, 1981; Johnstone et al., 1985; Day et al. 1983).

Burger (1994b) suggested that there is no evidence of basin-wide low-energy deposition during high sea level phases. Rather than complex cyclic depositional processes, Burger suggested that deposition was largely controlled by local tectonics. This theory has also been supported by other authors who indicated that major north-trending transtension-related strike-slip faults are the primary control on deposition (e.g. Korsch et al., 1989: O'Brien et al., 1994a: Ingram and Robinson, 1996). These tectonic processes, which controlled the formation of the Clarence-Moreton Basin and other Mesozoic basins in the region, are linked to large-scale tectonic processes associated with the development of the New England Orogen and the reorganisation of plates initiated in the Late Carboniferous (Korsch et al., 1989). These processes can be summarised as:

- Cambrian to Carboniferous
  - From the Cambrian onwards, eastern Australia was an active tectonic plate margin. During the Devonian and Carboniferous, the broader region of the Clarence-Moreton Basin was characterised by a west-dipping subduction zone (Rosenbaum, 2012) and a forearc basin (Tamworth and Yarrol belts), bounded to the west by a volcanic arc and to the east by an accretionary wedge (Leitch, 1975).
- Permian to Middle Triassic
  - Subduction ceased locally at the end of the Carboniferous, and was followed by orogenic deformation and accretion of exotic terranes during the Permian and Triassic when eastern Australia was part of an active Gondwanan convergent plate margin. Seismic reflection data indicates that during the Late Permian, basin formation beneath the Esk Trough was initiated by trans-tension along dextral strike-slip faults (O'Brien et al.,

1994a). During the Early Triassic, this trans-tension shifted further eastwards to the position of the present Logan sub-basin, initiating formation of the Esk Trough through thermal relaxation (Korsch et al., 1989). Sedimentation in the various Mesozoic basins then commenced in the Early to Middle Triassic in a back arc setting (Doig and Stanmore, 2012) during an episode of strike-slip faulting associated with dextral trans-tension on the West Ipswich Fault (Korsch et al., 1981). This resulted in the deposition of up to 5000 m of sediments in the Esk Trough through thermal relaxation.

- Late Triassic to Early Cretaceous
  - A brief compressional phase in the Middle Triassic was followed by a second tensional episode that initiated the intermontane Ipswich Basin, where deposition was restricted to the east of the north-trending West Ipswich Fault. This separated the stable basement to the west from the tectonically active region to the east (Korsch et al., 1981).
  - Initial sedimentation in the Clarence-Moreton Basin formed coal measures (Nymboida Coal Measures) during the Middle Triassic (Scheibner and Basden, 1998) in the southern part of the basin (Korsch et al., 1981). The southern extent of deposition was probably limited by the Coffs Harbour oroclinal bend (Harrington and Korsch, 1987). Following uplift, deformation and erosion during the Late Triassic, a final tensional phase initiated the deposition of the Bundamba Group in the Clarence-Moreton Basin (Korsch et al., 1981; Johnstone et al., 1985). From the Late Triassic and probably extending into the Cretaceous, a long period of thermal cooling prevailed with the associated thermal relaxation recognised as the dominant driving force for high rates of subsidence across the region. This enabled deposition of sediments in the Clarence-Moreton Basin over rift sequences and basement highs (Korsch et al., 1981; 1989; O'Brien et al., 1994a). Minor dextral strike-slip movements along the basin-forming faults produced locally enhanced subsidence or uplift (Korsch et al., 1981).
- Mid Cretaceous to Cenozoic
  - Rifting of the east coast of Australia and formation of the Tasman and Coral sea basins began in the mid Cretaceous and continued for much of the Cenozoic (Doig and Stanmore, 2012). This rifting and sea floor spreading resulted in heating and uplift of the eastern Clarence-Moreton Basin and the end of dextral transpression, and lava-field type volcanism was associated with this extensional phase during the early Cenozoic (Cohen et al., 2013). However, most Cenozoic lavas in the Clarence-Moreton Basin are related to central volcanoes associated with hot-spot activity from the latest Eocene (~35 Ma) until the earliest Miocene (~23 Ma), forming prominent volcanic features such as the Main Range Volcanics, Mount Warning and Mount Barney in the Clarence-Moreton Basin (Figure 18) (Cohen et al., 2013). Doig and Stanmore (2012) suggested that the location of Mount Warning on the faulted margin of the Clarence-Moreton Basin indicates that extensional stressed occurred at the time of eruption and that pre-existing faults formed pathways for the injection of the volcanics magmas to form large shield volcanoes.

Erosional events

Numerous erosional events have re-shaped the thickness and distribution of sedimentary rocks in the Clarence-Moreton Basin. Russell (1994) noted that additional sediments of up to 3 km in the east and 1.5 km in the west would have been deposited throughout the basin, but were later removed by erosion. Willis (1985) estimated that about 1.5 km of eroded Cretaceous sediments are required to model the thermal maturity profiles below 1 km in the Clarence-Moreton Basin. Gleadow and O'Brien (1994) used the inflection point in apatite fission track apparent age/temperature curves for well Kyogle 1 to calculate an original overburden thickness of 2 to 3 km.

Evidence of erosional events has been reported for many of the stratigraphic units within the Clarence-Moreton Basin. Ingram and Robinson (1996) noted that the deposition of the Nymboida and Ipswich coal measures was interrupted by several mild periods of folding and erosion. Following uplift, deformation and erosion during the Late Triassic, a new cycle of deposition formed the Bundamba Group, overlying older units and separated by a regional unconformity (Stewart and Adler, 1995). Depositional gaps in the Ripley Road Sandstone sedimentation record were linked to a period of erosion/non-deposition associated with a significant eustatic sea level fall at the base of the Sinemurian (Burger, 1994a). Similarly, an originally larger extent has been inferred for the Koukandowie Formation and the Walloon Coal Measures, with both units now reduced to their current limits by uplift and erosion (Ingram and Robinson, 1996). Doig and Stanmore (2012) suggested that the restriction of the Kangaroo Creek Sandstone and Grafton Formation to the central parts of the Clarence-Moreton Basin in New South Wales is the result of widespread erosion, and that they originally extended over a wider area. The entire Cenozoic was marked by erosion, or unroofing, of the sedimentary sequences in the Clarence-Moreton Basin accompanied by widespread volcanism and deposition of alluvial sequences. Higher exhumation rates in south-eastern Queensland than in central Queensland may also explain the absence of Cretaceous successions in this part of the basin (Bryan et al., 2012; Cook et al., 2013).

1.1.3.4 Coal and hydrocarbons

1.1.3.4.1 Coal

Economic coal occurrences in the Clarence-Moreton Basin have been reported primarily from the Walloon Coal Measures, where large near-surface deposits of thermal coal areas are widespread. Many historic records exist from the Clarence-Moreton Basin with mining of the Walloon Coal Measures in both open pit and underground operations since the 1870s (e.g. Matheson, 1993). However, at present there are only two operating coal mines in the Clarence-Moreton Basin (Jeebropilly and New Oakleigh coal mines), and these occur west of Ipswich (approximately 60 km south-west of Brisbane). The coal of the Walloon Coal Measures in the Clarence-Moreton Basin has been described as slightly higher in rank than the coals of the Surat Basin,and it is highly volatile and sub-bituminous (Matheson, 1993; Ingram and Robinson, 1996). The maceral composition of the coal is dominated by vitrinite, whereas the disseminated organic material is composed of vitrinite, and lesser liptinite and inertinite (Ingram and Robinson, 1996). The thickness of coal within the Walloon Coal Measures decreases south of the Casino and Lismore troughs (Doig and Stanmore, 2012).

Coal is also present in other formations in the Clarence-Moreton Basin. For example, the coal of the Koukandowie Formation is compositionally similar to the Walloon Coal Measures. Coal also present in the Triassic sedimentary sequences of the Ipswich and Nymboida Coal Measures (Ingram and Robinson, 1996; Chern, 2004). Chern (2004) suggested that the Ipswich Coal

Measures locally contain thick thermal coal with a moderate to high ash content, but that their lateral extent is discontinuous. Coal mining operations of the Nymboida Coal Measures have in the past been restricted to small areas near Nymboida (Ingram and Robinson, 1996) in the south-western Clarence-Moreton Basin in New South Wales.

Depth below surface

The Walloon Coal Measures form extensive areas of outcrop throughout the Laidley sub-basin in Queensland and along the periphery of the Logan sub-basin in New South Wales. They are covered by several hundred metres of volcanic rock (Main Range Volcanics and Lamington Volcanics) in the western Laidley and Logan sub-basins. In the centre of the Logan sub-basin in New South Wales, the Walloon Coal Measures are covered by the thick sedimentary sequences of Orara Formation and the Grafton Formation, and therefore mostly occur at depths of about 450 to 650 m. The Ipswich Coal Measures outcrop along the eastern part of the Ipswich Basin near Ipswich, and are buried underneath the thick sedimentary sequences of the Bundamba Group and Walloon Coal Measures throughout the remainder of the Laidley sub-basin in Queensland. The Nymboida Coal Measures outcrop at the south-western margin of the Clarence-Moreton Basin in New South Wales. Throughout the rest of the Clarence-Moreton Basin in New South Wales, the Late Triassic coal measures underlie rock of the Bundamba Group, possibly as restricted sediment packages within palaeovalleys as suggested by seismic interpretations (Ties et al., 1985b; Willis, 1994).

1.1.3.4.2 Conventional and unconventional hydrocarbon

The Clarence-Moreton Basin is considered under-explored for hydrocarbons (Ingram and Robinson, 1996; Doig and Stanmore, 2012). Nevertheless, hydrocarbon shows in the Clarence-Moreton Basin date to 1902, when flows of methane were reported from the Grafton-1 well in New South Wales. Since then, numerous oil and gas shows have been reported in the Clarence-Moreton Basin.

O'Brien et al. (1994b) indicated that the sedimentary sequences and especially the Walloon Coal Measures and Koukandowie Formation of the Clarence-Moreton Basin contain abundant oil prone organic material. In addition, Ingram and Robinson (1996) suggested that the Raceview Formation and Ipswich and Nymboida Coal Measures also have source rock potential.

Ingram and Robinson (1996) identified two primary reservoir targets in the Clarence-Moreton Basin in New South Wales, the Ripley Road Sandstone and the Heifer Creek Member. The Ripley Road Sandstone is the most widespread quartzose sandstone-dominated unit within the basin. In addition to the primary targets, Ingram and Robinson (1996) also identified five secondary reservoir targets, which include the Ipswich and Nymboida Coal Measures, Raceview Formation, Gatton Sandstone and the Walloon Coal Measures. Source rock potential has also been attributed to the Kangaroo Creek Sandstone (or Kangaroo Creek Sandstone Member, according to the proposed change in stratigraphy) (Arrow Energy, 2005).

Four different types of traps have been identified in the Clarence-Moreton Basin (Ties et al., 1985b; O'Brien and Wells, 1994; Ingram and Robinson, 1996): drape over sub-Clarence-Moreton Basin topography, reservoir pinch-outs against sub-Clarence-Moreton Basin topography, hanging wall anticlines on minor thrusts and stratigraphic traps.

Examples of these traps include reservoir pinch-outs of the Ripley Road Sandstone and the Raceview Formation near the flanks of base-Clarence-Moreton Basin features such as the Central Platform, the South Moreton Anticline and at the basin margin (O'Brien et al., 1994b). Other major structural traps are high angle reverse fault traps associated with Late Cretaceous to Early Cenozoic deformation. Stratigraphic traps are widespread throughout the Clarence-Moreton Basin, represented primarily by the fine-grained floodplain deposits that occur within most units (Ingram and Robinson, 1996).

Ingram and Robinson (1996) have identified nine primary play areas in NSW where geological conditions are particularly favourable for the potential accumulation of hydrocarbons, including the Casino Trough, South Moreton Anticline, Grafton Trough and the south-western basin margin.

The Clarence-Moreton Basin (as well as underlying infrabasins) formed over basement rocks that are intensively intruded by granite (Sommacal et al., 2008). These granitic rocks may have potential as a geothermal energy source, and may also have influenced the maturity of overlying coal measures. In addition, Cenozoic intrusive and extrusive igneous activity could have been important locally for generating hydrocarbons, although it is possible that this Miocene magmatic activity may have been a general heating event in the Clarence-Moreton Basin, which could have affected hydrocarbon generation on a regional scale (Ingram and Robinson, 1996).

Coal seam gas exploration within the Clarence-Moreton bioregion in Queensland and New South Wales has intensified during the last approximately 10 years, although the exploration occurs at a much smaller scale than for example in the western part of the Cecil Plains sub-basin (part of Northern Inlands Catchments bioregion, Section 1.1.3.1.1) or in the adjacent Surat Basin (less than 100 CSG exploration wells have been drilled within the Clarence-Moreton bioregion to date). The focus of recent CSG exploration activities in the Clarence-Moreton bioregion has been near Casino, primarily targeting the Walloon Coal Measures in the Casino Trough (Ward and Kelly, 2013). The exploration activities in New South Wales confirmed that there is a high gas content in the coals of the Walloon Coal Measures in New South Wales (Doig and Stanmore, 2012).

1.1.3.5 Potential basin connectivities

1.1.3.5.1 Basement: underlying and adjoining basins

The Clarence-Moreton Basin is the youngest of a series of Mesozoic basins in south-east Queensland and north-east New South Wales, and is genetically linked to:

- Esk Trough
  - The Esk Trough contains sedimentary rocks of Middle Triassic age, which may be possible correlatives of the Nymboida Coal Measures (Ingram and Robinson, 1996). The Esk Trough is not a pure pull-apart basin associated with either two parallel strike-slip faults or a major bend in a single strike-slip fault (Korsch et al., 1989). An unconformity between the Esk Trough and the Clarence-Moreton Basin sedimentary succession represents a break of about 12 million years during which time sediments and volcanics of the Ipswich Basin were deposited further to the east (Korsch et al., 1989). Sedimentary rocks in the Esk Trough wedge-out against the Gatton Arch, and the Clarence-Moreton Basin directly overlies the Esk Trough in this vicinity.

- Ipswich Basin
  - the Ipswich Basin is a partly fault-bounded, asymmetric intermontaine basin in south-east Queensland and north-east New South Wales (Chern, 2004). It is interpreted to have formed during a second phase of extension associated with strike-slip faulting.
- Nambour Basin
  - The Late Triassic to Early Jurassic Nambour Basin is a small basin north-east of the Clarence-Moreton Basin in south-east Queensland. It includes the Landsborough Sandstone, which overlies the Paleozoic basement and the Middle Triassic rocks of the Ipswich Basin.
- Surat Basin
  - The Surat Basin is separated from the Clarence-Moreton Basin at its north-western boundary by the sub-surface pre-Jurassic Kumbarilla Ridge (Johnstone et al., 1985). Sedimentation was continuous from the Lower Jurassic across this ridge, but all units thin significantly across the ridge, and only four stratigraphic units (Woogaroo Subgroup/Precipice Sandstone, Gatton Sandstone/Evergreen Formation, Koukandowie Formation/Hutton Sandstone and Walloon Coal Measures) are common to both the Surat and Clarence-Moreton basins. The Helidon Ridge (Figure 17), a basement ridge running south-west from Helidon is considered to be the groundwater-divide and thus the eastern margin of the Great Artesian Basin in this area (Smerdon and Ransley, 2012).

1.1.3.5.2 Potential connectivity with basement aquifers or fracture systems

There is currently a very limited understanding of the hydraulic connectivity between the basal Clarence-Moreton Basin aquifers and the basement rock aquifers. Faults are abundant and fractures are common features throughout the Clarence-Moreton Basin. However, most rocks that form the basement to the Clarence-Moreton Basin sedimentary sequences are part of the New England Orogen, which is dominated by granitic plutons, igneous complexes or metasedimentary rocks. These rock types are commonly considered low-yielding aquifers; however, there are currently insufficient data to determine the degree of hydraulic connectivity between Clarence-Moreton Basin sequences and the underlying basement rocks.

1.1.3.5.3 Cenozoic cover to the basin

Paleogene and Neogene

Paleogene and Neogene volcanoes and fissure eruptions were widespread throughout the Clarence-Moreton Basin. These features were associated with rifting of the east coast of Australia which began during the Early Cretaceous (Bryan et al., 2012).

Prominent central volcanoes within the Clarence-Moreton Basin include the: Main Range Volcanics, Mount Warning, Focal Point, Tweed and Mount Barney igneous complexes, Lamington Volcanics and Alstonville Plateau (Figure 19). These large igneous complexes in south-east Queensland and north-eastern New South Wales are associated with large-scale volcanic migratory ‘swell and pinch’ volcanic chains developed over intraplate plumes (Sutherland, 2003; Cohen et al., 2013). Two major eruptive centres occur in south-east Queensland (the Tweed and Focal Peak shield volcanoes) in addition to many smaller vents and fissures that have been identified to the north and north-west where lavas and sills of the Main Range Volcanics form the crest of the Great Dividing Range (Donchak et al., 2007). The Main Range Volcanics consist of massive, fine-grained olivine basalt, occurring mainly as flows with minor mudstone and fine-grained sandstone locally interbedded with the flows. The lavas of the Main Range Volcanics are typically less than about 200 m (DNRM, 2013, pers. comm.). However, locally near Toowoomba (Figure 19), they reach thicknesses of approximately 250 m and maximum thicknesses of up to 900 m have been reported from the Southern Main Range near prominent central volcanoes (Cohen et al., 2013). These rocks unconformably overlie the Marburg Subgroup and Walloon Coal Measures and are dated as Late Eocene to earliest Miocene (Cohen et al., 2013). The Alstonville Plateau consists of a sequence of Miocene basaltic flows, interbedded with weathering horizons and sediments (Brodie, 2007; Santos and Eyre, 2011). The flows of the Alstonville Plateau are the southern extent of the Lamington Volcanics (Figure 19), which are associated with the Tweed Shield Volcano which erupted between 23 and 20 Ma (Brodie, 2007).

Quaternary

Alluvial sediments: Extensive alluvial sequences have variably infilled river basins in the Clarence-Moreton Basin in Queensland and New South Wales. The thickness of alluvial sediments typically increases downstream from the headwaters to lower parts of the river basins, associated with the change from v-shaped to broader u-shaped valleys. For example, in the Lockyer Valley (Queensland), the maximum thickness of alluvial sequences is approximately 30 to 35 m, with a distinct fining upwards sequence of gravels and coarse sands at the base, and fine-grained floodplain sediments at the top. In the Bremer river basin and Warrill Creek basin, as well as in the Logan river basin, the alluvial sediment thickness is about 20 to 25 m. Similarly, the thickness of alluvial sediments in the Richmond river basin varies, to a maximum of 25 m. Only limited drillhole control exists in the Clarence river basin, hence the thickness of the alluvial sediments is poorly constrained. The headwaters of the Queensland alluvial systems and the Richmond River alluvial system are deeply incised into the Cenozoic Volcanics. As a result, the composition of alluvial sequences is dominantly volcanic-derived, forming the characteristic black soils of these regions. In contrast, the headwaters of the Clarence river basin are formed by rocks of the New England Orogen, which are dominated by plutonic and metasedimentary rocks, resulting in different alluvial sediment compositions in this river basin.

Quaternary coastal sediments and acid sulfate soils: the floodplains in the eastern Richmond river basin, Clarence river basin and Tweed river basin form large back barrier lagoons infilled with Quaternary sediments. These Quaternary coastal or estuarine sediments are dominated by permeable marine sand and impermeable estuarine clay, which are commonly pyritic and can develop into coastal acid sulfate soils if disturbed (Santos and Eyre, 2011).

Potential connectivity and pathways to the surface

Geological structures, particularly faults, can significantly influence vertical connectivity between aquifers. Depending on the characteristics of the fault zone and the aquifers, faults can form either barriers or conduits to groundwater flow, or they can compartmentalise regional groundwater flow systems by juxtaposing rocks of contrasting hydraulic properties. In the Clarence-Moreton Basin, particularly the Logan sub-basin, significant fault off-sets have been inferred based on seismic data (Figure 20). Such fault displacements occur commonly in the

Clarence-Moreton Basin and juxtapose rock units with contrasting hydraulic properties. Many faults may also extend to the surface and potentially form preferential pathways linking deeper and shallower aquifers (Figure 20).

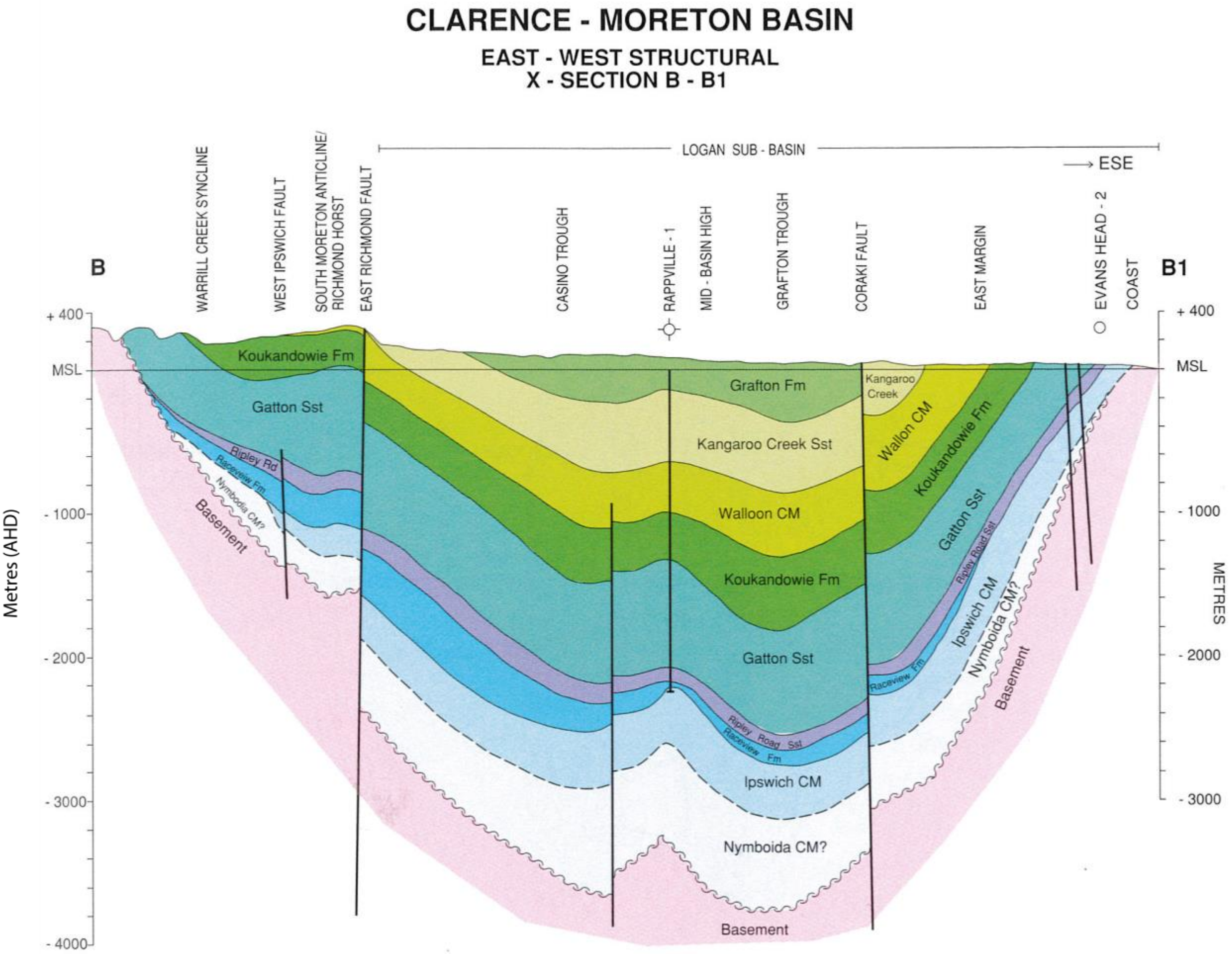

Figure 20 Cross-section through the Clarence-Moreton Basin in New South Wales showing fault orientations and fault offsets

a. The location of this cross-section is shown in Figure 17.

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1.1.4 Hydrogeology and groundwater quality

Summary

The groundwater bearing formations in the Clarence-Moreton bioregion include shallow water-bearing formations (aquifers) formed by the alluvium along river courses and floodplains and deeper formations composed of sedimentary or volcanic rocks. The important alluvial aquifers in the Clarence-Moreton bioregion include the Lockyer Valley alluvial aquifer, Bremer/Warrill alluvium, Logan/Albert river alluvium, Tweed River alluvium, Clarence River alluvium and the Richmond River alluvium. Some of these aquifers are economically important, for example, the Lockyer Valley alluvial aquifer, which is heavily stressed seasonally as it is used for irrigation, with continuous monitoring of water quality and quantity.

The alluvial aquifer systems are typically less than 35 m thick and are tapped using shallow wells. In contrast, deeper aquifers, such as the sandstone aquifers in the Walloon Coal Measures and Koukandowie Formations, vary in their water qualities and are not typically used for beneficial purposes. They are often below a few hundred metres from the ground surface and their water-bearing capacity varies considerably depending on lithological variability.

Their groundwater quality ranges from brackish to saline with maximum salinities equivalent to half the salinity of sea water reported locally. Flow of water in the alluvial aquifers in the Clarence-Moreton bioregion is controlled by a number of factors. An important control is the flow of the associated creek or river, and the alluvial aquifers are often directly connected to the ground surface and are fed by diffuse recharge from rainfall and stream recharge. Thus, the water level and availability in these aquifers are directly related to the recharge and groundwater use. The intake beds of the deeper bedrock aquifers are often not on the ground surface immediately above them.

The Clarence-Moreton bioregion extends across the state boundary between Queensland and New South Wales. Queensland and New South Wales governments have established Water Resource Plans and Water Sharing Plans to guide the management of the water in these aquifers. They organise different aquifers into different groundwater management areas and sustainable groundwater use volumes are estimated for each aquifer.

Groundwater quality and quantity monitoring data availability varies considerably across different aquifers in the Clarence-Moreton bioregion. While alluvial aquifers such as the Lockyer Valley alluvium has a considerable number of monitoring bores, most deep bedrock aquifers are only monitored by a few observation bores in the entire basin. One of the key challenges for the Clarence-Moreton Bioregional Assessment will be to deal with this scarcity of data across deep rock formations and provide recommendations as to what data (and where) will be required for future assessments.

1.1.4.1 Groundwater systems

1.1.4.1.1 System boundaries and hydrostratigraphic units

The major hydrostratigraphic units present in the Clarence-Moreton bioregion are:

- Cenozoic to recent alluvium and volcanic formations
  - alluvial systems are shallow formations along the river valleys and flood plains within the basin and the volcanic formations include the Cenozoic basalt aquifers. The alluvial aquifer systems include the Lockyer Valley alluvium, the Bremer River, Warrill Creek and Purga Creek alluvial systems, the Logan/Albert river alluvial systems, the Tweed River alluvium, the Clarence River alluvium and the Richmond River alluvium.
- Jurassic to Cretaceous sandstones
  - including the Grafton Formation, the Orara Formation, the Walloon Coal Measures, the Koukandowie Formation and the Gatton Sandstone
- Woogaroo Subgroup
  - with a Triassic to Early Jurassic origin
- basement aquifers
  - Paleozoic age basement rocks, Permian to Triassic intrusive rocks and Permian to Triassic sedimentary and metasedimentary rocks.

Alluvial aquifer systems

Alluvial aquifers are the major source of groundwater supply within the basin. The unconfined alluvial aquifers receive much of their recharge from river and creek beds as well as from rainfall (diffuse) recharge. In the headwaters and especially where the alluvial aquifers are incised deep into the Main Range Volcanics, bedrock also is a substantial contributor of recharge to the alluvium. In addition, at the edge of the alluvial aquifer systems, Clarence-Moreton bioregion formations recharge the alluvium locally.

The Lockyer Valley alluvium extends over more than 200 km^2 and is approximately 30 to 35 m thick (Hair, 2007; Cox and Raiber, 2013) throughout much of the unconfined to semi-confined aquifer. It is one of the most heavily developed aquifer systems in the Clarence-Moreton bioregion. The alluvium is characterised by coarse gravel towards the headwater areas in the southern tributaries where the gradient is steep; the gradient decreases towards the north-east where the alluvium is dominated by clay, sandy clay, sand, sandy gravel or gravel. The alluvial sediments are generally marked by fining-upwards sequences throughout the Lockyer Valley. The central and lower portions of the valley have a considerable cover of clays ranging from a thickness of 2 to 20 m. The groundwater yields from the alluvium ranges up to 50 L/second, although low supplies in the order of 0.01 L/second have also been reported (Pearce et al., 2007b).

The Bremer River, Warrill Creek and Purga Creek alluvial systems are composed of Cenozoic to Quaternary alluvial and colluvial sediments, deposited along the major drainage systems spread over the Bremer river basin which is located 40 km south-west of Brisbane and which is a tributary system to the Brisbane River. The aquifer material generally consists of unconsolidated alluvial and colluvial sediments adjacent to existing channels and drainage lines with the flood plain sediments being predominant in the lowermost sections (Pearce et al., 2007a).

Most of the groundwater resources in the Logan sub-basin are found in the Logan/Albert rivers alluvium, and this also includes smaller tributaries such as Teviot Brook. The majority of the alluvium where most of the groundwater is extracted has a thickness ranging between 5 and 25 m in this sub-basin. Further details of the alluvial aquifer in the Logan sub-basin are reported in the Logan Basin Draft Resource Plan - Environmental Investigations Report – Volume I (DNRM, 2007).

The Tweed River alluvium is composed of the shallow ‘upriver’ alluvial aquifer and the coastal floodplain alluvial aquifers. The shallow ‘upriver’ alluvial aquifer is characterised by coarse material and is well connected to the surface water system. The coastal floodplain alluvial aquifers are composed of relatively fine material often interspersed with silt and clay layers. The Richmond River alluvium belongs to the north-east of the New South Wales part of the Clarence-Moreton bioregion. It comprises Quaternary fluvial and estuarine sediments of gravel, sands, silts and mud. They form unconfined to semi-unconfined aquifers with medium to high permeability. These aquifers are generally shallow with good water quality and yields in the order of 0.5 to 1 L/second (Brodie, 2007). Similarly, the Clarence and Coffs river alluvial systems are formed by the Clarence River and cover an area of about 924 km^2 in the New South Wales part of the Clarence-Moreton bioregion.

Bedrock aquifer systems

The Main Range Volcanics have thicknesses of typically less than 250 m near Toowoomba (Figure 18, Section 1.1.3) but reach maximum thicknesses of up to 900 m in the southern Main Range (Section 1.1.3.5.3). They are one of the most important aquifer systems in the Clarence-Moreton bioregion. While there is only limited irrigation associated with the basalts of the Main Range due to the steep gradients, they have a strong influence on recharge to alluvial aquifer systems and are a major source of creek flow particularly in the headwaters of the Lockyer Valley basin, Bremer/Warrill river basins and in the Logan river basin.

The Alstonville Plateau basalt aquifers represent an area of highland basalts that rise up above the alluvial floodplain sediments, located between Lismore and Ballina, and covering an area of approximately 391 km^2. The Cenozoic basalt sequence is recognised as an important aquifer system in the Lower Richmond river basin in the Clarence-Moreton bioregion in north-east New South Wales. The aquifer is comprised of a Cenozoic Basalt Plateau that overlies older sedimentary rocks of the Clarence-Moreton bioregion. They also include the Lismore Basalt unit, which is the south-easterly portion of the larger Lamington Volcanic. The aquifer nature range from shallow unconfined to deep semi-confined aquifer systems in fractured horizons.

In the New South Wales part of the Clarence-Moreton bioregion, the alluvial deposits are underlain by the Orara and Grafton formations, Walloon Coal Measures and the Marburg Subgroup (consisting of Koukandowie Formation and Gatton Sandstone, Section 1.1.3). While unconfined groundwater systems occur at shallow depths in the alluvial systems, Cenozoic volcanics and older sediments of the basin, the sandy nature of Kangaroo Creek Sandstone and Piora members suggests that they may act as confined aquifers or aquitards at depth in the basin. But they have poor aquifer properties below about 150 m and have limited hydraulic communication beyond a limited area adjacent to the outcrop (Doig and Stanmore, 2012). The Rappville and Bungawalbin members in the Grafton and Orara formations are likely to act as aquicludes and thus prevent vertical migration of water across them thus isolating any local aquifer system that may exist (Doig and Stanmore, 2012). Much more work is required to verify the hydraulic nature of these formations.

The Walloon Coal Measures are often considered as an aquitard on a regional scale due to their low permeability and storage capacity. They are dominated by fine-grained sediments and contain shales and siltstones. However, particularly towards the basin margin, sandstones are more dominant in the Walloon Coal Measures sequence, and the Walloon Coal Measures are likely to act as an aquifer in these areas (Doig and Stanmore, 2012). The Mclean Sandstone, which represents the upper part of the Walloon Coal Measures, as well as the underlying Koukandowie Formation are considered as low permeability aquifers, aquitards or aquicludes at depths below any near surface groundwater system influence (Doig and Stanmore, 2012). The Gatton Sandstone underlying the Koukandowie Formation is also a low permeability aquifer. The Woogaroo Subgroup contains quartzose sandstone, shale, siltstone and conglomerate and has medium-grained sandstones devoid of carbonaceous material and is considered to be a good aquifer system.

In the Queensland part of the Clarence-Moreton bioregion, the Grafton and Orara formations are absent and the Quaternary alluvium and Cenozoic Main Range Volcanic rest directly above the Walloon Coal Measures. Other older formations follow similar hydraulic characteristics as in the New South Wales side of the basin. It may be noted that the hydraulic characteristics of these formations are generalised and are likely to be variable in different parts of the basin due to the variable nature of lithology within each lithographic unit (Section 1.1.3).

Basement aquifer systems

Only very limited data are available on the hydrogeology of the hydraulic basement to the Clarence-Moreton bioregion and the basement blocks that limit the Clarence-Moreton bioregion in Queensland and New South Wales. While there is only limited information available, yields are likely to be low, although higher yields of up to 16 L/second have, for example, been reported for the Neranleigh Fernvale Beds near the Gold Coast (Metgasco, 2007). Variable yields have also been reported for Permian to Triassic intrusive rocks in south-east Queensland (Helm et al., 2009), with typical yields ranging up to 2 L/second, but higher yields of 2 to 5 L/second obtained in areas of locally enhanced fracturing. However, generally, most of the basement rocks are assumed to have relatively limited storage (Helm et al., 2009).

1.1.4.2 Groundwater quality

In this section, groundwater quality is reported in terms of either salinity (mg/L) or electrical conductivity (EC; µS/cm) as reported in the referenced documents. The readily available data pertaining to alluvial aquifers and basin aquifers are summarised in Table 6 and Table 7, respectively. A more comprehensive discussion on groundwater quality and groundwater chemistry will follow in the future report: Conceptual Modelling of the Clarence-Moreton bioregion. Groundwater quality data for the alluvial aquifers is more abundant and was compiled on a river basin basis as shown in Table 6. Data for the river basins in south-east Queensland were primarily sourced from two hydrogeological investigations conducted for the National Action Plan for Salinity and Water Quality (Pearce et al., 2007a, 2007b) as well as from the Queensland Department of Natural Resources and Mines database (2013). According to the Bureau of Meteorology (2010) no quality assured data is available for the New South Wales region. However, New South Wales groundwater quality data were compiled from a number of relevant studies (e.g. McKibbin and New South Wales Department of Land and Water Conservation, 1995; Brodie, 2007; Metgasco, 2007; New South Wales groundwater database, 2013).

1.1.4.2.1 Spatial variability of groundwater quality

Groundwater quality throughout the alluvial, volcanic and basin aquifers in the Clarence-Moreton bioregion exhibits a strong degree of spatial and temporal variability.

Alluvial and coastal aquifers

Typically, groundwater in the alluvium is fresher than groundwater in the sedimentary bedrock (Table 7), although there are areas in the alluvium where salinity can reach levels similar to those observed in the bedrock aquifers (e.g. Walloon Coal Measures). This is mainly due to discharge of groundwater from the underlying formations into the alluvial aquifers, longer residence time of infiltrating groundwater in the unsaturated zone during groundwater recharge within low permeability sediments and evapotranspiration from shallow watertables (Pearce et al., 2007a). Groundwater quality in the Lockyer Valley alluvium is spatially and temporally highly variable ranging from fresh to very saline (Pearce et al., 2007a). The primary controls of the spatial variability are the nature of connectivity of the alluvial aquifer with surface water and the underlying bedrock.

Near the headwaters of the Lockyer Creek and in the upper parts of the tributaries to the Lockyer Creek, groundwater is commonly fresh, marking the strong influence as a major source of recharge to the alluvial aquifer of the Main Range Volcanics which generally contain good quality groundwater (Raiber and Cox, 2012; Watkinson et al., 2013). Further down gradient, groundwater becomes more saline due to discharge from the underlying basin aquifers. Water in the Bremer/Warrill alluvium is mostly fresher than groundwater from the underlying sedimentary units (here primarily Walloon Coal Measures). A gradual increase in the EC of alluvial groundwater is observed in the down gradient river direction, that is, alluvial groundwater quality is better in the upstream direction (Pearce et al., 2007b). Similar to the patterns observed in the Lockyer Valley, the observed spatial changes in the Bremer/Warrill alluvial systems are due to the dominance of recharge to the alluvium from the Main Range Volcanics in the headwaters near the Great Dividing Range, and the progressively increasing influence of the connectivity with the Walloon Coal Measures down gradient.

The typical salinity in the Logan/Albert River alluvium is in the range of 500 to 2600 mg/L with a significant increase since 1950s in some parts (Queensland Water Resources Commission, 1991). The groundwater quality in the Richmond River and Clarence River alluvium is generally good (State of Catchments, 2010), however, this assessment is based on only limited quality assured data. In the Casino area, the highest beneficial groundwater use is for stock and agricultural purposes (Metgasco, 2007). According to Beale et al. (2004), although groundwater salinity data are not available for most of the Clarence River alluvium, some measured high salinity samples in creeks, such as Tooloom Creek, Washpool Creek, and Peacock Creek, corresponds with local high groundwater salinities.

The pH of groundwater in the alluvial aquifers is mostly around 7.0. However, in some areas, groundwater contained in sediments where acid sulfate soils in coastal or estuarine areas have developed can be characterised by low pH of approximately 3.5 (Johnston et al., 2004, 2009; Santos and Eyre, 2011). These ASS materials are often found at 1 to 2 m under the ground surface (Tulau, 1999). It has been confirmed that some pollution has been caused by the acid sulfate soil materials in the Richmond and Clarence river floodplains (Tulau, 1999; Santos et al., 2011). When the acid sulfate soils are exposed to air due to watertable fluctuation, sulfuric acid will be generated. Consequently, the pH of groundwater in these areas will decline. Furthermore, the decrease of pH can increase the solubility of many minerals and consequently may cause water salinity variation. However, this influence should be limited to shallow groundwater and surface water systems.

Bedrock aquifer systems

Water quality in bedrock aquifers ranges from fresh to very saline with typically higher variability than that in the overlying alluvial aquifers (Table 6). For example, groundwater contained in the Main Range Volcanics is generally fresh due to thin soil coverage and rapid recharge through the well-developed fracture network which only allows a limited degree of evapotranspiration to occur. In contrast, the salinity of groundwater in the Walloon Coal Measures can vary from 750 to 19,475 mg/L (Metgasco, 2007). The salinity distribution can be affected by a number of factors, such as lithological variability and the relative position within the basin, recharge processes, depth, residence time and interaction with surface water.

Near the Great Dividing Range, where bedrock aquifers are overlain by the Main Range Volcanics, groundwater quality in the Walloon Coal Measures and other bedrock aquifers is typically similar to the groundwater quality in the Main Range Volcanics, highlighting that recharge of the basin aquifers occurs primarily through the overlying Main Range Volcanics in these areas. Elsewhere, salinity in the basin aquifers is generally higher than that observed in alluvial aquifers as recharge primarily occurs through the thick clay-rich regolith profiles, which allow only small rates of recharge and which promote a high degree of evapotranspiration of infiltrating rainwater prior to recharge.

A notable exception to this is the Woogaroo Subgroup, which mostly contains groundwater of drinking water quality (Pearce et al., 2007b; Raiber and Cox, 2012). However, the data currently available cannot depict a complete spatial and temporal quality evolution across the Clarence-Moreton bioregion. This is due to the lack of groundwater observation bores especially in the deeper parts of the bedrock aquifers.

Basement aquifer systems

Only very limited information is available on the groundwater quality of basement aquifers. Electrical conductivities ranging from 1,000 to 10,000 µS/cm have been reported for the Neranleigh Fernvale Beds in south-east Queensland (Metgasco, 2007). Depending on the fracture network and regolith developed on the rocks, groundwater quality is likely to be highly variable.

1.1.4.2.2 Temporal variability of groundwater quality

An assessment of temporal variability of groundwater in the alluvial aquifers is currently limited to the Lockyer Valley. Here, data from Watkinson et al. (2013) and the groundwater database (Department of Natural Resources and Mines, 2013) demonstrate a distinct change in groundwater quality of the alluvial systems of the Lockyer Valley following the 2011 floods. During the drought, groundwater salinity had progressively increased in some areas due to a lack of surface water recharge and upwards discharge from the underlying bedrock into the alluvium induced by continuous pumping (Watkinson et al., 2013). Following the break of drought and the subsequent flooding in 2011, alluvial groundwater has become fresher in most parts of the river basin. For example, in the lower Lockyer Valley near the outlet, the electrical conductivity has increased to approximately 25,000 µS/cm, and following the flood, the electrical conductivity at the same location has decreased to approximately 2500 µS/cm (Watkinson et al., 2013). A similar influence of episodic flood events on groundwater recharge has been noted in other similar river basins in south-east Queensland (e.g. King et al., in press) and is also likely for other river basins with similar lithology within the Clarence-Moreton bioregion. In contrast, groundwater quality in the bedrock aquifers is less likely to be influenced by short-term climatic patterns.

Table 6 Salinity summary of the bedrock aquifers

Hydrostratigraphic unit	Salinity min. (mg/L)	Salinity mean (mg/L)	Salinity max. (mg/L)	Number of samples	EC min. (uS/cm)	EC mean (uS/cm)	EC max. (uS/cm)	pH	Reference
Main Range Volcanics		169		285				7	(McKibbin, 1995)
				2		3112			(Pearce et al., 2007b),
	220		1,900		285		2700		DNRM(2013)
Grafton Formation		1125		24				7	(McKibbin, 1995)
					540	-	3400		(Metgasco, 2007)
Orara Formation		513		24				7	(McKibbin, 1995)
	1,500	–	2,000						(Metgasco, 2007)
Walloon Coal Measures		750		10	3,000	–	6,000	8	(McKibbin, 1995)
	1,500	–	19,475		3,000	–	6,000		(Metgasco, 2007)
				37		8,554			(Pearce et al., 2007b)
Koukandowie Formation	359	4,248	14,496	9		6,607			(Pearce et al., 2007a)
Gatton Sandstone	333	6,452	24,294	42		9,971			(Pearce et al., 2007a)
				11		7,643			(Pearce et al., 2007b)
Woogaroo Subgroup		866		7				8	(McKibbin, 1995)
	961	2,518	4,147	6		4,225			(Pearce et al., 2007a)

Table 7 Salinity summary of the alluvial aquifers

Alluvium unit	Salinity minimum (mg/L)	Salinity mean (mg/L)	Salinity maximum (mg/L)	Number of samples	EC minimum (µS/cm)	EC mean (µS/cm)	EC maximum (µS/cm)	Reference
Lockyer Valley alluvium	91	1,904	18,000	307		3,327		(Pearce et al., 2007a), Department of Natural Resources and Mines, 2013)
					350		25,000	DNRM (2013) Raiber (unpublished data)
Bremer / Warrill alluvium				100		2,508		(Pearce et al., 2007b)
	~500		~6,350		500		1,000	DNRM (2013)
Logan/Albert River alluvium		872						(Energex, 2010)
	500	–	2,600					(QWRC, 1991)
Richmond River alluvium		594		401				(McKibbin, 1995)
					1,000	–	2,500	(Metgasco, 2007)
Clarence River alluvium		544		24				(McKibbin, 1995)
Tweed River alluvium		427		1				(McKibbin, 1995)

1.1.4.3 Groundwater flow

Groundwater flow in the pre-Cenozoic aquifers of the Clarence-Moreton bioregion is divided into a westerly and easterly flow component. The groundwater divide between an easterly and westerly flow direction (and thus, the eastern boundary of the Great Artesian Basin) is believed to be the Helidon Ridge (Smerdon et al., 2012), located near the western boundary of the Laidley Sub-basin. However, the exact orientation of this groundwater divide is at present poorly constrained due to insufficient monitoring bores. In addition, the location of the groundwater divide is likely to be different for different aquifers. Generally, flow in the alluvial aquifers follows that of the associated creeks and rivers with water levels responding to recharge, pumping and irrigation stresses. A few groundwater flow models have been built for the Lockyer Valley alluvial aquifer system in recent years. A detailed analysis of the groundwater flow in the Richmond River alluvial aquifer is presented in Drury (1982).

Vertical hydraulic relationships between shallow and deep aquifers or between different bedrock aquifers are poorly constrained throughout much of the Clarence-Moreton bioregion. However, where sufficient groundwater chemistry and water level are available (e.g. Lockyer Valley and Bremer/Warrill river basins), it is possible to infer hydraulic relationships between alluvial and bedrock aquifers. For example, groundwater chemistry and water level data show that the alluvial aquifer systems are strongly connected to the basalts of the Main Range Volcanics in the upper reaches of the river basins in south-east Queensland and north-east New South Wales. Further down gradient, where the alluvial aquifer systems commonly overlie Clarence-Moreton bioregion sedimentary sequences, the nature of the connectivity between alluvium and bedrock is more variable, both spatially and temporally. The high salinities of alluvial groundwater in some areas confirm that there is mixing of water between the alluvial and Clarence-Moreton Basin aquifers. However, elsewhere, distinct water chemistry and groundwater levels suggest that there is only limited connectivity.

1.1.4.3.1 Groundwater levels and yields

Groundwater levels in the unconfined to semi-confined alluvial aquifers range from 10 to 30 m, and are heavily influenced by recharge from excess rainfall and groundwater extraction for irrigation. Under the current management and climatic conditions, the Lockyer Valley alluvial aquifer remains under stress, and the groundwater resources there are exploited beyond their sustainable yields with pumping often continued until bore yields significantly decline, however, groundwater levels partially recover during high rainfall years. Since the 1970s, the majority of the monitoring bores in the Lockyer Creek basin have shown a net fall in groundwater level ranging from 5 to 15 m (Hair, 2007). A number of different studies have been undertaken to quantify the groundwater resources of Lockyer Valley alluvial aquifer (Durick and Bleakley, 2000; Hair, 2007; Chee et al., 2012; Bleakley and Boreel, 2012a, 2012b, 2012c; Wolf et al., 2012). Similar trends have been observed in the Bremer/Warrill alluvium since the 1960s with more significant declines since 1992. However, the break of drought in 2008 and the flooding of 2011 have resulted in a very significant recovery of groundwater levels in the Lockyer Valley and other river basins in south-east Queensland, with water levels often recovering to the pre-drought levels of the early 1990s.

In the Clarence area, the Richmond River alluvium also has shallow watertables. They have bore yields in the range 0.5 to 1.0 L/second. These unconfined to semi-confined aquifers have medium to high permeability and are replenished by the recharge from excess rainfall (Brodie, 2007). Groundwater levels in the Richmond and Clarence alluvial and coastal areas are of particular importance because of the presence of acid sulfate soils combined with drainage activities on a large scale. Acid sulfate soils are found underlying coastal flood plains and wetlands in the Richmond and Clarence river basins in New South Wales (locations reported in Section 1.1.2). Maintaining acid sulfate soils in a fully saturated state is the key to keeping them stable with drainage exposing the pyrites, which upon exposure to oxygen and oxidation, will generate acid. Johnston et al. (2004) concluded that the acidity of drainage water was highly sensitive to the hydraulic gradient between the groundwater table and the adjacent drain water level with most seepage occurring while the back swamp groundwater table being within a narrow elevation range, referred to as an ‘acid export window’. Land and Water Management Plans have been developed by the relevant councils with a primary focus on managing the impacts of acid sulfate soils. For instance, the plan developed by the Richmond River County Council has established a requirement for managing acidic and potentially acidic soils underlain by an artificially lowered watertable.

The Cenozoic Basalt aquifer in the Alstonville Plateau in the New South Wales part of Clarence-Moreton bioregion has productive areas within the 20 to 100 m depth range with yields ranging from 0.5 to 1.5 L/second. Despite the low to medium yielding nature of these basalt aquifers, high yields of up to 30 L/second have been reported at shallow depths.

In the pre-Cenozoic Clarence-Moreton bioregion aquifers in Queensland, the groundwater potentiometric contours show that groundwater levels and flows generally follow the topographic gradients (Pearce et al., 2007a, 2007b). For the pre-Cenozoic formations of the Clarence-Moreton bioregion, availability of groundwater level data is rather sparse both spatially and temporally. Groundwater level data for the Clarence-Moreton bioregion aquifers are available for much of the Lockyer Valley and in the Bremer/Warrill/Purka river/creek basins. The details of this are available in the corresponding hydrogeological investigations reports for these basins (Pearce et al., 2007a, 2007b, DNRM, 2005) as well as in the groundwater database (Department of Natural Resources and Mines, 2013). However, the spatial and temporal resolution of the basin's groundwater level data is not adequate to support a long-term trend analysis, and in particular, there is a lack of nested bore sites where different basin aquifers are monitored at the same site in order to determine vertical relationships.

The pre-Cenozoic aquifers within the Clarence-Moreton Basin sequence are generally low yielding with average yields ranging from 0.5 to 2.5 L/second in the sandstones, siltstones and conglomerates of the Bundamba Group. Reported average and maximum bore yields for the Walloon Coal Measures, Kangaroo Creek Sandstone and Grafton Formation are 0.5, 0.4 and 0.3 L/second, respectively (Brodie, 2007). The maximum yields reported for these aquifers are 5, 10 and 1.5 L/second, respectively. The most significant aquifer in the Clarence-Moreton bioregion Management Area is the Woogaroo Subgroup. The Ripley Road Sandstone is the upper unit in the Woogaroo Subgroup, and is equivalent to the Precipice Sandstone of the Surat Basin. Past investigators have referred to this sequence as the Helidon Sandstone (which is not a current stratigraphic name anymore). The unit comprises fine- to coarse-grained quartzose sandstones occurring from the surface to a maximum depth of 500 m. It is a reliable producer of good quality water, with yields of up to 15 L/second thus providing base flow to the creeks where it is present within the Lockyer Creek.

1.1.4.3.2 Groundwater planning and use

Groundwater planning and management is performed by the respective state governments in the Clarence-Moreton bioregion. Water resources in New South Wales are governed by a number of acts and are administered by the New South Wales Department of Primary Industries, specifically New South Wales Office of Water (Anderson et al., 2013). The Office of Water is primarily responsible for the strategic management of the state's fresh water resources where groundwater planning and management is implemented through ten-year water sharing plans. Water Sharing Plan Areas are subdivided by Groundwater Management Areas and Groundwater Sources. The major coal producing basins of New South Wales contain 35 Water Sharing Plans, 60 Groundwater Management Areas and 184 Groundwater sources (Anderson et al., 2013). The long-term average annual extraction limits (LTAAEL) for the aquifer systems are reported in respective Water Sharing Plans. The LTAAEL is the proportion of the long-term average annual recharge of water to the groundwater system that is available for extraction. The pre-Cenozoic aquifers are classified into one management unit called the Clarence-Moreton Groundwater Management Area. There is currently limited use of this aquifer system.

Similarly, Water Resource Plans in Queensland have been established for the management of the artesian and some sub-artesian groundwater resources. Great Artesian Basin Water Resource Plan and Resource Operation Plan governs the management of the artesian aquifers. Water sharing plans and water resources plans relevant to the Clarence-Moreton bioregion are listed in Table 8. The allocation and licensing of water are subject to these water sharing/ water resource plans. An entitlement and licence is required to take water from a sub-artesian aquifer mentioned in the Water Resource/Water Sharing Plans.

Various studies conducted in recent years report the overuse of the alluvial groundwater resources in the Clarence-Moreton bioregion. For example, Hair (2007) reported that under the current management and climatic conditions, the Lockyer Valley alluvial aquifer remains under stress with the groundwater resource being heavily pumped beyond the sustainable levels. A water balance calculation by Hair (2007) indicated that during average rainfall years, the total groundwater pumping throughout the Lockyer Valley exceeded recharge by approximately 3375 ML/year. Similarly, enhanced declining trends in the water levels of the Bremer Valley alluvial aquifer have been noted since the 1990s resulting from excessive use. The aquifer risk assessment report published by the New South Wales Department of Land and Water Conservation (1998) classified the Richmond alluvium as a high risk aquifer and the Tweed and Clarence coastal sands as medium risk aquifers. Basalt aquifers of the Alstonville Plateau have been formalised into a groundwater management area which has been classified as a highly stressed aquifer due to the risk of over-extraction or contamination (DLWC, 1998).

1.1.4.3.3 Groundwater monitoring and assessment

Adequate monitoring information is available only for the alluvial aquifers. The Lockyer Valley alluvial aquifer has approximately 400 existing monitoring bores located throughout the valley. Groundwater levels are monitored in most of these bores on a quarterly basis. Around 130 monitoring bores have been recorded in the groundwater database for the Bremer/Warrill alluvium. While the oldest record commenced as early as 1964, there are only a few bores with adequate long-term records. As part of the National Action Plan for Salinity and Water Quality (Pearce et al., 2007a), 50 monitoring bores were installed in the Walloon Coal Measures and Marburg Subgroup aquifers as well as in the alluvial aquifer in the Bremer river basin and the water levels in these bores were measured on a three month basis since 2004. A number of piezometers have been installed in the Richmond River alluvium by the New South Wales Department of Natural Resources in the late 1990s and some have continuous data loggers to record hydrographs of groundwater levels. Similarly long-term monitoring of groundwater levels in the Alstonville basalt aquifers commenced in 1987 with construction of two nested bores and an addition of another seven bores in 1999.

In general, however, groundwater level monitoring is sparse in the bedrock aquifers and this is particularly the case on the New South Wales side of Clarence-Moreton bioregion. For instance, there are not many bores in the New South Wales part of the basin, which have more than 100 records of groundwater level data.

1.1.4.3.4 Knowledge gaps

Based on the literature and database reviews that underpinned this contextual statement, a lack of knowledge on the hydrogeology of the Clarence-Moreton bioregion is significant compared to other basins where CSG activity is taking place such as the Surat Basin. While different aquifer systems have been delineated and characterised, there is a lack of continuous monitoring of water quality and quantity that is adequate enough to support any numerical modelling framework with the exception of the alluvial aquifers of the Lockyer Valley and possibly the Bremer river basin, Warrill Creek and Purga Creek basins. Even for monitored bores, screening information is absent in many instances from the digital groundwater database in New South Wales, which limits the use of these data (although records of the hydrostratigraphic unit of the screened interval may exist as hard copies). Lack of knowledge on the vertical connectivity of the different aquifer layers poses a challenge to any meaningful application of groundwater models to predict the pathways of coal seam gas impacts. It is notable that the water sharing plans for some of the groundwater management areas are in the development phase. Similarly, with groundwater quality monitoring in the New South Wales part of the Clarence-Moreton bioregion, the data are sparse and where available, data quality is often limited. For instance, the depth at which water quality is measured is often missing from the datasets resulting in ambiguity about the aquifer being monitored. In general, scarcity of data that supports hydrogeological characterisation in addition to groundwater quality and quantity data represent the main challenges for the Clarence-Moreton Bioregional Assessment.

Table 8 Water Sharing Plans for the Clarence-Moreton bioregion

Groundwater system	Water Sharing Plan / Water Resource Plan	Date effective	Groundwater Management Area (Entitlement)
Lockyer Valley Alluvial Aquifer	Water Resource (Moreton) Plan (2007)	2011-11-24	Lockyer Valley
Bremer/Warrill Alluvium	Water Resource (Moreton) Plan (2007)	2011-11-24	Bremer/Warrill Alluvium
Logan/Albert river alluvium	Water Resource (Logan Basin) Plan (2007)	2009-12-18	N/A
Richmond River Alluvium	Richmond river Area Regulated, Unregulated and Alluvial	2010-12-17	Northern River Region – Richmond River Alluvium GWMA (4151 ML)
Clarence River Alluvium	Clarence Unregulated and Alluvial Water Sources	2014 (anticipated)	Northern River Region – Clarence Alluvium GWMA
Tweed River Alluvium	Water Sharing Plan for the Tweed River Area Unregulated and Alluvial Water Sources 2010	2010-01-10	Tweed River Area and Alluvial Water Sources
Alstonville Basalt	Alstonville Plateau Water Sharing Plan	2014-07-01 (anticipated)	proposed to be merged with North Coast Fractured and Porous Rock Groundwater Sharing Plan
Walloon Coal Measures, Marburg Subgroup and Woogaroo Subgroup (Queensland)	Water Resources (Great Artesian basin) Plan 2006	2006-03-31	Clarence-Moreton Management Area

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1.1.5 Surface water hydrology and surface water quality

Summary

The hydrology and water quality section includes analysis of (i) surface water systems, including discussion about rainfall, evaporation, river systems, flooding history and water storage infrastructure in each of the relevant river basins, (ii) surface water quality, including existing monitoring, load estimates and key water quality issues including acid sulfate soils; and (iii) surface water flow, which describes existing stream flow monitoring locations and data available.

The Clarence-Moreton bioregion covers an area from south-east Queensland to north-east New South Wales and includes seven Australian Water Resources Council catchments: three in Queensland and four in New South Wales (Figure 21). The ones in Queensland include the Brisbane river basin, Logan-Albert river basin and South Coast basin and in New South Wales the Tweed river basin, Brunswick river basin, Richmond river basin and Clarence river basin. The Clarence-Moreton bioregion boundary does not follow the full extents of these river basins but does include parts of each of them.

River basin sizes in the Clarence-Moreton bioregion range from 508 km^2 for the Brunswick river basin to over 22,000 km^2 for the Clarence river basin. Rainfall ranges from an annual mean of 922 mm for the Brisbane river basin to 1879 mm for the Brunswick river basin. Mean annual evaporation ranges from 800 to 1131 mm and runoff coefficients (runoff divided by rainfall) vary by a factor of more than two (0.14–0.40) across the Clarence-Moreton bioregion. The Clarence river basin has the largest annual runoff of all of the river basins in the Clarence-Moreton bioregion. Water storages exist in all river basins but the largest is the South East Queensland (SEQ) Water Grid (Queensland Water Commission, 2010) which connects many of the river basins and population centres in south-east Queensland through more than 535 km of pipeline.

The largest total export of sediment in the Clarence-Moreton bioregion comes from the Clarence river basin which has loads nearly 200 times higher than those from pre-European conditions. The largest sediment export rate (per unit area) comes from the Tweed River. Total phosphorus export is the highest for the Brisbane river basin which has loads more than five times those from pre-European conditions. Although the largest annual total nitrogen export comes from the Clarence river basin, the Logan-Albert River exports the highest amount of nitrogen per unit area. Serious water quality problems are associated with the drainage of acid sulfate soils located in the coastal areas of New South Wales with 14,700 ha of the Clarence wetlands being affected by drainage activities. Drainage of acid sulfate soils results in the flow of acidic (low pH) water into the surface water system, with reported pH as low as 2.5.

All river basins that are represented in the Clarence-Moreton bioregion have active or discontinued river gauging stations. However, in some river basins there are no gauges located within the defined boundaries of the Clarence-Moreton bioregion. Flooding is a regular occurrence in all river basins of the Clarence-Moreton bioregion and is most

commonly associated with the remnants of cyclonic activity, which bring heavy rains to the region.

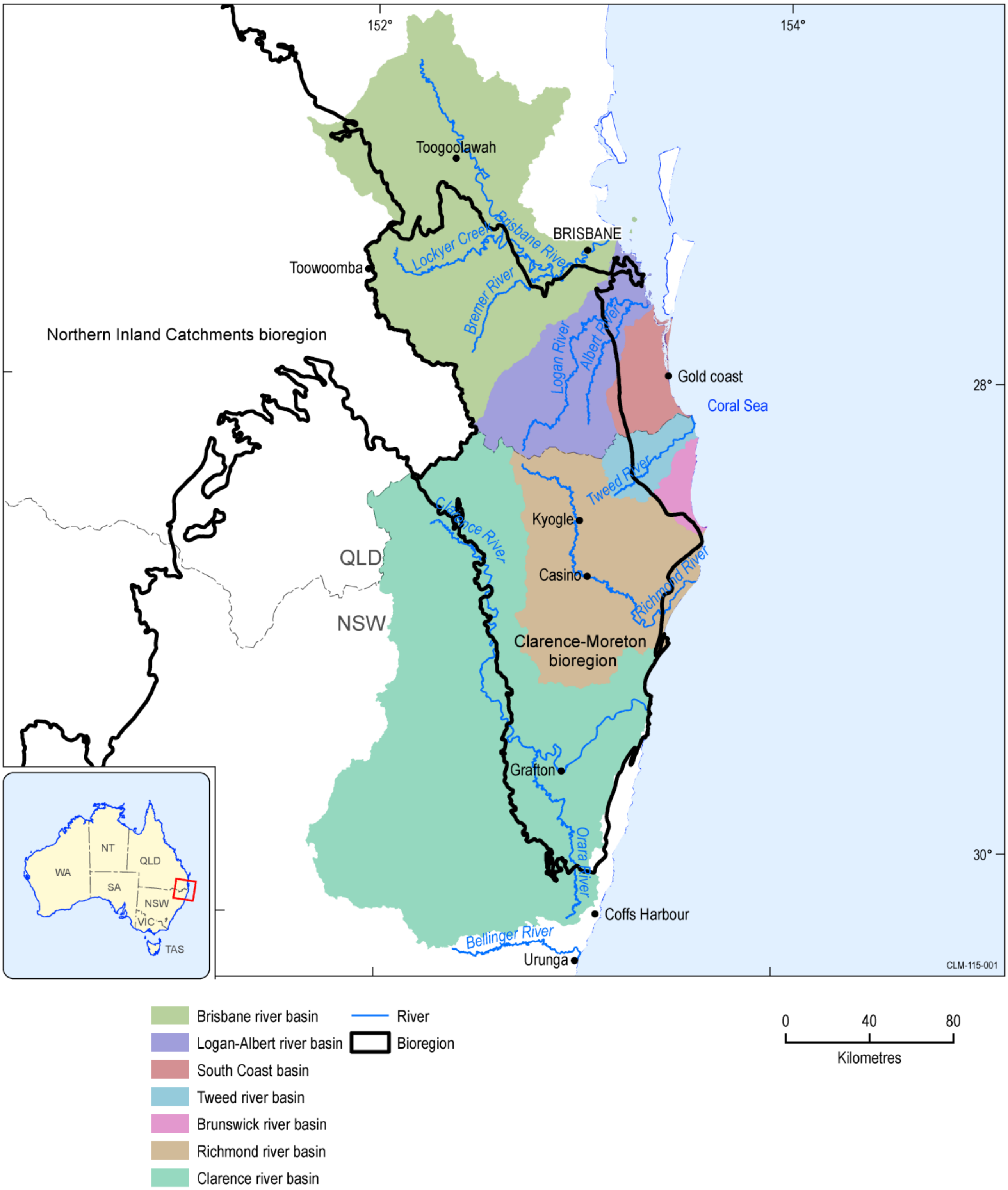

Figure 21 Clarence-Moreton bioregion and associated river basins

1.1.5.1 Surface water systems

This section describes the rainfall, evaporation, river systems, flooding history and water storage infrastructure in each river basin of the Clarence-Moreton bioregion. Table 9 details the area, percentage agricultural land, rainfall, evaporation and runoff for each river basin as reported for the National Land and Water Resources Audit (NLWRA, 2001). River basin sizes in the bioregion range from 508 km^2 for the Brunswick River to over 22,000 km^2 for the Clarence River. Rainfall ranges from an annual mean of 922 mm for the Brisbane river basin to 1879 mm for the Brunswick river basin. Mean annual actual evaporation ranges between 800 to 1131 mm and runoff coefficients (runoff divided by rainfall) vary by a factor of more than two (0.14–0.40) across the bioregion (NLWRA, 2001). The water supply infrastructure in each river basin is described in more detail in the following sections, but it is also worth noting the existence of the SEQ water grid (Queensland Water Commission, 2010) which connects many of the river basins and population centres in south-east Queensland. The SEQ water grid connects the water supply system provided by 12 dams in the region – from the Gold Coast in the south to the Sunshine Coast in the north and Toowoomba in the west. A total of 535 km of pipeline connects the dams and water supply systems so that water can be moved throughout the region to meet demands. The grid is also connected to the Western Corridor Recycled Water Project and the Gold Coast desalination plant.

Table 9 River basin characteristics and annual rainfall, actual evaporation (canopy + soil) and runoff

Basin	Brisbane River	Logan-Albert River	South Coast	Tweed River	Brunswick River	Richmond River	Clarence River
Area (km^2)	13,572	4141	1349	1077	508	7020	22,284
Agricultural land proportion (%)	16%	15%	27%	23%	31%	10%	5%
Rainfall (mm/y)	922	1055	1551	1846	1879	1334	1111
Actual evaporation (mm/y)	800	862	1043	1105	1131	947	854
Runoff (mm/y)	129	199	509	742	752	390	257
Runoff (GL/y)	1751	824	687	799	382	2737	5726
Runoff coefficient (runoff/rainfall)	0.14	0.19	0.33	0.40	0.40	0.29	0.23

Source data: NLWRA (2001)

1.1.5.1.1 Brisbane river basin

The Brisbane river basin (Figure 22) is the most northerly in the Clarence-Moreton bioregion and covers an area of 13,572 km^2. The description presented here is relevant to the entire Brisbane river basin; however, it should be noted that only 42% of this river basin (mainly in the south) is included within the bioregion boundary. The headwaters are located on the eastern side of the Great Dividing Range with the river draining to the coast into Moreton Bay downstream of Brisbane. A number of tributaries contribute to the Brisbane River including the Bremer and Stanley rivers, and the Cooyar, Emu, Cressbrook, Lockyer, Laidley, Buaraba and Warrill creeks. A water resource management plan has been established for the Brisbane river basin to control the allocation and sustainable use of water. Details are provided in the Queensland Government's Water Resource (Moreton) Plan 2007 and those interested in further information are directed to this piece of legislation. The Water Resources Plan defines the availability of water, sustainable extractions of surface water, groundwater and overland flow, and priorities for future water requirements.

The major water supply storages include Wivenhoe Dam (capacity 1165 GL) and Somerset Dam (capacity 380 GL), which combined account for approximately 70% of the water storage capacity for the city of Brisbane. These dams are part of the SEQ Water Grid, which links water storages and allows water transport through this region. Wivenhoe and Somerset dams also have an additional flood storage capacity of 1974 GL. Other significant storages in the Brisbane river basin include Moogerah Dam (capacity 84 GL) on Warrill Creek and Atkinson (capacity 30 GL) and Clarendon (capacity 24 GL) dams in the Lockyer Valley.

The major areas of irrigated agriculture are located within the Central Lockyer Valley, Lower Lockyer and Warrill Valley water supply schemes. Other smaller areas of irrigation are fed by a number of small water storages and groundwater bores. Of the total area of the Brisbane river basin, 4% is used for irrigated agriculture (CLUM, 2012).

Mean annual rainfall for the basin is 922 mm and mean annual actual evaporation is 800 mm (Table 9). The river flows year round and modelled mean annual flow for the entire basin is 1751 GL (NLWRA, 2001). The runoff coefficient (runoff/rain) is 0.14 making it the lowest of any of the basins in the bioregion (NLWRA, 2001). In part, this relatively low runoff coefficient is a consequence of the basin's relatively low rainfall, but is also partly due to the substantial level of flow regulation in the basin.

The Brisbane river basin is occasionally subjected to cyclonic activity and associated monsoon depressions which can bring extremely high rainfall and, therefore, flooding to this region. There have been 11 major floods in the Brisbane River at the city since 1830 with the most recent occurring in 2011, which resulted in widespread inundation of much of the low-lying areas of the basin. The occurrence of floods in the Brisbane River at the city has been greatly reduced since the construction of the Wivenhoe Dam in 1984. The mean annual flow at Savages Crossing gauge, which is located on the Brisbane River downstream of Wivenhoe Dam and 131 km from the river mouth, is 755 GL for the period between 1961 and 2012. The upstream catchment area at this point is equivalent to 75% of the total area of the Brisbane river basin. The maximum daily flow recorded during this period is 641 GL.

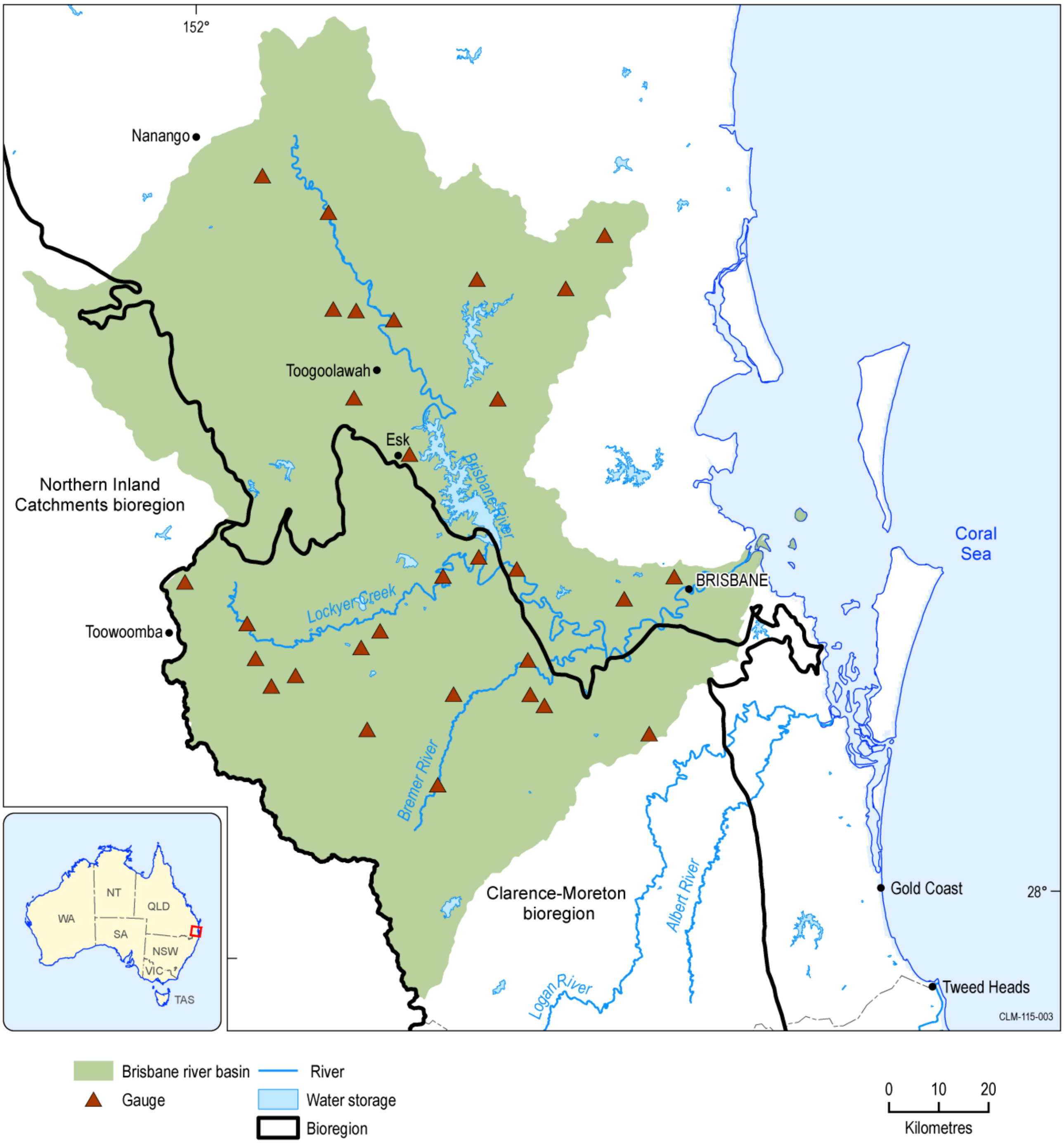

Figure 22 Brisbane river basin, major water storages and active stream gauging locations

1.1.5.1.2 Logan-Albert river basin

The Logan-Albert river basin (Figure 23) covers an area of 4141 km^2. Its headwaters are located in the Border Ranges which include parts of the Mount Barney and Lamington national parks. This basin has two main rivers: the Logan River, which accounts for about 80% of the total basin area; and the Albert River, which contributes the remaining 20%. Most of the Logan river basin (85%) is located within the bioregion boundary. The excluded area covers a large component of the coastal lowlands. The two rivers join and flow into the lagoons and tidal wetlands of southern Moreton Bay. The tributaries of the Logan River include Teviot Brook and Christmas and Running creeks. Major water storages in the Logan river basin include Maroon Dam (capacity 44 GL) and Wyaralong Dam (capacity 103 GL). A water resource management plan has been established for the Logan-Albert river basin to control the allocation and sustainable use of water. Details are provided in the Queensland Government's *Water Resource (Logan Basin) Plan 2007* and those interested in further information are directed to this piece of legislation. The *Water Resources Plan* defines the availability of water, sustainable extractions of surface water, groundwater and overland flow, and priorities for future water requirements.

About 16% of the Logan-Albert river basin is under agricultural production, but just 3% of the total area is accounted for by irrigated agriculture (CLUM, 2012). While irrigation occurs across a number of areas of the Logan-Albert river basin, the Logan River Water Supply Scheme is the largest and includes an irrigation area along a 101 km stretch of the Logan River and along a 27 km stretch of Burnett Creek (Seqwater, 2012). This scheme includes the Maroon and Wyaralong dams, the Cedar Grove, Bromelton and South Maclean weirs and an off-stream storage at Bromelton.

Mean annual rainfall for the basin is 1055 mm and mean annual actual evaporation is 862 mm (Table 9). The river flows year round and modelled mean annual flow for the entire basin is 824 GL with a runoff coefficient of 0.19 (NLWRA, 2001). According to the Bureau of Meteorology's flood warning alerts, average basin rainfall in excess of 200 mm in 24 hours may result in moderate flooding while average basin rainfall in excess of 300 mm in 24 hours may result in severe flooding. The most notable flood was that of January 1974, in which major flooding occurred throughout south-east Queensland. The streamflow gauge on the Logan River at Yarrahappini has a catchment area equivalent to 58% of the total area of the Logan-Albert river basin and is located 78 km from the river mouth. Its mean annual flow was 310 GL for the period between 1970 and 2012. The maximum daily flow recorded during this period was 368 GL (i.e. greater than the mean annual flow).

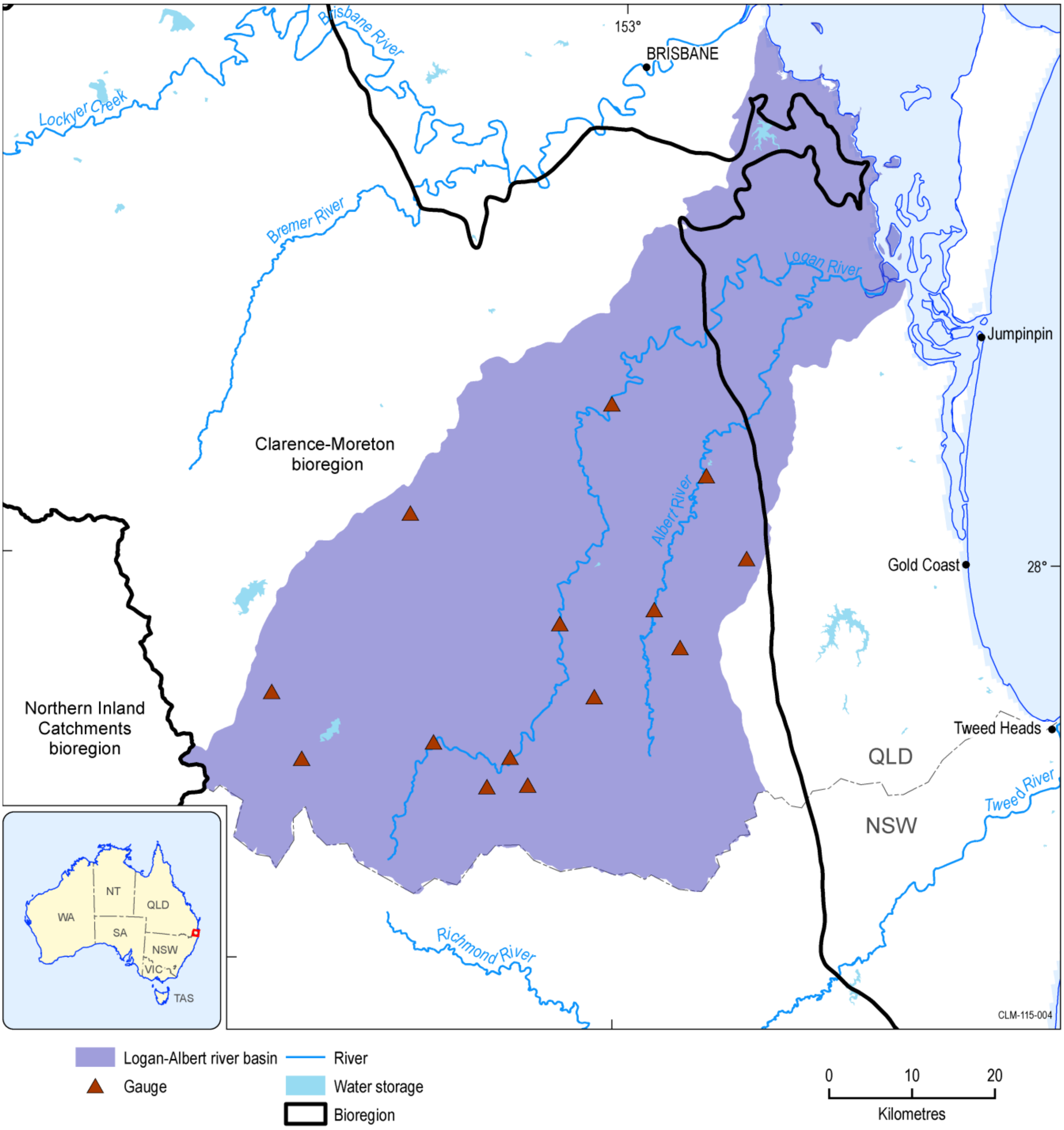

Figure 23 Logan-Albert river basin, major water storages and active stream gauging locations

1.1.5.1.3 South Coast basin

The total area of the South Coast basin is 1349 km^2 (Figure 24). This basin includes the Coomera River and the Nerang River, both of which flow into the Broadwater and then to the Coral Sea. Mudgeeraba Creek flows into the Nerang River while the three remaining major creeks – Reedy, Tallebudgera and Currumbin – flow directly to the Coral Sea. Only 10% of the South Coast basin falls within the Clarence-Moreton bioregion, with the intersecting area forming the south-western headwaters of the basin.

A water resource management plan has been established for the South Coast basin to control the allocation and sustainable use of water. Details are provided in the Queensland Government's *Water Resource (Gold Coast) Plan 2007* and those interested in further information are directed to this piece of legislation. The *Water Resources Plan* defines the availability of water, sustainable extractions of surface water, groundwater and overland flow, and priorities for future water requirements.

The major water storages in the South Coast basin include Hinze Dam and Little Nerang Dam. Hinze Dam is the largest with a capacity of 311 GL and it provides most of the water for the Gold Coast and some flood mitigation. This dam has been built in a number of stages with the latest being completed in 2011. Little Nerang Dam (7 GL capacity) is a secondary source of water for the Gold Coast. Some irrigated agriculture is found in this basin (0.1% of total area) but it is not widespread (CLUM, 2012).

Mean annual rainfall for the basin is 1551 mm and mean annual actual evaporation is 1043 mm (Table 9). The rivers flow year round and modelled mean annual flow for the entire basin is 687 GL with a runoff coefficient of 0.33 (NLWRA, 2001). Most flooding in this basin is associated with cyclonic activity. Since records commenced in 1920, there have been four major flooding events. The mean annual flow for the Nerang River at Glenhurst (146002B), which is the furthest point downstream on the largest river system in this basin, was 88 GL for the period between 1970 and 2012. The maximum daily flow recorded during this period was 100 GL.

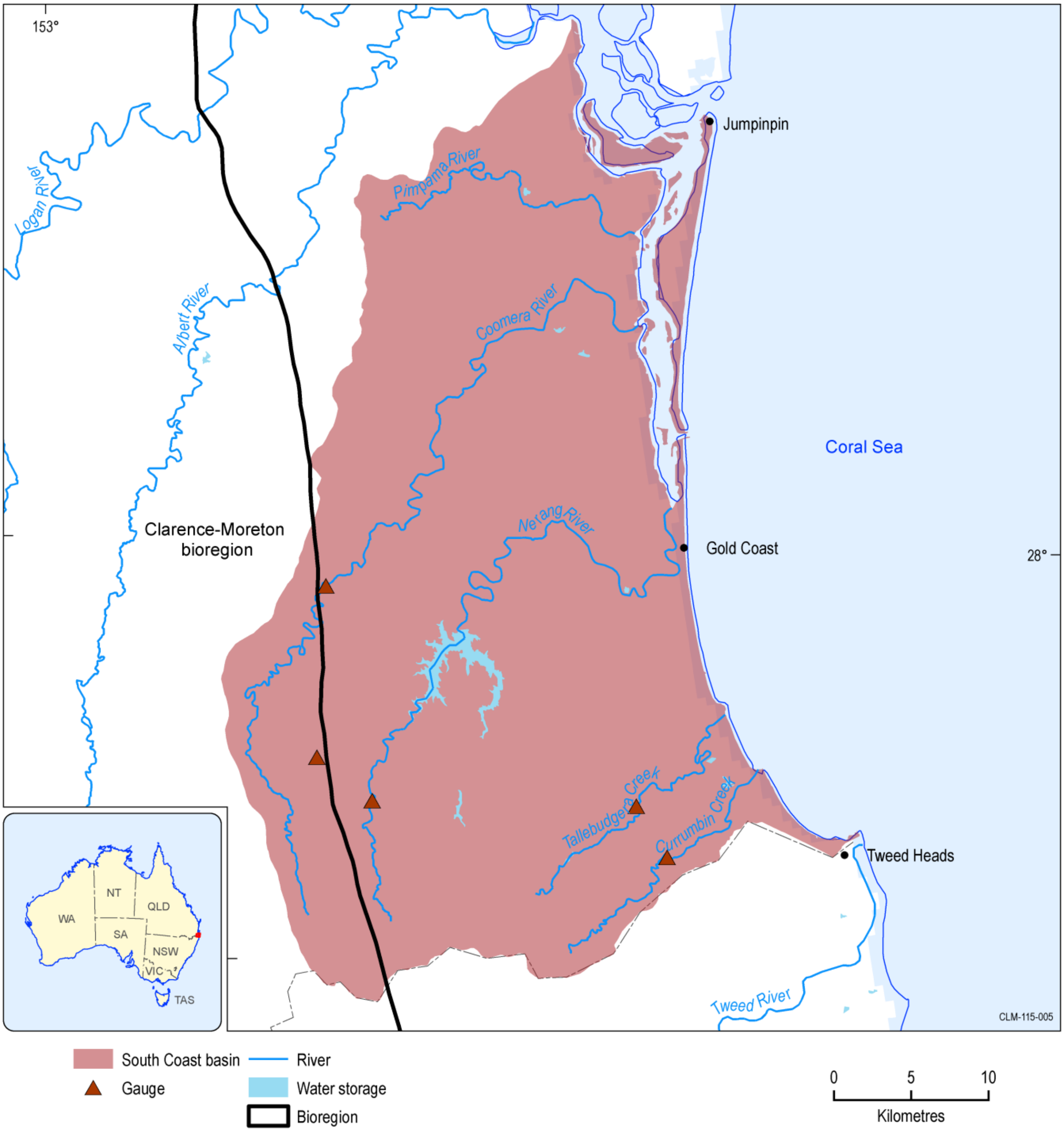

Figure 24 South Coast basin, major water storages and active stream gauging locations

1.1.5.1.4 Tweed river basin

The Tweed river basin (Figure 25) covers an area of 1077 km^2. Only 39% of the basin falls within the Clarence-Moreton bioregion and most of this represents headwater areas. The basin is formed in the caldera of the now extinct Tweed Volcano of which Mount Warning is the volcanic plug. Major tributaries to the Tweed River include the Rous and Oxley rivers and numerous smaller creeks. The Tweed River flows to the Coral Sea at Tweed Heads. Cobaki Broadwater, Terranora Broadwater and Cudgen Lake are large natural near-coastal water bodies in this basin.

A water resource management plan has been established for the Tweed river basin to control the allocation and sustainable use of water. Details are provided in the NSW Government's *Water Sharing Plan for the Tweed River Area Unregulated and Alluvial Water Sources 2010* and those interested in further information are directed to this piece of legislation. The *Plan* defines the availability of water, sustainable extractions, storage operation rules, and management of water access licences.

Most of the water use in this basin is for town supply, however, it is also used for irrigation of pasture for dairying and horticulture. Irrigation accounts for less than 1% of the total area (CLUM, 2012). The Clarrie Hall Dam (capacity 15 GL) is the only dam in the Tweed river basin and is used to supplement the water supply for the Tweed Shire. Weirs exist on the Oxley River at Tyalgum and at Bray Park on the Tweed River.

Mean annual rainfall for the basin is 1846 mm and mean annual actual evaporation is 1105 mm (Table 9). The river flows year round and modelled mean annual flow for the entire basin is 799 GL. Its runoff coefficient of 0.40 is the highest in the bioregion (NLWRA, 2001). As with other basins in this region, flooding is associated with cyclonic activity. The last major flood in the area occurred as a result of the passing of ex-tropical cyclone Oswald in 2013. The mean annual flow at Uki (201900) on the Tweed River, which has an upstream catchment area of 275 km^2, was 142 GL for the high quality data period between 1968 and 2012. The maximum daily flow recorded during this period was 54 GL.

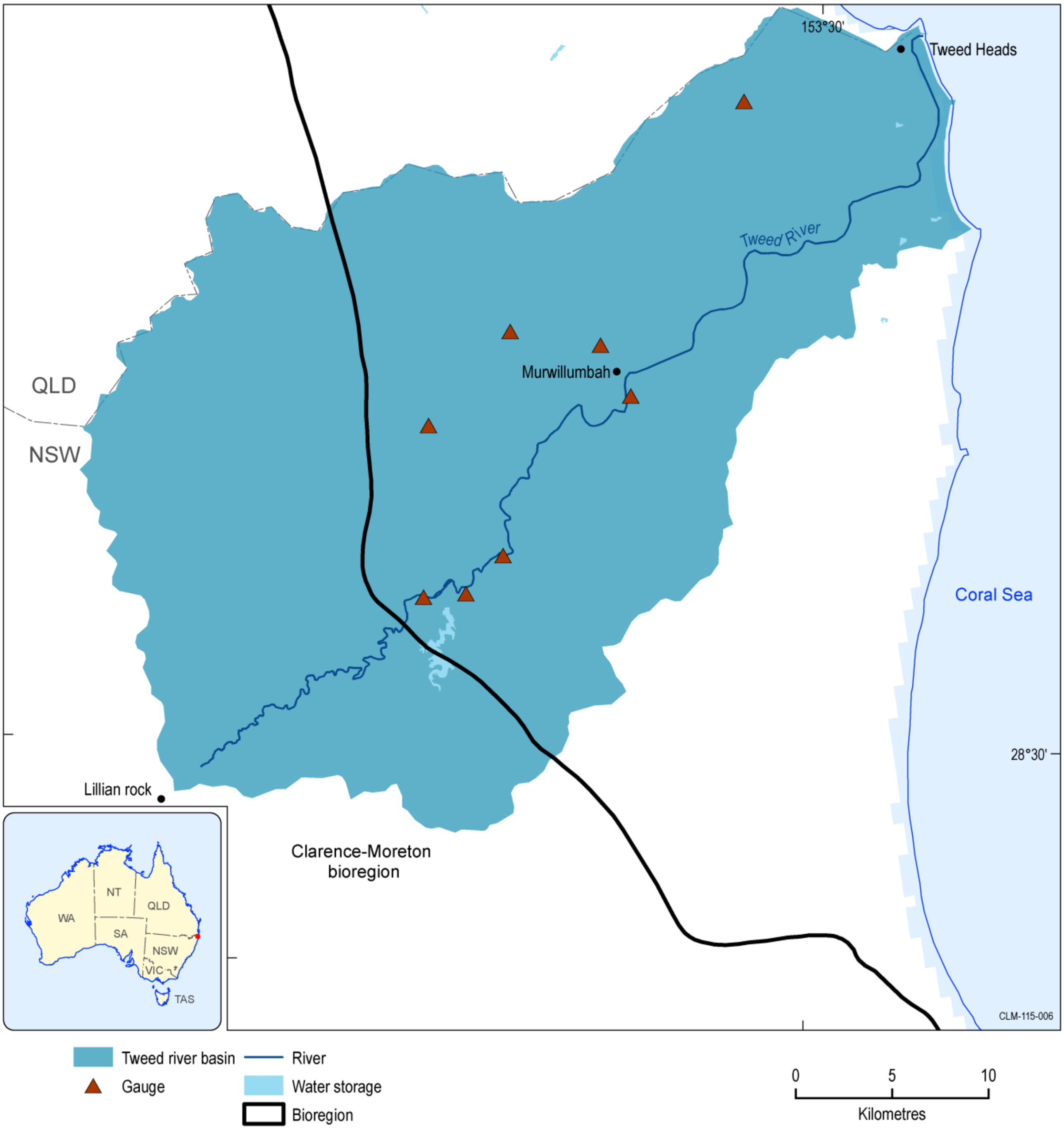

Figure 25 Tweed river basin, major water storages and active stream gauging locations

1.1.5.1.5 Brunswick river basin

The Brunswick river basin (Figure 26) is the smallest in the Clarence-Moreton bioregion and covers an area of 508 km^2. Only 11% of the Brunswick river basin is contained within the Clarence-Moreton bioregion, comprising the headwaters at the southern end of the basin. A water resource management plan has been established for the Brunswick river basin to control the allocation and sustainable use of water. Details are provided in the NSW Government's *Water Sharing Plan for the Upper Brunswick River Water Source 2003* and those interested in further information are directed to this piece of legislation. The *Plan* defines the availability of water, sustainable extractions, storage operation rules, and management of water access licences.

A weir is located on Mullumbimby Creek upstream of the Mullumbimby township and further upstream is the Mullumbimby hydro-power station. The water supply for Mullumbimby comes from the Laverty's Gap weir which is on the Wilsons River in the neighbouring Richmond river basin. Most of the major creeks and rivers in the Brunswick river basin flow to the sea through a large estuary which then drains to the ocean through Brunswick Heads. Lacks Creek and Marshalls Creek in the north, and Tyagarah and Simpsons Creek in the south join the Brunswick River at its estuary. Mullumbimby Creek, Yankee Creek and Pipeclay Creek join the Brunswick River upstream. Belongil Creek forms a small estuary behind the beach north of Byron Bay.

More than 30% of the basin is under agricultural production (NLWRA, 2001), while irrigated agriculture accounts for a little over 1% of the total area (CLUM, 2012). Water is used to irrigate pasture for dairying, turf farming and horticulture.

Mean annual rainfall for the basin is 1879 mm, which is the highest amongst all basins of the Clarence-Moreton bioregion. Mean annual actual evaporation is 1131 mm, which is also the highest in the bioregion (Table 9). The rivers flow year round and modelled mean annual flow for the entire basin is 382 GL with a runoff coefficient of 0.40 (NLWRA, 2001). Major floods have occurred in this basin in 1974, 1976, 1978 and 2005 with extensive inundation of low-lying areas. The mean annual flow on the Brunswick River at Durrumbul, which has an upstream catchment area of 34 km^2, was 31 GL between 1955 and 2012. The maximum daily flow recorded during this period was 11 GL.

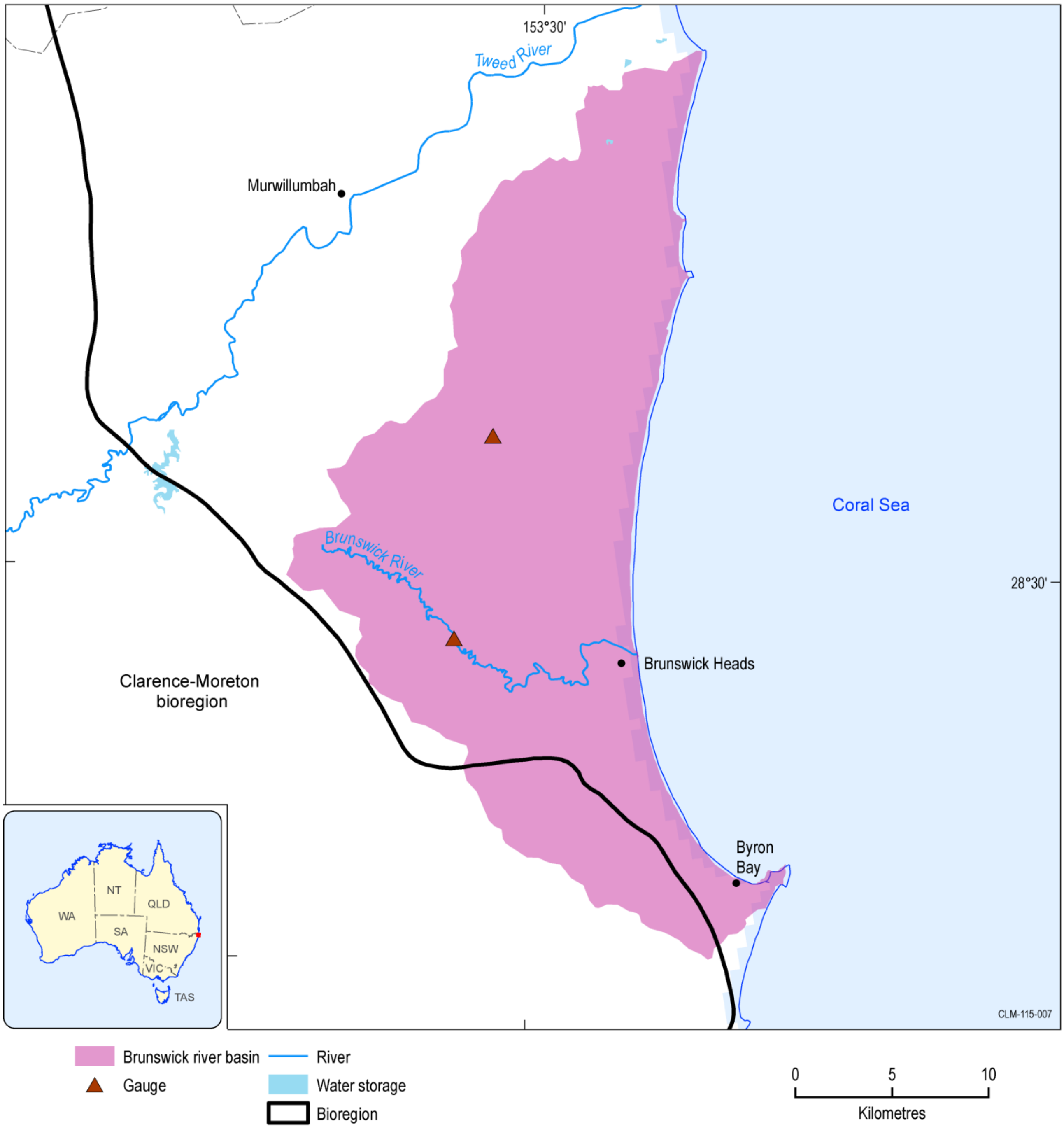

Figure 26 Brunswick river basin, major water storages and active stream gauging locations

1.1.5.1.6 Richmond river basin

The Richmond river basin (Figure 27) covers an area of 7020 km^2. The vast majority (95%) of this basin falls within the Clarence-Moreton bioregion. Its headwaters are located in the Border Ranges, Tweed Volcano and the Richmond Range. The major tributaries to the Richmond River include Wilsons River, Coopers Creek, Terania Creek, Leycester Creek, Iron Pot Creek, Shannon Brook, Sandy Creek and Bungawalbin Creek. The Richmond River has a large barrier estuary which flows to the ocean at Ballina. The Evans River forms in a small sub-basin to the south which flows to the coast at Evans Head. This river is joined to the Richmond River by a canal that was constructed to alleviate flooding.

A water resource management plan has been established for the Richmond river basin to control the allocation and sustainable use of water. Details are provided in the NSW Government's Water Sharing Plan for the Richmond River Area Unregulated, Regulated and Alluvial Water Sources 2010 and those interested in further information are directed to this piece of legislation. The Plan defines the availability of water, sustainable extractions, storage operation rules, and management of water access licences.

Water storages in the basin include Toonumbar Dam (capacity 11 GL),which stores water for irrigation stock and town water; and Rocky Creek Dam (capacity 14 GL) and Emigrant Creek Dam (capacity 0.82 GL), which provide water for the towns of Lismore and Ballina. There are three weirs on the Richmond River near Casino and one on the Wilsons River that provides water to Mullumbimby in the Brunswick river basin. Approximately 1% of the Richmond river basin is used for irrigated agriculture (CLUM, 2012). Irrigated pastures are found around the alluvial flats of the Richmond and Wilson rivers and groundwater is used to irrigate fruit and nut crops on the Alstonville Plateau.

Mean annual rainfall for the basin is 1334 mm and mean annual actual evaporation is 947 mm (Table 9). The rivers flow year round and modelled mean annual flow for the entire basin is 2738 GL with a runoff coefficient of 0.29 (NLWRA, 2001). Many major floods have been documented for the Richmond River and the towns of Ballina, Casino and Lismore. As with other basins in the Clarence-Moreton bioregion, these floods are normally associated with extreme rainfall derived from cyclonic activity. The mean annual flow on the Richmond River at Casino (203004), which has an upstream catchment area of 1790 km^2, was 587 GL for the high quality data period between 1944 and 2012. The maximum daily flow recorded during this period was 154 GL.

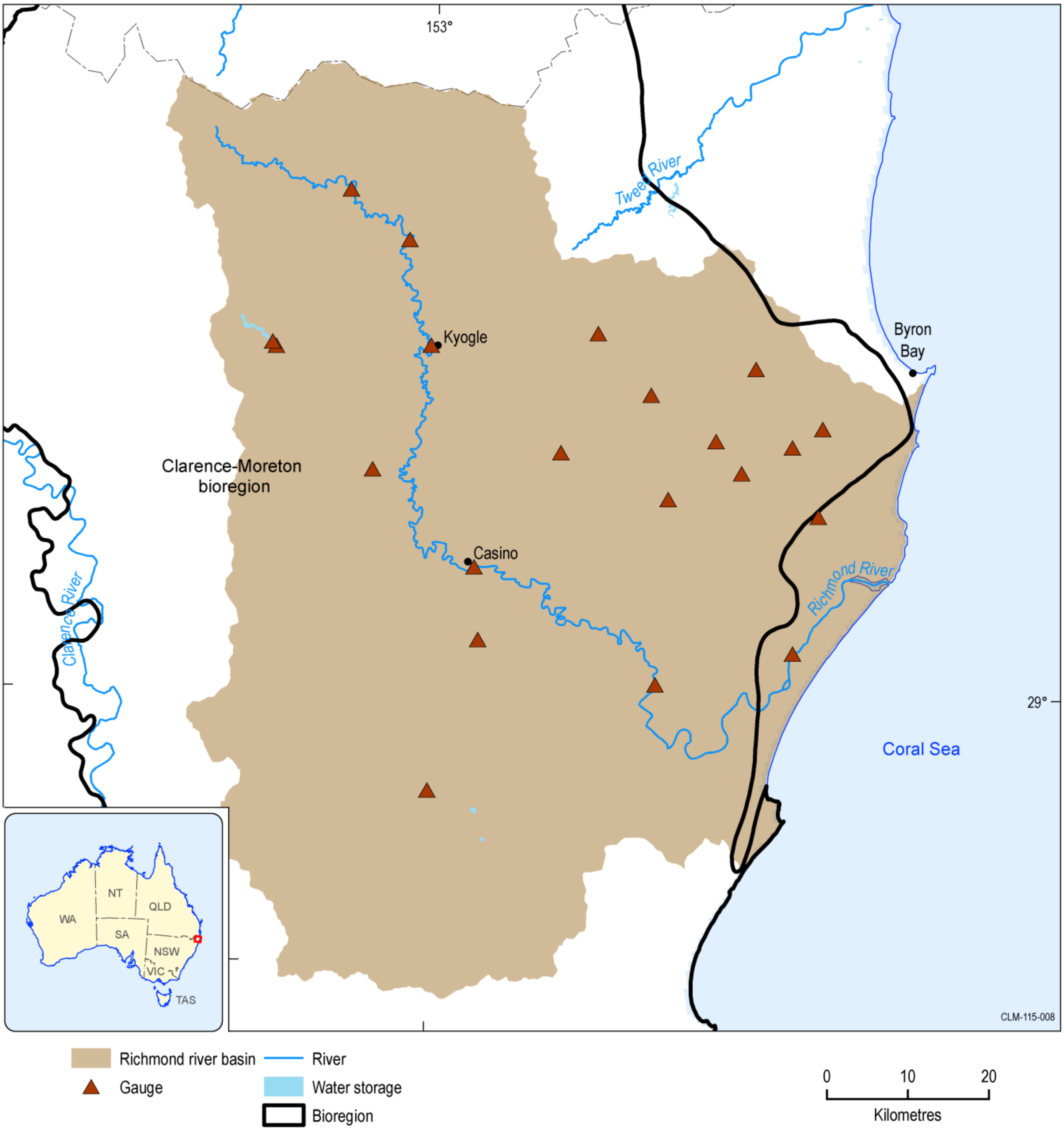

Figure 27 Richmond river basin, major water storages and active stream gauging locations

1.1.5.1.7 Clarence river basin

The Clarence river basin (Figure 28) has the largest area and discharge of all NSW coastal river basins. The total area is 22,284 km^2. Of the total area, 35% – mainly in the lower parts of the basin – falls within the Clarence-Moreton bioregion boundary. The headwaters are located in the Macpherson Ranges in the north; the Baldblair Ranges, Doughboy Ranges and the Dorrigo Plateau in the south; and the Great Dividing Range in the west. The major tributaries to the Clarence River include the Maryland, Cataract, Timbarra, Mann, Guy Fawkes, Nymboida and Orara rivers. Before entering the Coral Sea at Yamba, the river passes through a large estuary system which includes Wooloweyah Lagoon and The Broadwater.

A water resource management plan has been established for parts of the Clarence river basin to control the allocation and sustainable use of water. Details are provided in the NSW Government's *Water Sharing Plan for the Dorrigo Plateau Surface Water Source and Dorrigo Basalt Groundwater Source 2003* and those interested in further information are directed to this piece of legislation. The *Plan* defines the availability of water, sustainable extractions, storage operation rules, and management of water access licences. A merger of this *Plan* with a proposed plan for Clarence River unregulated and Alluvial water sources is likely in the future.

Most of the Clarence river basin is unregulated. Major water storages in this basin are associated with the Nymboida River and include Shannon Creek Dam (capacity 30 GL), Karangi Dam (capacity 6 GL) and Rushford Road Reservoir (100 ML). A weir on the Nymboida River supplies water to the Karangi Dam. Non-irrigated agriculture dominates the Clarence Valley with only small areas of irrigation. An Australian Bureau of Statistics analysis (ABS, 2006) estimated that 0.3% of the total agricultural land in the Clarence valley was irrigated.

The mean annual rainfall for the basin is 1111 mm and mean annual actual evaporation is 854 mm (Table 9). The river flows year round and modelled mean annual flow for the entire basin is 5727 GL – the largest in the bioregion. The runoff coefficient is 0.23 (NLWRA, 2001). The headwaters for the Clarence river basin represent some of the highest rainfall areas in NSW. As a result, flooding is a regular occurrence. There have been 73 major and moderate flood events since 1839 (based on the Grafton streamflow gauge). Extensive levee walls have been constructed to protect Grafton and Maclean from flooding. The mean annual discharge between 1923 and 2012 of the Clarence River at Lilydale gauge (204007), which has an upstream catchment of 16,690 km^2, was 3400 GL. The maximum daily flow recorded during this period was 1200 GL.

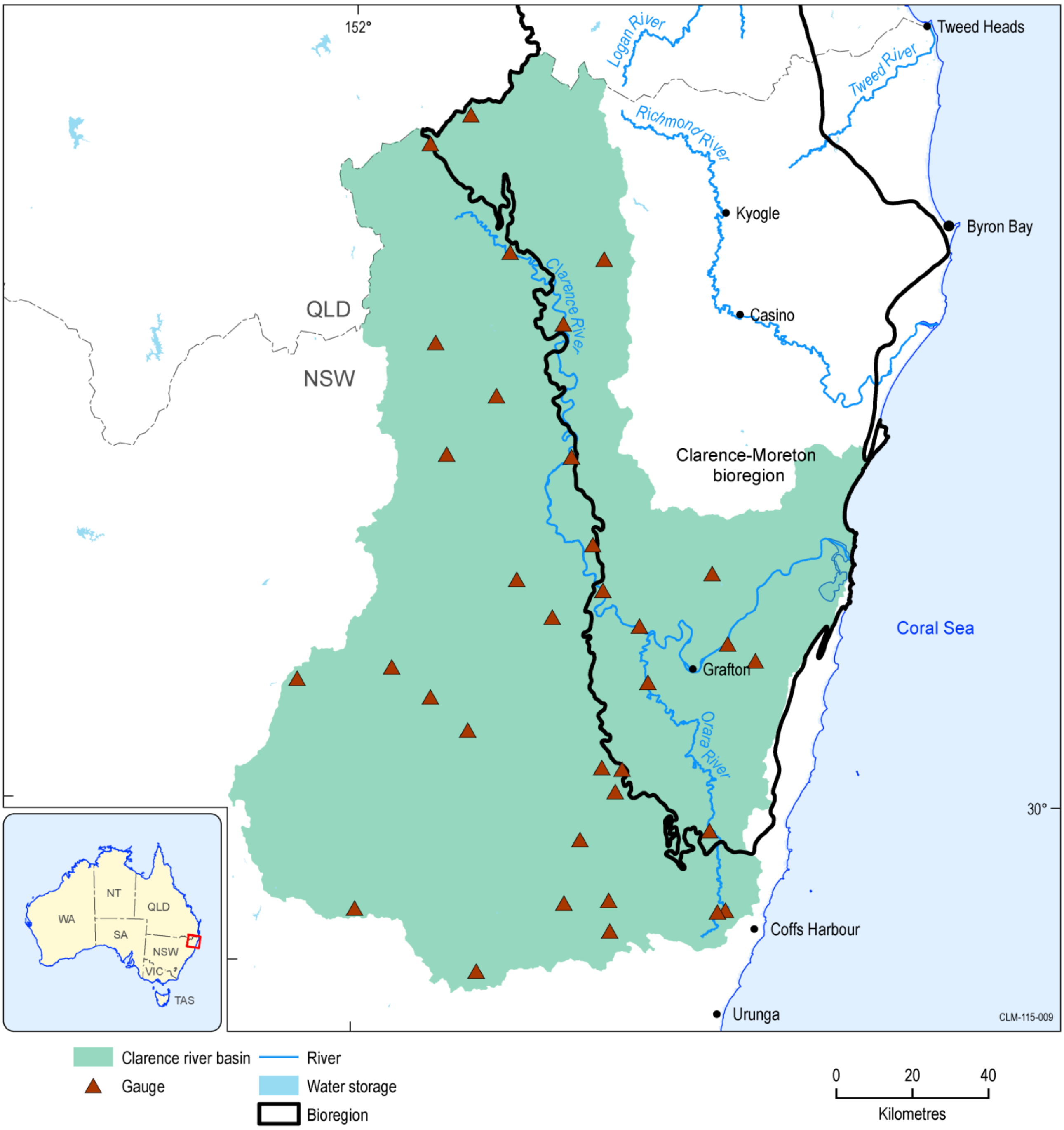

Figure 28 Clarence river basin, major water storages and active stream gauging locations

1.1.5.2 Surface water quality

This section discusses available water quality data for surface waters and also reports on whole-of-basin exports of sediment, phosphorus and nitrogen. It should be noted that while there are some long-term water quality monitoring programs for locations in most basins in the Queensland (Natural Resources and Mines) and NSW (NSW Office of Water) sections of the Bioregion, there is no comprehensive monitoring program that covers all key rivers and tributaries. Environmental values and water quality objectives have also been established for riverine, estuarine, coastal waters and groundwater, within the South East Queensland Natural Resource Management area legislated under the *Environmental Protection (Water) Policy 2009*, and within New South Wales as guidelines in the Protection of the Environment Operations Act 1997 (NSW DEC, 2006a; 2006b). The data on basin export loads are sourced from a modelling analysis which was undertaken for the National Land and Water Resources Audit (NLWRA, 2001). The National Land and Water Audit provides the only consistent Bioregion-wide assessment of water quality. A follow up report for the National Land and Water Resource Audit (NLWRA, 2002a, 2002b) presented broader regional assessments and developed indices to facilitate comparison of basin and river condition. Loads of sediment, nutrient and phosphorus across the basins of the Clarence-Moreton bioregion are summarised in Table 10 and will be discussed in more detail in the sections below. Acid sulfate soils occur throughout the bioregion, especially in the Richmond and Clarence river basins (see Section 1.1.2.1.2). The impacts of acid sulfate drainage are discussed in Section 1.1.5.2.7.

Table 10 Modelled estimates of total annual sediment, phosphorus and nitrogen export

Basin	Brisbane River	Logan-Albert River	South Coast	Tweed River	Brunswick River	Richmond River	Clarence River
Sediment export to coast (kt/y)	247	189	21	58	2	241	683
Sediment export rate (t/ha/y)	0.18	0.47	0.19	0.55	0.16	0.36	0.31
Sediment ratio (Euro:pre-Euro)	37	35	10	16	5	32	198
Phosphorus export to coast (t/y)	685	265	93	46	3	235	624
Phosphorus export rate (kg/ha/y)	0.5	0.64	0.67	0.42	0.06	0.33	0.28
Phosphorus ratio (Euro:pre-Euro)	5.3	4.7	1.4	1.8	2.1	2.9	3.8
Nitrogen export to coast (t/y)	3162	1251	397	499	35	1941	4799
Nitrogen export rate (kg/ha/y)	2.33	3.01	2.89	4.58	0.64	2.77	2.16
Nitrogen ratio (Euro:pre-Euro)	2.7	3.2	1.5	1.4	1.5	2.3	2

Source data: NLWRA (2001)

1.1.5.2.1 Brisbane river basin

The Brisbane river basin has a sediment export of 247 kt/year – the second highest sediment export of all of the Clarence-Moreton bioregion basins (Table 10). While the total load is high, the areally averaged export rate is one of the lowest in the bioregion. Modelling estimates suggest that sediment export rates have increased by a factor of 37 since pre-European times. Total annual phosphorus export is the highest of any bioregion basin and is 5.3 times greater than that before European settlement. Total annual nitrogen export is around 3162 t which is estimated to be 2.7 times greater than before European settlement.

A water quality report card is prepared for the Brisbane river basin each year by the Ecosystem Health Monitoring Program (EHMP, 2012). For freshwater reaches the following groups of parameters are monitored: physical chemical (pH, electrical conductivity, temperature, dissolved oxygen), nutrient cycling, ecosystem processes, aquatic invertebrates and fish. These factors are combined to produce report card grades that range from A (excellent) to F (fail). The most recent report card (EHMP, 2012) showed that most of the upper Brisbane river basin was in fair (C) to poor (D) condition while the middle basin failed (F) the assessment criteria. The lower reaches received poor (D) ratings. The Queensland Government also undertakes continuous water quality monitoring (electrical conductivity, turbidity, pH and temperature) at many of its stream gauging locations. An ambient water quality monitoring program also exists in which manual measurements of electrical conductivity, temperature, pH, turbidity, dissolved oxygen and total alkalinity are made (see DNRM (2012) for further details). Salinity in the creeks and river of the Lockyer Valley have been investigated by Tien et al. (2004) who showed that mean salinity in Laidley, Lockyer and Tenthill Creeks between 1995 and 2003 was 470, 1700 and 1378 µS/cm. Salinity increased in these streams during the dry season periods. Yu et al. (2013) analysed 10 years' worth of salinity and turbidity data collected from 16 sites in a transect from the mouth of the Brisbane River to the limit of tidal extent (86.6 km upstream) and they showed that salinity increased by a factor of 30 over this transect. Salinity variation in this same part of the Brisbane River estuary was also reported by Bayly (1965). Modelled pollutant loads (total phosphorus (TP), total nitrogen (TN) and total suspended sediment (TSS)) for the Brisbane river basin have also been given by Chiew et al. (2002).

1.1.5.2.2 Logan-Albert river basin

The Logan-Albert river basin has a modelled annual mean sediment export of 189 kt and the sediment export rate is the second highest of the bioregion basins at 0.47 t/ha/year (Table 10). It is estimated that sediment export rates have increased by a factor of 35 since pre-European times. A study of the sources of sediment within the Logan-Albert river basin was undertaken by Hancock and Roth (2011) who estimated the relative contribution from different land uses. They found that approximately 70% of the sediment delivered to the estuary came from the southern and eastern parts of the basin from soils derived from the Lamington Group rocks. Channel bank erosion was the major sediment source. Total annual phosphorus export averages 265 t and this is 4.7 times greater than those before European settlement. Total annual mean nitrogen export of 1251 t is estimated to be 3 times greater than before European settlement. The nitrogen export rate is the highest per unit area of any of the Clarence-Moreton bioregion basins.

A water quality report card (EHMP, 2012) is also prepared for the Logan-Albert river basin each year. The most recent report card (EHMP, 2012) graded the Logan river basin a D+ while the Albert River was graded a C. The Queensland Government also undertakes continuous water quality monitoring (electrical conductivity, turbidity, pH and temperature) at many of its stream gauging locations in the Logan-Albert river basin. Ambient water quality monitoring is also undertaken with manual measurements of electrical conductivity, temperature, pH, turbidity, dissolved oxygen and total alkalinity (see DNRM (2012) for further details). Modelled pollutant loads (TP, TN and TSS) for the Logan-Albert river basin have also been given by Chiew et al. (2002). Further monitoring of water quality on the Logan-Albert river basin is being undertaken by CSIRO as part of a peri-urban supersite which was set up as part of the Terrestrial Ecosystem Research Network (TERN). The equipment continuously monitors a variety of parameters including water temperature, pH and electrical conductivity, along with river flow, depth, sediment, dissolved organic material and nutrients. While there are no known reports on the surface water salinity in the streams of the upper part of the Logan-Albert river basin, Matveev and Steven (2013) studied the effect of salinity, turbidity and flow on fish biomass in the estuary of this basin and showed that salinity and turbidity were important seasonal drivers of fish abundance. Averaged over the two years of the study the salinity in the Logan River was 13.6 g/L while in the Logan River it was 7.27 g/L. Average pH was similar in the Logan and Albert rivers at 7.56 and 7.19, respectively.

1.1.5.2.3 South Coast basin

The South Coast basin has a modelled annual mean sediment export of 21 kt and the sediment export rate is the second highest of the bioregion basins at 0.19 t/ha/year (Table 10). It is estimated that sediment export rates have increased by a factor of 10 since pre-European times. Phosphorus and nitrogen export rates have increased by about 40% and 50% respectively since European settlement. Annual mean nitrogen and phosphorus export rates are 2.89 t and 0.67 t, respectively (NLWRA, 2001).

As with other basins in south-east Queensland, a water quality report card (EHMP, 2012) is prepared for the South Coast basin each year. The most recent report card (EHMP, 2012) graded the catchments of South Coast basin as being in good condition with grades of B− to B+. The Queensland Government also undertakes continuous water quality monitoring (electrical conductivity, turbidity, pH and temperature) at some of its stream gauging locations in the South Coast basin. Ambient water quality monitoring is also undertaken with manual measurements of electrical conductivity, temperature, pH, turbidity, dissolved oxygen and total alkalinity (see DNRM (2012) for further details). Modelled pollutant loads (TP, TN and TSS) for the South Coast basin have also been given by Chiew et al. (2002). A study of the salinity of the Coomera River estuary was undertaken by Benfer et al. (2007) who showed that parts of the system become hypersaline between wet season flushing events, therefore these systems are adapted to large fluctuations in salinity throughout the year.

1.1.5.2.4 Tweed river basin

The Tweed river basin has a modelled total annual mean sediment export of 58 kt which, when averaged, yields the highest sediment export rate in the bioregion at 0.55 t/ha/year (Table 10). It is estimated that sediment export rates have increased by a factor of 16 since pre-European times. Phosphorus and nitrogen export rates have increased by a factor of 1.8 and 1.4 respectively since European settlement. Total annual mean nitrogen export is 0.42 t and the nitrogen export rate is the highest in the bioregion at 4.58 t/ha/year. Total annual mean phosphorus export is 46 t (NLWRA, 2001).

A water quality report card is also prepared for the Tweed river basin with involvement from the local council. The most recent report card graded the freshwater streams of the Tweed river basin as being in fair to poor condition (C− to D) while the estuarine areas were rated as fair to good (C to B−). The NSW Government also undertakes continuous water quality monitoring (electrical conductivity, turbidity, pH and temperature) at some of its stream gauging locations in the Tweed river basin. Beale et al. (2004) undertook a study of salinity in parts of the Tweed river basin using measurements and modelling approaches. They found that median salinity, as inferred from electrical conductivity, was very low (0 – 200 µS/cm) and that values remained below 400 uS/cm for 80% of the time. A value of 1600 µS/cm is defined as the threshold for ecological damage

1.1.5.2.5 Brunswick river basin

The Brunswick river basin has the lowest sediment export of all of the bioregion basins at 2 kt/year (Table 10). This basin also has the lowest sediment export rate of 0.16 t/ha/year. This produces a sediment load 5 times greater than pre-European levels. Total annual phosphorus export (3 t/year) is also the lowest by far and is a factor of 2.1 greater than pre-European values. Total annual nitrogen export is around 35 t/year which is estimated to be 1.5 times greater than before European settlement (NLWRA, 2001).

The NSW Government also undertakes continuous water quality monitoring (electrical conductivity, turbidity, pH and temperature) at some of its stream gauging locations in this basin. Further water quality sampling has been undertaken by the NSW Government and local councils at various times and much of this data is stored within databases. Data can be accessed by request. In parts of the Brunswick river basin, Beale et al. (2004) undertook a study of salinity using measurements and modelling approaches and found that salinity was very low (0 to 200 µS/cm) and that values remained below this level for 80% of the time.

1.1.5.2.6 Richmond river basin

The Richmond river basin has an annual mean sediment export of 241 kt which represents an increase by a factor of 32 since pre-European times (Table 10). The sediment export rate is 0.36 t/ha/year. The total annual phosphorus export rate (235 t/year) is 2.9 times greater than that before European settlement. The mean annual nitrogen export is estimated to be 1941 t. Nitrogen export rates are 2.3 times greater than before European settlement (NLWRA, 2001).

The NSW Government also undertakes continuous and opportunistic water quality monitoring (electrical conductivity, turbidity, pH and temperature) at many of its stream gauging locations. The Richmond River County Council monitors electrical conductivity, pH, dissolved oxygen, temperature and turbidity at four locations within the estuary. A host of other water quality measurement have been made in basins in northern NSW by councils and NSW Government departments in response to fish kills in areas of these basins. Large numbers of fish have been known to die following dramatic declines in dissolved oxygen following floods. The floods bring increased dissolved organic loads which deplete oxygen levels (Walsh et al., 2004). Beale et al. (2004) undertook a study of salinity in parts of the Richmond river basin using measurements and modelling approaches. They found that in most of the locations they studied median electrical conductivity values were less than 400 µS/cm. However there were streams with median electrical conductivity of between 400 and 800 µS/cm. The differences between locations are attributed to underlying geology.

Eyre and Pont (2003) investigated the loads of nitrogen and phosphorus from diffuse sources during 1996 across the Northern rivers basin in NSW (which includes all the NSW basins included in the Clarence-Moreton bioregion). They found that up to 76% of the total annual nitrogen load and 73% of the total annual phosphorus load was transported in less than 20% of the time. This contrasts with typical temperate systems where it takes 50% or more of the time to deliver 75% of the annual load. They also showed that nitrogen exports were dominated by organic forms with an average of about 80% of the total nitrogen load which consisted of particulate nitrogen and dissolved organic nitrogen. This reflects the high percentage of forest cover in these basins. Phosphorus loads were more evenly distributed between dissolved inorganic, particulate and dissolved organic forms.

1.1.5.2.7 Clarence river basin

The annual mean sediment export from the Clarence river basin is 683 kt which is almost three times larger than for any other basin in the bioregion. The sediment export rate is 0.31 t/ha/year and modelling estimates suggest that sediment export rates have increased by a factor of 198 since pre-European times (NLWRA, 2001). Total annual phosphorus export is the second highest in the bioregion (624 t/year) and is 3.8 times greater than those before European settlement. Total annual nitrogen export is also the highest of all the bioregion at 4799 t/year which estimated to be 2.0 times greater than before European settlement.

The NSW Government undertakes continuous and opportunistic water quality monitoring (electrical conductivity, turbidity, pH and temperature) at many of its stream gauging locations in this basin. Artificial drainage of the floodplain has resulted in increases in acid flux in this basin, which reduce water quality and have detrimental effects on ecosystems. Such processes have been documented and measured in various studies (e.g. Johnston et al., 2004a; Tulau, 1999). Fish kills, as a result of low dissolved oxygen, have also been documented for the Clarence River (Walsh et al., 2004). Beale et al. (2004) undertook a study of salinity in much of the upper parts of the Clarence river basin and reported median salinity levels of less than 200 µS/cm. Local salinity hotspots were attributed to underlying geology.

Serious water quality problems are associated with the drainage of acid sulfate soils, which results in the flow of acidic (low pH) water into the surface water system. It has been estimated that more than 500 km^2 of land is affected by drainage works in the Lower Clarence (DLWC, 1998). Tulau (1999) reported that 92% of the 14,700 ha of Clarence wetlands have been affected by drainage. (Johnston et al., 2004a) reported high acid flux rates of up to 5300 mol H^+/ha/year from drains located on the lower Clarence River floodplain. Groundwater seepage to ditch drains represents the main hydrological pathway for acid flux with weirs and floodgates affecting the magnitude of acid fluxes (Johnston et al., 2004a, 2004b).

DLWC (1998) identified areas of severely affected acid sulfate soil in the Lower Clarence floodplain for which strategies for rehabilitation should be developed. These areas included (1) Everlasting Swamp – an infilled back lagoon system located on the north-western side of the Clarence River near Lawrence, (2) Shark Creek – a right bank distributary creek which joins the South Arm of the Clarence River approximately 2 km north of Tyndale, (3) the low elevation floodplain and low elevation deltaic island areas downstream of Harwood Island and (4) Alumy Creek – an old flood channel incised into the surrounding floodplain near Grafton. The minimum recorded pH at

Sportsmans Creek located in the Everlasting Swamp area is 2.68 (Beveridge, 1998). Corrosion of concrete structures indicating strongly acidic waters were noted in the Everlasting Swamp and Shark Creek areas (Tulau, 1999). The pH in Wooloweyah Lagoon ranged from 6.6 to 8.2 with a much lower pH of 3.5 noted at the Palmers Island drain, both of which are located in the lower estuary floodplain (Maclean Shire Council, 1996). The lowest pH of 2.5 was reported in Alumy Creek with low pH values persisting from December 1994 to February/March 1996 (Tulau, 1999).

1.1.5.3 Surface water flow

1.1.5.3.1 Brisbane river basin

Active streamflow gauging stations in the Brisbane river basin that fall within the Clarence-Moreton bioregion are listed in Table 11. The longest running gauging station is Stanley River at Peachester where the first measurements were made in 1927. Numerous other gauges either within this basin but outside of the bioregion or that are no longer operational have data that is readily available from <watermonitoring.derm.qld.gov.au>. None of these gauging locations are on the lower reaches of the Brisbane River due to tidal influences.

Table 11 Mean daily flow between the start of records and September 2013 for active gauging stations in the Brisbane river basin that are located within the Clarence-Moreton bioregion

Gauging stations	Area (km^2)	Mean daily flow (ML)	Mean annual flow (mm)	Start of record
Bremer River at Walloon	622	185	109	1 October 1961
Warrill Creek at Amberley	914	296	118	1 October 1961
Bremer River at Adams Bridge	125	53	155	30 September1968
Purga Creek at Loamside	215	41	70	23 November1973
Lockyer Creek at Helidon Number 3	357	70	72	19 November 1987
Lockyer Creek at O'Reillys Weir	2965	619	76	12 January 1948
Laidley Creek at Mulgowie	167	82	179	6 March 1967
Lockyer Creek at Rifle Range Road	2490	319	47	1 February 1988
Tenthill Creek at Tenthill	447	75	61	18 March 1968
Ma Ma Creek at Harms	227	13	21	25 August 1995
Laidley Creek at Warrego Highway	462	95	75	8 November 1990
Sandy Creek at Forest Hill	94	5	19	5 September 1995
Flagstone Creek at Brown-Zirbels Road	157	13	30	1 June 1993
Stanley River at Peachester	104	214	752	1 July 1927
Kilcoy Creek at d/s Kilcoy Weir	131	121	337	16 June 2005
Stanley River at Woodford	249	376	552	6 February 2002
Cressbrook Creek at Rosentretters Crossing	447	54	44	20 August 1986

Source data: Queensland Government (2013)

1.1.5.3.2 Logan-Albert river basin

Active streamflow gauging stations in the Logan-Albert river basin that fall within the Clarence-Moreton bioregion are listed in Table 12. The longest running gauging station is Albert River at Bromfleet where the first measurements were made in 1927. Numerous other gauges either within this basin but outside of the bioregion or that are no longer operational have data that is readily available from <watermonitoring.derm.qld.gov.au>. None of these gauging locations are on the lower reaches of the Logan-Albert River due to tidal influences.

Table 12 Mean daily flow between the start of records and September 2013 for active gauging stations in the Logan-Albert river basin that are located within the Clarence-Moreton bioregion

Gauging stations	Area (km^2)	Mean daily flow (ML)	Mean annual flow (mm)	Start of record
Logan River at Forest Home	175	140	292	1 October 1953
Logan River at Round Mtn	1262	520	150	1 July 1957
Running Ck at Dieckmans Bridge	128	116	331	26 November 1965
Teviot Brook at Croftby	83	40	176	7 February 1966
Logan River at Yarrahappini	2416	869	131	21 April 1969
Burnett Ck at Upstream Maroon Dam	82	42	187	5 May 1970
Logan R at Rathdowney	533	216	148	14 December 1973
Christmas Ck at Tramway Lane	166	106	233	26 June 2006
Palen Creek at Ward Road	95	43	165	29 June 2007
Teviot Brook at Coulson	421	102	88	7 June 2011
Albert River at Lumeah No2	169	134	289	1 October 1953
Albert River at Bromfleet	544	370	248	1 October 1927
Cainbable Creek at The Gorge	42	24	209	1 June 1962
Canungra Creek at Main Road Bridge	101	101	365	24 January 1973

Source data: Queensland Government (2013)

1.1.5.3.3 South Coast basin

There is only one active streamflow gauging station in the South Coast basin that falls within the Clarence-Moreton bioregion (Table 13). The gauge on Back Creek at Beechmont has been running since 1971. Numerous other gauges either within this basin but outside of the bioregion or that are no longer operational have data that is readily available from <watermonitoring.derm.qld.gov.au>.

Table 13 Mean daily flow between the start of records and September 2013 for active gauging stations in the South Coast basin that are located within the Clarence-Moreton bioregion

Gauging station	Area (km^2)	Mean daily flow (ML)	Mean annual flow (mm)	Start of record
Back Creek at Beechmont	7	13	678	5 June 1971

Source data: Queensland Government (2013)

1.1.5.3.4 Tweed river basin

There are no active streamflow gauging stations in the Tweed river basin that fall within the Clarence-Moreton bioregion. Numerous other gauges either within this basin but outside of the bioregion or that are no longer operational have data that is readily available from <waterinfo.nsw.gov.au/>.

1.1.5.3.5 Brunswick river basin

There are no active streamflow gauging stations in the Brunswick river basin that fall within the Clarence-Moreton bioregion. Numerous other gauges either within this basin but outside of the bioregion or that are no longer operational have data that is readily available from <waterinfo.nsw.gov.au/>.

1.1.5.3.6 Richmond river basin

Active streamflow gauging stations in the Richmond river basin that fall within the Clarence-Moreton bioregion are listed in Table 14. The longest running gauging station is Coopers Creek at Repentance where the first measurements were made in 1920. Numerous other gauges either within this river basin but outside of the bioregion or that are no longer operational have data that is readily available from <waterinfo.nsw.gov.au/>.

Table 14 Mean daily flow between the start of records and September 2013 for active gauging stations in the Richmond river basin that are located within the Clarence-Moreton bioregion

Gauging stations	Area (km^2)	Mean daily flow (ML)	Mean annual flow (mm)	Start of record
Coopers Creek at Repentance	62	209	1231	11 February 1920
Richmond River at Casino	1790	1617	330	26 May 1943
Richmond River at Wiangaree	702	773	402	29 May 1943
Leycester River at Rock Valley	179	254	518	23 August 1951
Byron Creek at Binnaburr	39	112	1049	28 August 1951
Wilsons River at Eltham	223	503	824	22 August 1957
Ironpot Creek at Toonumbar	98	88	328	26 July 1967
Coopers Creek at Ewing Bridge	148	371	916	17 May 1969
Myrtle Creek at Rappville	332	160	176	29 May 1969
Eden Creek at Doubtful	581	418	263	18 December 1970
Shannon Brook at Yorklea	492	248	184	24 May 1972

Source data: NSW Government (2013)

1.1.5.3.7 Clarence river basin

Active streamflow gauging stations in the Clarence river basin that fall within the Clarence-Moreton bioregion are listed in Table 15. The longest running gauging station is Clarence River at Tabulam where the first measurements were made in 1909. Numerous other gauges either within this river basin but outside of the bioregion or that are no longer operational have data that is readily available from <waterinfo.nsw.gov.au/>.

Table 15 Mean daily flow between the start of records and September 2013 for active gauging stations in the Clarence river basin that are located within the Clarence-Moreton bioregion

Gauging stations	Area (km^2)	Mean daily flow (ML)	Mean annual flow (mm)	Start of record
Peacock Creek at Bonalbo	47	21	163	25 March 1960
Clarence River at Tabulam	4550	2135	171	1 May 1909
Sportsmans Creek at Gurranang Siding	202	132	239	28 February 1972
Clarence River at Lilydale	16,690	9295	203	28 March 1922
Orara River at Bawden Bridge	1790	2015	411	16 June 1955
Orara River at Glenreagh	446	595	487	15 November 1972

Source data: NSW Government (2013)

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1.1.6 Surface water – groundwater interactions

Summary

Unconfined aquifers, such as alluvial aquifer systems, are typically in direct connection with surface water features such as streams and wetlands. There are also likely to be hydraulic connections where bedrock aquifers directly underlie streams — especially where these streams are deeply incised into the bedrock. Surface water – groundwater interactions are an important part of the hydrological cycle for the Clarence-Moreton Basin. In some instances, streams can provide recharge to the shallow aquifers (losing streams) and elsewhere, baseflow from aquifers can sustain streamflow (gaining streams). In addition, the extraction of groundwater for irrigation or other purposes can also affect stream hydrology. The nature of this interaction is likely to be different, both spatially and temporally, and controlled by many factors such as climate variability, topographic gradients and the lithological and hydraulic properties of the underlying aquifer.

Acid sulfate soils are associated with coastal sediments along the eastern coastline in the Clarence and Richmond river basins. They can discharge significant concentrations of weathering products – including metals and acids – to streams or wetlands. The abundance of coastal acid sulfate soils in the Tweed, Clarence and Richmond river basins makes understanding the interaction between these sediments, shallow groundwater and surface water bodies very important.

In this section, an overview is given for each river basin on the interaction between surface water bodies and groundwater within different river basins and from different hydrostratigraphic units.

Mapped wetlands and groundwater-dependent ecosystems (GDE), which are the surface expression of groundwater discharge, can be viewed for the different river basins within the Clarence-Moreton bioregion in Queensland on the Department of Environment and Heritage Protection Interactive Wetland*Info* website (Department of Environment and Heritage Protection, 2013). In addition to the information on the Interactive Wetland*Info* site, a mapping program is currently underway that will delineate the wetlands and GDEs for these river basins in more detail (M Ronan, 2013, pers. comm.). In NSW, recent mapping of groundwater-dependant ecosystems in coastal river basins including the Clarence river basin and Richmond river basin is available from NSW Office of Water (2013).

1.1.6.1 Lockyer Valley

As the Lockyer Valley is a major food bowl, a considerable amount of work has been conducted to study the interaction between surface water and groundwater (e.g. Zahawi, 1975; Shaw, 2007, Watkinson et al., 2013). In a 2012 survey of surface water chemistry, surface water electrical conductivities were measured at 25 sampling locations of 15 different streams (Raiber, unpublished data). The survey showed that the electrical conductivity of stream water in the Lockyer Valley is highly variable, ranging from very fresh (approximately 190 µS/cm) to saline (14,000 µS/cm). The freshest surface waters were associated with creeks that drain the Woogaroo

Subgroup, which is generally characterised by fresh groundwaters (Section 1.1.4.2). Fresh surface waters were also associated with creeks that are deeply incised into the Main Range Volcanics (e.g. Laidley Creek) in their headwaters. In these areas, the alluvial valleys are typically v-shaped, and the alluvium is generally thin and consists primarily of coarse sediments such as boulders, gravels and sands. There is a strong degree of connectivity between the volcanic bedrock, the alluvium and the streams in these areas.

In contrast, the most saline surface waters were encountered in the upper reaches of streams where these directly overlie the Gatton Sandstone, the Koukandowie Formation and the Walloon Coal Measures, and where these streams have developed only thin and narrow alluvial systems.

Both the strong similarities in the salinities and chemistries (including isotopes) of these creeks and the underlying bedrock in the tributaries to the Lockyer Creek – and especially in their upper reaches – confirm that there is a strong degree of connectivity between the bedrock, the alluvium and the creeks.

In the lower reaches of the Lockyer Valley and, in particular, along the central drainage line of the Lockyer Creek, the nature of surface water – groundwater interactions is more complex and more variable. Sixteen recharge weirs on streams have been built throughout the Lockyer Valley in order to artificially enhance surface recharge to the alluvial aquifer (Cox and Raiber, 2013) as the rates of rainfall recharge in the Lockyer Valley are comparatively small due to the thick clay layer on top of the alluvial sequence. Part of this complexity is due to the irregular and episodic patterns of rainfall. A recent study by Watkinson et al. (2013) on surface water – groundwater interactions in the lower Lockyer Valley and Mid-Brisbane river basin confirmed that droughts and floods have significant influence on surface water – groundwater interactions in this area. For example, during the drought, there was insufficient baseflow to sustain perennial flow in the creeks of the lower part of the Lockyer Valley and the Mid-Brisbane river basin. Following the floods of early 2011, a significant increase in surface water salinities was observed in the Lockyer Valley and at a major regional water treatment plant near Brisbane. This change was attributed to the re-connection of the creeks with the underlying alluvium and bedrock, which generally contain brackish-to-saline groundwater.

Conversely, recent isotopic analysis of groundwater and surface water by Raiber (unpublished data) demonstrated that after the break of the drought and the flooding in 2012, surface water recharge to the alluvium replenished the depleted alluvial aquifer throughout much of the Lockyer Creek alluvium to pre-drought levels. This was accompanied by a decrease in salinity in some locations from up to approximately 25,000 µS/cm observed at the peak of the drought to approximately 500 to 3000 µS/cm after the floods (Section 1.1.4.2.1.3).

1.1.6.2 Bremer river basin, Warrill Creek and Purga Creek basins

The Bremer River and Warrill Creek are deeply incised into the Main Range Volcanics in their headwaters and form thin and comparatively narrow alluvial systems that overlie the Walloon Coal Measures throughout the rest of their river basins. The Purga Creek alluvium directly overlies the Walloon Coal Measures or other Clarence-Moreton bedrock formations throughout its entire course. Pearce et al. (2007a) noted that Purga Creek is characterised by higher salinities than the Bremer River and Warrill Creek, and they have also observed that the Purga Creek and the

Walloon Coal Measures have similar hydrochemistries. This was also independently confirmed by a report from the Bremer Catchment Association (2005), in which high electrical conductivities of approximately 6500 µS/cm were measured for Purga Creek in comparison to the much lower electrical conductivities of less than 1000 µS/cm measured for the Bremer River and the Warrill Creek. Pearce et al. (2007a) indicated that this was probably due to a strong contribution of baseflow from the Walloon Coal Measures to Purga Creek, whereas interaction between the Main Range Volcanics and Bremer River and Warrill Creek generated fresher surface waters. A more detailed assessment of salinity issues in Purga Creek is currently being conducted (R Shaw, 2013, pers. comm.).

1.1.6.3 Logan river basin, Albert river basin and Teviot Brook basin

Logan River and its major tributaries, Albert River and Teviot Brook, are located in south-east Queensland. The Walloon Coal Measures and other Clarence-Moreton stratigraphic units form the bedrock over much of their catchments. There is, at present, only a limited understanding of surface water – groundwater interaction in these river basins. However, some knowledge of Logan River has been gained from a study where different techniques for estimating groundwater discharge to streams were tested in 10 selected river basins in eastern Australia (Cook et al., 2010).

A PhD thesis (Duvert, *In prep*.) is currently examining the nature of the connectivity between the bedrock, the alluvium and the stream in the Teviot Brook basin, a sub-basin of the Logan-Albert river basin.

1.1.6.4 Richmond river basin

Although a substantial amount of work has been conducted on different aspects of surface – groundwater interaction within the Richmond river basin (e.g. Drury, 1982; Sammut et al., 1996; Brodie et al., 2007, 2009; Sundaram et al., 2009; Santos and Eyre, 2011; Santos et al., 2011; Davis, 2012; Atkins et al., 2013), no comprehensive basin-wide assessment has been conducted. Brodie et al. (2007) compared different techniques and their applicability to assess surface – groundwater interactions in the Richmond river basin. They concluded that within the Richmond river basin, the groundwater component of baseflow varies substantially depending on the aquifer system. Their study showed that towards the north, the aquifers of the Alstonville Basalt, as well as North Coast Fractured Rocks (which are composed of fractured basalts), can maintain perennial streams. In the southern part of the river basin, the geology changes from the fractured rocks of the basalts to the lower permeability sedimentary sequences of the Clarence-Moreton Basin. Brodie et al. (2007) explained that Q90 flow rates (the flow rate exceeded 90% of the time) observed in creeks associated with these different hydrostratigraphic units and normalised for area vary by over two orders of magnitude, thus indicating a significantly higher baseflow volume from basalts to streams.

Davis (2012) analysed water chemistry and isotopes for several tributaries to the Richmond River. The presence of ^{222}Rn in surface waters confirmed the presence of groundwater; however, the study highlighted the need to conduct more comprehensive time series analysis of environmental tracers to capture spatial and seasonal or longer-term variability.

Coastal sand aquifers, such as the Woodburn Sands (located on the eastern coastline in the Richmond river basin), have a strong degree of connectivity to streams and wetlands – including the Tuckean Swamp (Drury, 1982; Metgasco, 2007). Drury (1982) suggested that groundwater infiltrates through floodplain deposits and discharges into the Tuckean Swamp as well as the Richmond River; however, the Tuckean Swamp may recharge underlying aquifers during drought conditions.

Santos et al. (2011) analysed the times-series of surface water and groundwater chemistry in the Richmond river basin. They suggested that seepage from shallow groundwater is the major pathway that releases metals such as Al and Mn (from coastal acid sulfate soils) to the Richmond River.

Recent mapping of groundwater-dependant ecosystems in the coastal parts of the Richmond river basin has identified wetland clusters and their relationship to geology and landform and the likely water source (NSW Office of Water, 2013).

1.1.6.5 Tweed river basin

Similar to the Clarence and Richmond river basins, acid sulfate soils dominate the floodplain of the Tweed river basin (MacDonald et al., 2007). These acid sulfate soils, when oxidised due to falling groundwater levels, produce acidic, metal-rich discharge.

1.1.6.6 Clarence river basin

Recent mapping of groundwater-dependant ecosystems in the coastal parts of the Clarence Valley has identified wetland clusters and their relationship to geology and landform and the likely water source (NSW Office of Water, 2013). Types of wetlands that have been identified as part of this mapping include, for example, swamps, coastal salt marshes and freshwater wetlands.

In the Clarence river basin, ditch drains are used to drain water from the acid sulfate soil back swamps of the Clarence River floodplain to the estuary. Acid flux dynamics are mainly controlled by the tidally influenced groundwater gradients and by the hydraulic conductivity (K) of the sulfuric horizons, which are highly heterogeneous. Acid flux rates from groundwater seepage are strongly positively correlated to effluent groundwater hydraulic gradients. Direct groundwater seepage is the primary pathway for acid flux in high K and/or steep-gradient areas. High hydraulic conductivity (>120 m/d) in the sulfuric horizons are due to extensive macropores and, when combined with tidal modulation of drain water levels, encourages rapid seepage of acidic groundwater. However, in areas with a low K and/or smaller groundwater gradients, an episodic discharge flux pathway is due to dilute surface runoff following dissolution of sulfide oxidation products accumulated on the soil surface (Johnston et al., 2004a). Floodgate operations can result in complex site-specific interactions between drain water and adjacent groundwater. Johnston et al. (2005) reported that a 4-day floodgate opening event caused recharge of adjacent acid groundwater during the opening phase, raising the potentiometric groundwater level above local low-tide minima. This was followed by tidally modulated drawdown of acid groundwater and enhanced acid export in the period immediately following floodgate closure.

Weirs affect the water head in the drain, with the changed head difference between the drain and the nearby aquifer impacting acid flux from groundwater seepage (Johnston et al., 2004b).

Therefore, sound understanding of surface-groundwater interaction processes that control the acid fluxes from shallow groundwater systems that contain acid sulfate soils is of vital importance.

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1.1.7 Ecology

Summary

The Clarence-Moreton bioregion covers a large part (24,292 km^2) of the south-east Queensland Interim Bioregionalisation of Australia (IBRA) region, which consists of five subregions: Clarence Lowlands, Clarence Sandstones, Woodenbong, Richmond-Tweed Scenic Rim and Moreton Basin. Most of the steeper slopes are protected by national parks and forest reserves. Vegetation communities consist of subtropical rainforest and wet sclerophyll forest in the mountain slopes and plateaus, transitioning to dry sclerophyll forest and woodlands in lowland areas, as well as coastal floodplains and estuaries. The lower slopes and floodplains are used extensively for agriculture. The coastal plains and lowland areas have been extensively altered by land clearing for agriculture and urban and peri-urban settlement, as well as through natural and modified drainage across wetlands and floodplains. Urban growth is continuing to put pressure on the natural ecosystems.

The Clarence-Moreton bioregion has 14 threatened ecological communities with 7 of these also listed endangered by the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*. Of these threatened communities, 5 are directly associated with water bodies and riverine systems. These are the swamp sclerophyll forest on coastal floodplains, montane peatlands and swamps of the New England tableland, lowland rainforest on floodplains, coastal saltmarsh, and the subtropical coastal floodplain forest. The Clarence-Moreton bioregion is home to 432 threatened species listed under the Queensland, New South Wales and Commonwealth legislations. These include: amphibians (13 species), insects (9 species), gastropod (1 species), fish (5 species), birds (94 species), mammals (42 species), reptiles (18 species) and plants (250 species).

A number of lacustrine and palustrine wetlands are situated around the region, including some substantial wetlands in the Clarence Lowlands. Some of these wetlands are included in *A Directory of Important Wetlands in Australia* (Environment Australia, 2001). A number of endangered species use the wetlands as their habitat, including 13 frog species. These wetlands are also important to local and migratory bird species with at least 11 species listed in the international migratory bird agreements. There are also 5 threatened fish species associated with the wetlands.

1.1.7.1 Ecological systems

The eastern boundary of the bioregion is defined by estuary zones along the coastline, while the Great Dividing Range with the higher tablelands and ridges to the west form the western boundary, indicative of complex and varied vegetation communities and ecosystems. Seven river basins are defined within the bioregion (Figure 21) with hydrological summaries given in Section 1.1.5.

Of ecological importance to the Tweed river basin, although outside the bioregion, is Stotts Island and Ukerebagh Island in the Tweed estuary, with listing in *A Directory of Important Wetlands in Australia* (Environment Australia, 2001). Tweed estuary contains the largest remnant of lowland floodplain subtropical rainforest in New South Wales and Ukerebagh Island Nature Reserve protecting endangered communities of littoral rainforest, mangroves, saltmarsh and seagrasses in one of the largest estuarine wetlands (NSW Office Of Water, 2012). The river basin also contains Wollumbin (formerly Mount Warning) as the highest peak with an elevation 1156 m. Within the Richmond river basin the landscape varies from 100 m elevation to coastal floodplain, with the lower regions supporting extensive wetland areas, including Tuckean Swamp (NSW Office Of Water, 2012). The river basin has about 800 km^2 of land protected by national parks and reserves, especially in the north. Volcanic activity has played an important role in creating spectacular landforms and steep slopes of eucalypt forests with rainforest patches interspersed throughout leading down to lowlands and plains of forests and agricultural lands in the Richmond and Tweed river basins. The World Heritage Area Tweed Volcano group of the Gondwana Rainforests of Australia contains ancient rainforest plant and animal communities with evolutionary links to Gondwana. The area forms part of largest area of subtropical rainforest in Australia and has numerous national parks, such as Border Ranges National Park, Wollumbin National Park, Nightcap National Park, Toonumbar National Park and Richmond Range National Park and many forest reserves.

The Clarence river basin consists of tableland areas in the west that fall away to relatively large, flat floodplains towards the coast. The Clarence Lowlands supports saline basins, swamps and tidal delta flats in the main estuaries and meander plains, and backswamps, levees and terraces along the major drainage lines of the alluvial plain. The area has special conservation interest to state and federal governments (NSW Department of Environment and Climate Change, 2008) for its wetlands and remnant rainforest with particular ecological importance for its species diversity. Around 20% of the river basin is protected as national park and about 30% as state forest under a Regional Forest Agreement (Department of Agriculture, 2013).

The Upper Lockyer in the Brisbane river basin maintains forested hills with the mid and lower river basin largely cleared for intensive agriculture. Eucalypt-dominated communities exist in riparian zones and aquatic vegetation is poor, being mostly filamentous algae and *Elodea* species as aquatic ecosystems are being impacted by water overuse in this river basin. Unstable stream banks and gully erosion has resulted from removal or degradation of the riparian vegetation (DNRM, 2013). The Bremer River in the Brisbane river basin contains a highly turbid river with very poor water quality, resulting from industrial and domestic pollution, high nutrient concentrations and abundant bacteria. The river system has two significant wetlands: Purga Nature Reserve and Daly’s Lagoon near Ripley. Daly’s Lagoon has an endangered plant species – swamp tea-tree (*Melaleuca irbiana*) and a diversity of migratory wader birds. Lake Moogerah is a water supply and irrigation dam on Reynolds Creek, a tributary of the Bremer River. It is stocked with Australian bass, golden perch, saratoga, silver perch and Mary River cod, which is a significant investment for recreational angling (DNRM, 2013).

The Logan-Albert river basin is dominated by urban and agricultural land use, with the Logan River environmental condition rated as very poor due to high turbidity and degradation associated with land clearing. Urban (stormwater and sewage) and agricultural inputs dominate the upper and middle reaches of the river. The Logan River flows through subtropical rainforest onto fertile valley floors, becoming tidal about 60 km from its mouth and includes Lake Maroon and Wyaralong Dams. Stocking of the fish, such as Australian bass, golden perch, saratoga, silver perch and Mary

River cod is taking place on Lake Maroon (DNRM, 2013). The Albert River within the river basin begins at Lamington National Park and flows through forested area into grazing and intensive agriculture and rural residential before joining the Logan River 11.2 km upstream from its mouth (DNRM, 2013). Riparian vegetation mainly consisted of *Casuarina*, *Callistemon*, *Eucalyptus*, *Ficus* and *Lomandra* species. Exotic species are also dominant (DNRM, 2013).

1.1.7.2 Terrestrial species and communities

The Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* is a legal framework to protect and manage nationally and internationally important ecological communities, flora, fauna and heritage places that are identified in the Act as of national environmental significance. Queensland's *Nature Conservation Act 1992* and the New South Wales *National Parks and Wildlife Act 1974* regulate the protection of wildlife and protected areas and places within the bioregion. The bioregion includes parts of two natural resource management regions: South East Queensland Catchments and North Coast Local Land Services. A regional plan has been developed for both areas to target ecological sustainability priorities in the next two decades (DERM, 2009; Northern Rivers CMA, 2013; RDA-Northern Rivers, 2013; SEQ Catchments, 2013).

The Clarence-Moreton bioregion consists of five IBRA subregions (Figure 29, Table 16, and Table 17) and is listed as a National Biodiversity Hotspot.

The bioregion consists of:

- moist volcanic soils derived from basalts supporting subtropical and warm temperate rainforests, or wet sclerophyll forests. Dominant plants include black booyong (*Argyrodendron actinophyllum*), white booyong (*Argyrodendron trifoliolatum*), hoop pine (*Araucaria cunninghamii*), bangalow palm (*Archontophoenix cunninghamiana*), climbing palm (*Calamus muelleri*), rough tree fern (*Cyathea australis*), Australian cedar (*Toona australis*), teak (*Flindersia australis*), white mahogany (*Eucalyptus acmenoides*), small-fruited grey gum (*Eucalyptus propinqua*), tallowwood (*Eucalyptus microcorys*) and Sydney blue gum (*Eucalyptus saligna*)
- low hills and slopes derived from sedimentary materials to form sandy loams supporting dry sclerophyll forests and woodlands with grassy or shrubby understorey. Dominant species include red bloodwood (*Corymbia gummifera*), pink bloodwood (*C. intermedia*), Baileys stringbark (*Eucalyptus baileyi*), blackbutt (*E. pilularis*), scribbly gum (*Eucalyptus signata*), bastard white mahogany (*E. umbra*), turpentine (*Syncarpia glomulifera*), fern-leaved banksia (*Banksia oblongifolia)*, hairpin banksia (*B. spinulosa var. collina*), *Leptospermum polygalifolium*, flaky-barked teatree (*L. trinervium*), grass tree (*Xanthorrhoea latifolia)*, wiry panic (*Entolasia stricta*) and blady grass (*Imperata cylindrica var. major*)
- sedimentary and alluvial soils on relatively flat river plains. Most of this area has been cleared for grazing and intensive agriculture.

There are 202 flora species found in the north coast of New South Wales listed in the schedules of the New South Wales *Threatened Species Conservation Act 1995*. Of these, 108 are endangered, 89 are vulnerable and 5 are considered extinct in the bioregion (National Land and Water Resources Audit, 2002). There are 157 fauna species recorded in the north coast New South Wales and these are listed in the schedules of the New South Wales Threatened Species Conservation Act (National Land and Water Resources Audit, 2002). Of these, 36 are listed as endangered and 121 are listed as vulnerable (Table 18 and Table 19).

There are 88 animal species and 165 plant species listed as rare or threatened in the south-east Queensland region. Rare or threatened species includes those listed as extinct, extinct in the wild, critically endangered, endangered, vulnerable or conservation dependent under either the Nature Conservation Act (Queensland) or the EPBC Act (DEHP, 2013g) (Table 18 and Table 19).

High level plant and animal endemism exists in the Clarence-Moreton region with many plants reaching southern or northern limit of their distributions. This includes *Zieria prostrata* and *Elaeocarpus* sp. Rocky Creek. *Z. prostrata* is restricted to Moonee Beach Nature Reserve and is listed as endangered in both the NSW TSC Act and the EPBC Act (NSW National Parks and Wildlife Service, 1998). *Eleocarpus.* sp Rocky Creek is found in only four locations on the southern edge of the Mount Warning caldera and is also listed as endangered in both the NSW TSC Act and the EPBC Act (NSW National Parks and Wildlife Service, 2003).

The subtropical habitats of the north coast New South Wales and south-east Queensland are rich in bird diversity, with many endemic species and species with restricted distributions, especially in rainforest habitats where there are also several threatened species. The rainforest areas of the Scenic Rim/Richmond/Tweed part of the bioregion is important for the logrunner (*Orthonyx temminckii*), paradise riflebird (Ptiloris paradiseus), the Albert's lyrebird (*Menura alberti*), rufous scrub-bird (*Atrichornis rufescens*), the Coxen's fig-parrot (*Cyclopsitta dipthalma coxeni*) and northern species of eastern bristlebird (*Dasyornis brachypterus*) (Birdlife International, 2013; National Land and Water Resources Audit, 2002). The Loveridge's frog (*Philoria loveridgei*), pouched frog (*Assa darlingtoni*) and Fleay's barred frog (*Mixophyes fleayi*) are also endemic to this rainforest area (ARC, 2013).

The threatened species and ecological communities in the bioregion have been exposed to numerous threatening processes (WetlandCare Australia, 2013) including:

- land clearing for agriculture and urban development, leading to habitat fragmentation and removal
- modified hydrological regimes and water extraction
- erosion and sedimentation
- invasive species impacts
- acid sulfate soils
- poor water quality and pollution
- impacts from industry, such as forestry, dredging and mining.

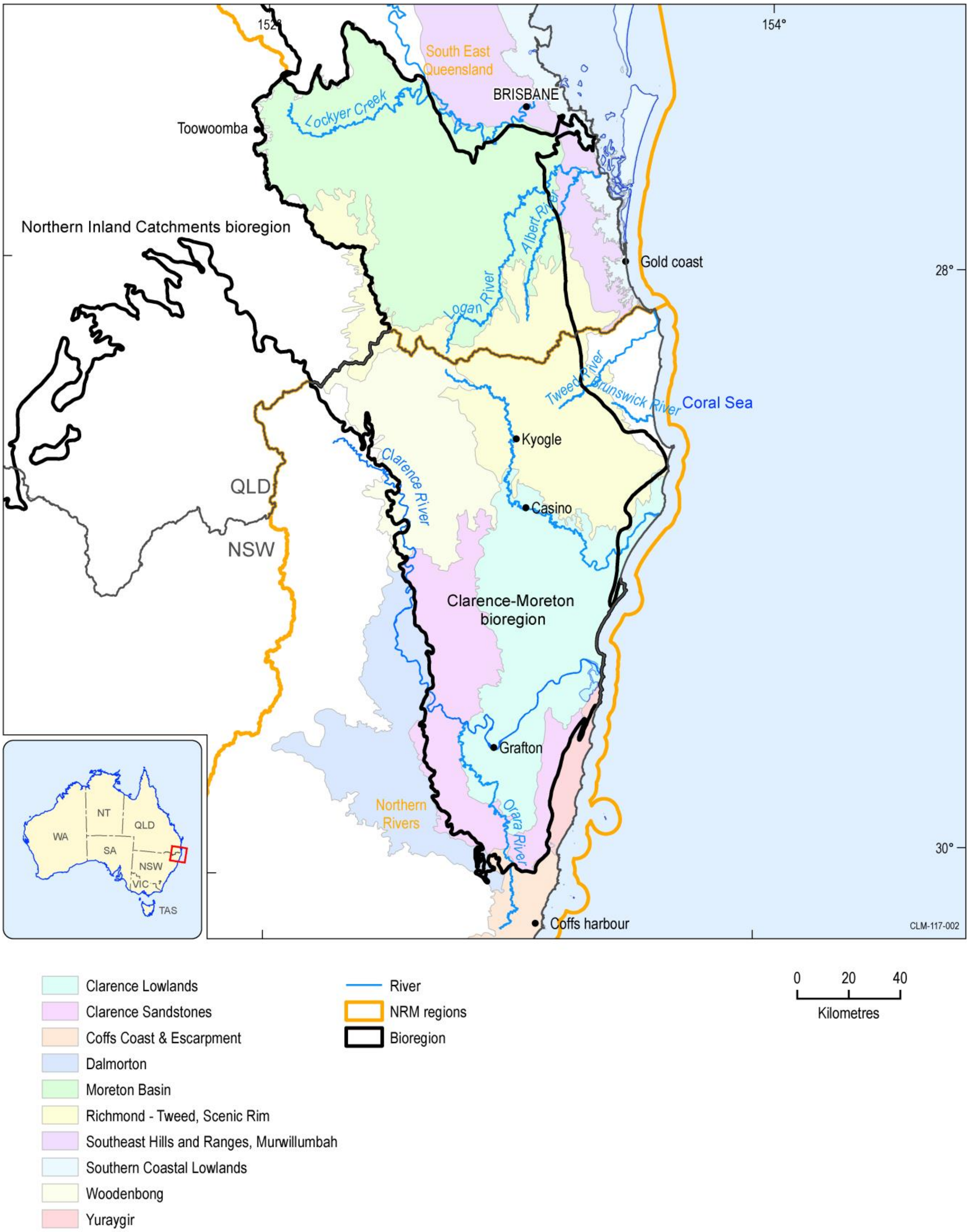

Figure 29 Clarence-Moreton bioregion with relevant natural resource management and Interim Biogeographic Regionalisations for Australia subregion boundaries

Table 16 Brief description of the south-east Queensland Interim Biogeographic Regionalisations for Australia subregions occurring in the Clarence-Moreton bioregion

IBRA subregion	Landform	Biodiversity values
Clarence Lowlands (CL)	Low stepped hills and plains, with hillier areas in west and south. Beach, dune and lagoon barrier systems and estuarine fills along the main streams.	Dry sclerophyll forests and woodlands of spotted gum (*Corymbia maculate*), grey gum (*Eucalyptus punctata*), blackbutt, (*E. pilularis*), red bloodwood (*Corymbia gummifera)* and white mahogany (*Eucalyptus acmenoides*) in the hills. Numerous wetlands.
Clarence Sandstones (CS)	Low to steep stony hillsides on sandstone to the steep gorges and rocky escarpments and outcrops.	Dry sclerophyll forests and woodlands of spotted gum (*Corymbia maculate*), grey gum (*Eucalyptus punctata*) blackbutt (*E. pilularis*), bloodwood (*Corymbia gummifera* and *C. intermedia*), needlebark (*Eucaptus planchoniana*), stringybark (*E. Caliginosa*), ironbark (*E. crebra*) and white mahogany (*E acmenoides*). Areas of listed old growth forests.
Woodenbong (W)	Hilly, basalt ridges and plateau remnants; outer sections of Mount Warning caldera slopes.	Rainforests on basalt as for Richmond-Tweed, including Antarctic beech (*Nothofagus moorei*). Wet and dry sclerophyll, including New England blackbutt (*Eucalyptus campanulata*), red bloodwood (*Corymbia gummifera)* and tallowwood (*Eucalyptus microcorys)* on sedimentary rocks.
Scenic Rim (SR) (now listed as Richmond-Tweed (R-T) in the New South Wales section)	Dissected volcanic caldera with central plug of Mount Warning. Basement rocks exposed around the plug and an outer rim of volcanic flows with well-developed radial drainage pattern. Steep slopes and relief of 1100 m.	Subtropical and warm temperate rainforests and wet sclerophyll forests including; black booyong (*Argyrodendron actinophyllum*), white booyong (*A. trifoliolatum*), hoop pine (*Araucaria cunninghamii)*, bangalow palm (*Archontophoenix cunninghamiana)*, rough tree fern (Cyathea australis), Australian cedar (*Toona ciliate*), teak (*Tectona grandis*), white mahogany (*Eucalyptus acmenoides*, small-fruited grey gum (*E. propinqua*), tallowwood (*E. microcorys)* and Sydney blue gum (*E. saligna*). Contains World Heritage listed Gondwana Rainforests of Australia.
Moreton Basin (MB)	Flat alluvial plains and low hills and ranges leading up to the steep escarpment of the Great Dividing Range.	Much of the area has been cleared for agriculture and rural landscapes. Some large tracts of dry sclerophyll open forests and woodlands scattered throughout with spotted gum (*Corymbia maculate*), lemon-scented gum (*C. citriodora*) and narrow-leaved ironbark (*Eucalyptus crebra*) and occasionally Queensland peppermint (*E. exserta*) and grey box (*E. microcarpa*) present in scattered patches or low densities. The understorey is usually grassy.

Source data: (i) NSW Environment and Heritage (2011), (ii) NSW National Parks and Wildlife Service (2012) and (iii) SEWPaC (2013).

Table 17 State legislated threatened ecological communities within the Clarence-Moreton bioregion grouped by Interim Biogeographic Regionalisations for Australia subregions

Community	IBRA subregion						Commonwealth status	Description
	CL	CS	W	SR	RT	MB		
Freshwater wetlands on coastal floodplains	■	■			■		Not listed	Coastal area subject to periodic flooding and standing water in low lying areas on alluvial flats dominated by herbaceous plants depending on water regime.
Subtropical Coastal Floodplain Forest	■	■			■		Not listed	Subtropical tall open forest occupying central and marginal sections of floodplain, dominated by forest red gum (*Eucalyptus tereticornis*), grey ironbark (*E. siderophloia*), pink bloodwood (*Corymbia intermedia*) and, north of the Macleay floodplain, swamp turpentine (*Lophostemon suaveolens*).
Coastal Cypress Pine forest	■						Not listed	Closed to open canopy of coastal cypress pine (*Callitris columellaris*), which may sometimes be mixed with eucalypts such as pink bloodwood (*Corymbia intermedia*), blackbutt (*Eucalyptus pilularis*) or scribbly gum (*E. signata*), wattles including Salwood (*Acacia disparrima subsp. disparrima*) and also black she-oak (*Allocasuarina littoralis*), coast banksia (*Banksia integrifolia subsp. integrifolia*) or old-man banksia (*B. serrata*) and/or rainforest trees. The understorey of shrubs, sedges and herbs is typically open to sparse.
Coastal Saltmarsh	■						Not listed	Coastal saltmarsh occurs in the intertidal zone on estuary and lagoon shores intermittently open to the sea and include plants like *Baumea juncea*, sea rush (*Juncus krausii subsp. australiensis*), samphire (*Sarcocornia quinqueflora subsp. quinqueflora*), marine couch (*Sporobolus virginicus*), streaked arrowgrass (*Triglochin striata*), knobby club-rush (*Ficinia nodosa*), creeping brookweed (*Samolus repens*), swamp weed (*Selliera radicans*), seablite (*Suaeda australis*) and prickly couch (*Zoysia macrantha*).
Grey Box-Grey Gum Wet Sclerophyll Forest			■				Not listed	Tall open tree canopy of eucalypts grey box *(Eucalyptus moluccana)* and small-fruited grey gum (*Eucalyptus propinqua*) and, less commonly *Eucalyptus biturbinata*, grey ironbark (*Eucalyptus siderophloia*) and hoop pine (*Araucaria cunninghamii*). Structurally complex understorey including rainforest trees and shrubs, vines, ferns and herbs.
Littoral Rainforest and Coastal Vine Thickets	■	■			■	■	Critically Endangered	Closed canopy of trees, shrubs, vines, herbs, ferns and epiphytes with some *Araucaria*, *Eucalyptus* or *Banksia* emergents possible. Ground stratum is sparse. Located as disjunct and isolated stands close to the coast or near an estuary.

Community	IBRA subregion						Commonwealth status	Description
	CL	CS	W	SR	RT	MB		
Lowland Rainforest	■	■	■	■	■	■	Critically Endangered	Closed canopy subtropical rainforest. High diversity and species richness between regions and stands. Canopy comprised of a range of tree species however a particular species may dominate e.g. palm forest, usually dominated by bangalow palm (*Archontophoenix cunninghamiana*) or cabbage palm (*Livistona australis*); and riparian areas dominated by *Syzygium floribundum* (syn. *Waterhousea floribunda*) (weeping satinash/weeping lilly pilly). Canopy and subcanopy species (including emergents) can include hoop pine (*Araucaria cunninghamii*), figs (*Ficus* spp.), white booyong (*Argyrodendron trifoliolatum/Heritiera trifoliolata*), black bean (*Castanospermum australe*), white walnut (*Cryptocarya obovata,* pepperberry), giant stinging tree (*Dendrocnide excelsa*), native tamarind (*Diploglottis australis*), rosewood (*Dysoxylum fraserianum*), red bean (*Dysoxylum mollissimum*), green tamarind (*Elattostachys nervosa*), hairy walnut (*Endiandra pubens*), bumpy ash (*Flindersia schottiana,* cudgerie, silver ash), white beech (*Gmelina leichhardtii*), bolly gum (*Neolitsea australiensis*), white bolly gum (*Neolitsea dealbata*), maidens blush (*Sloanea australis*), yellow carabeen (*Sloanea woollsii*), red cedar (*Toona ciliata*), and epiphytes such as *Platycerium* spp. and birds nest fern (*Asplenium australasicum*).
Lowland Rainforest on Floodplain	■	■			■		Critically Endangered	Stands can form a dense canopy with a rich diversity of plants and animals with riparian areas dominated by weeping satinash/weeping lilly pilly (*Syzygium floribundum* syn. *Waterhousea floribunda*). Typical tree species in the community include hoop pine (*Araucaria cunninghamii*), figs (*Ficus macrophylla*, *F. obliqua* and *F. watkinsiana*), black booyong (*Heritiera actinophylla*), white booyong (*Heritiera trifoliolata*), giant stinging tree (*Dendrocnide excelsa*), palms (*Archontophoenix cunninghamiana* and *Livistona australis*), silky oak (*Grevillea robusta*), black bean (*Castanospermum australe*) and brush cherry (*Syzygium australe*).
Montane Peatlands and Swamps of the New England Tableland			■				Endangered	Dense groundcover of sedges, grasses and forbs, except where a dense cover of tall shrubs casts deep shade. The community typically has an open to very sparse layer of shrubs, 1 to 5 m tall, (eg. Baeckea gunniana, B. utilis, Callistemon pityoides, Leptospermum spp.). Species of Epacris and Hakea microcarpa are also common shrubs. Soft-leaved species of Carex spp and Poa spp typically make up most of the groundcover biomass, Forbs growing amongst the sedges include Drosera spp., Geranium neglectum, Gratiola spp., Mitrasacme serpyllifolia, Ranunculus spp. and Viola spp. Hummocks of Sphagnum moss may occur.

Community	IBRA subregion						Commonwealth status	Description
	CL	CS	W	SR	RT	MB		
Swamp Sclerophyll Forest on Coastal Floodplains	■	■			■		Not listed	Open to dense stand of eucalypts and paperbarks. The most widespread and abundant dominant trees include swamp mahogany (Eucalyptus robusta), broad-leaved paperbark (Melaleuca quinquenervia). Other species associated with this community include swamp oak (Casuarina glauca), red mahogany (Eucalyptus resinifera), forest red gum (E. tereticornis), pink bloodwood (Corymbia intermedia), swamp box (Lophostemon suaveolens)
White Box Yellow Box Blakely's Red Gum Grassy Woodland and Derived Native Grassland			■	■		■	Critically Endangered	Can occur either as woodland or derived native grassland (i.e. grassy woodland where the tree overstorey has been removed). Characterised by species-rich understorey of native tussock grasses, herbs and scattered shrubs (where shrub cover comprises less than 30% cover), and a dominance or prior dominance of white box (Eucalyptus albens) and/or yellow box (E. melliodora) and/or Blakely's red gum (E. blakelyi) trees.
White Gum Moist Forest			■		■		Not listed	Tall moist open forest scattered in sheltered positions on foothills and ranges. Dominant species is Dunn's white gum (Eucalyptus dunnii) with flooded gum (E. grandis), Sydney blue gum (E. saligna), tallowwood (E. microcorys), brush box (Lophostemon confertus)
Brigalow (Acacia harpophylla dominant and sub-dominant)						■	Endangered	Acacia harpophylla open forest on sedimentary rocks. Can appear with Casuarina cristata and vine thicket species
Swamp Tea-tree (Melaleuca irbyana) Forest						■	Critically Endangered	Occurs as an open forest or thicket or scattered under open forest or woodland of narrow-leaved ironbark (Eucalyptus crebra), silver-leaved ironbark (E. melanophloia), grey box (E.moluccana), forest red gum (E. tereticornis) and spotted gum (Corymbia citriodora).

Source data: (i) <www.ehp.qld.gov.au/ecosystems/biodiversity/regional-ecosystems/>,
(ii) <www.environment.nsw.gov.au/threatenedSpeciesApp/> and
(iii) <www.environment.gov.au/biodiversity/threatened/communities/>.

Table 18 Threatened terrestrial species of the Clarence-Moreton bioregion

IBRA subregion	Type	Endangered	Vulnerable	Total
Clarence Lowlands	Fauna	8	21	29
	Flora	10	2	12
Clarence Sandstones	Fauna	9	54	63
	Flora	29	22	51
Richmond-Tweed	Fauna	17	15	32
	Flora	37		37
Woodenbong	Fauna	7	16	23
	Flora	18	8	26
South-east Queensland	Fauna	24	51	75
	Flora	48	95	143

Table 19 Species listed as threatened in the various IBRA subregions of the Clarence-Moreton bioregion

Class	IBRA subregion						Species	Threatened species	Threatened species
	CL	CS	W	SR	RT	MB		State	EPBC
Bird (only endangered shown)	■					■	Little tern (*Sternula albifrons)*	E,P	C,J,K
	■					■	Curlew sandpiper (Calidris ferruginea)	E,P	C,J,K
	■			■	■	■	Australasian bittern (Botaurus poiciloptilus)	E,P	E
				■	■	■	Eastern bristlebird (*Dasyornis brachypterus)*	E,P	E
	■			■		■	Australian painted snipe (*Rostratula australis)*	E,P	E
		■	■	■	■	■	Black-Necked stork (*Ephippiorhynchus asiaticus)*	E,P	
		■		■		■	Bush stone-curlew (*Burhinus grallarius)*	E,P	
	■				■		Pied oystercatcher (*Haematopus longirostris)*	E,P	
	■	■		■	■	■	Swift parrot (*Lathamus discolour)*	E,P	E
	■	■	■	■	■	■	Regent honeyeater (*Anthochaera phrygia)*	E E	
	■	■	■	■	■	■	Coxen's fig-parrot (*Cyclopsitta diophthalma coxeni)*	E E	
			■	■	■	■	Red goshawk (*Erythrotriorchis radiates*)	E V	
Mammal	■			■	■	■	Hastings river mouse (*Pseudomys oralis*)	E,P	E
	■	■	■	■	■	■	Brush-tailed rock-wallaby (*Petrogale penicillata*)	E,P	V
	■	■	■	■	■	■	Black-striped wallaby (*Macropus dorsalis*)	E,P	
	■	■	■	■	■	■	Spotted-tailed quoll (*Dasyurus maculatus)*	V,P	E
	■	■	■	■	■	■	Koala (*Phascolarctos cinereus)*	V,P	V
	■	■	■	■	■	■	Grey-Headed flying-fox (*Pteropus poliocephalus)*	V,P	V
	■	■	■	■	■	■	Large-Eared pied bat (*Chalinolobus dwyeri)*	V,P	V
	■	■	■	■	■	■	Long-Nosed potoroo (*Potorous tridactylus)*	V,P	V
	■	■	■	■	■	■	Brush-Tailed phascogale (*Phascogale tapoatafa)*	V,P	
	■	■	■	■	■	■	Common planigale (*Planigale maculata)*	V,P	
	■	■	■	■	■	■	Yellow-bellied glider (*Petaurus australis)*	V,P	
	■	■	■	■	■	■	Squirrel glider (*Petaurus norfolcensis)*	V,P	
	■	■	■	■	■	■	Rufous bettong (*Aepyprymnus rufescens)*	V,P	

Class	IBRA subregion						Species	Threatened species	Threatened species
	CL	CS	W	SR	RT	MB		State	EPBC
	■	■	■		■		Parma wallaby (*Macropus parma)*	V,P	
	■	■			■		Common blossom-bat (*Syconycteris australis)*	V,P	
	■	■	■	■	■	■	Yellow-bellied sheathtail-bat (*Saccolaimus flaviventris)*	V,P	
	■	■	■	■		■	Beccari's freetail-bat (*Mormopterus beccarii)*	V,P	
	■	■	■	■	■	■	Eastern freetail-bat (*Mormopterus norfolkensis)*	V,P	
	■	■	■	■	■	■	Hoary wattled bat (*Chalinolobus nigrogriseus)*	V,P	
	■	■	■	■	■	■	Eastern false pipistrelle (*Falsistrellus tasmaniensis)*	V,P	
		■	■	■	■	■	Golden-tipped bat (*Kerivoula papuensis)*	V,P	
	■	■	■	■	■	■	Little bentwing-bat (*Miniopterus australis)*	V	
	■	■	■	■	■	■	Eastern bentwing-bat (*Miniopterus schreibersii oceanensis)*	V,P	
	■	■	■		■		Southern myotis (*Myotis macropus)*	V,P	
	■	■	■	■	■	■	Greater broad-nosed bat (*Scoteanax rueppellii)*	V,P	
	■	■	■	■	■	■	Eastern cave bat (*Vespadelus troughtoni)*	V,P	
	■	■	■	■	■	■	Eastern chestnut mouse (*Pseudomys gracilicaudatus)*	V,P	
			■	■	■	■	Eastern pygmy-possum (*Cercartetus nanus)*	V,P	
			■	■	■	■	Eastern tube-nosed bat (*Nyctimene robinsoni)*	V,P	
	■		■		■	■	Eastern long-eared bat (*Nyctophilus bifax)*	V,P	
			■	■	■	■	Red-Legged pademelon (*Thylogale stigmatica)*	V	V
				■			Plains rat (*Pseudomys australis)*	V	V
				■		■	Long-Nosed potoroo (*Potorous tridactylus tridactylus)*	V	V
						■	Water mouse (*Xeromys myoides*)	V	V
Reptile						■	Long-Legged worm-skink (*Anomalopus mackayi*)	E	V
						■	Grey snake (*Hemiaspis damelii)*	E	
						■	Collared delma (*Delma torquata)*	V	V
	■		■	■	■	■	Three-Toed snake-tooth skink (*Coeranoscincus reticulatus)*	V,P	V
	■	■		■	■	■	White-Crowned snake (*Cacophis harriettae)*	V,P	

Class	IBRA subregion						Species	Threatened species	Threatened species
	CL	CS	W	SR	RT	MB		State	EPBC
	■	■	■	■		■	Pale-Headed snake (*Hoplocephalus bitorquatus)*	V,P	
	■	■	■		■		Stephens' banded snake (*Hoplocephalus stephensii)*	V	E
Insect				■	■	■	Richmond birdwing butterfly (*Ornithoptera richmondia*)	V	
		■					Giant dragonfly (*Petalura gigantea)*	E	
	■	■					Coastal petaltail (*Petalura litorea)*	E	
					■		Atlas rainforest ground-beetle (*Nurus atlas)*	E	
					■		Shorter rainforest ground-beetle (*Nurus brevis)*	E	
				■		■	Australian fritillary (*Argyreus hyperbius inconstans)*	E	
						■	Bulloak jewel (*Hypochrysops piceata)*	E	
				■		■	Illidge's ant-blue (*Acrodipsas illidgei)*	V	
						■	Pale imperial hairstreak (*Jalmenus eubulus)*	V	
Plants (only nationally endangered)		■					Dwarf heath casuarina (*Allocasuarina defungens*)	E,P	E
	■	■					Hairy melichrus (*Melichrus hirsutus)*	E,P	E
	■	■					Rupp's wattle (*Acacia ruppii)*	E,P	E
	■	■	■	■	■	■	Nightcap plectranthus (*Plectranthus nitidus)*	E,P	E
		■	■				Creek triplarina (*Triplarina imbricata)*	E,P	E
	■	■			■		Scented acronychia (*Acronychia littoralis)*	E,P	E
	■	■					Moonee quassia (*Quassia sp. Mooney Creek)*	E,P	E
			■		■	■	Native jute (*Corchorus cunninghamii)*	E,P	E
			■				White-flowered wax plant (*Cynanchum elegans)*	E,P	E
	■		■		■		Ripple-leaf muttonwood (*Myrsine richmondensis)*	E,P	E
	■		■		■	■	Southern ochrosia (*Ochrosia moorei)*	E,P	E
	■		■		■		Cryptic forest twiner (*Tylophora woollsii)*	E,P	E
					■		Isoglossa (*Isoglossa eranthemoides)*	E,P	E
					■		Smooth davidson's plum (*Davidsonia johnsonii)*	E,P	E
					■	■	Red-fruited ebony (*Diospyros mabacea)*	E,P	E

Class	IBRA subregion						Species	Threatened species	Threatened species
	CL	CS	W	SR	RT	MB		State	EPBC
					■		Crystal creek walnut (*Endiandra floydii)*	E,P	E
					■	■	*(Amyema plicatula)*	E,P	E
	■				■	■	Sweet myrtle (*Gossia fragrantissima)*	E,P	E
					■		Peach myrtle (*Uromyrtus australis)*	E,P	E
					■	■	Spiny gardenia (*Randia moorei)*	E,P	E
	■				■	■	Small-leaved tamarind (*Diploglottis campbellii)*	E,P	E
	■						Narrow-leaf melichrus (*Melichrus sp. Gibberagee)*	E,P	E
					■		Nightcap oak (*Eidothea hardeniana)*		CE
	■				■		Davidson's plum (*Davidsonia jerseyana)*	E	
	■				■		Southern swamp orchid (*Phaius australis)*	E	
	■						Lady tankerville's swamp orchid (*Phaius tancarvilleae)*	E	
		■					Banyabba shiny-barked gum (*Eucalyptus pachycalyx subsp. banyabba)*	E,P	E
		■					Beadle's grevillea (*Grevillea beadleana)*	E,P	E
	■		■				Mason's grevillea (*Grevillea masonii)*	E,P	E
					■		Minyon quandong (*Elaeocarpus sp. Rocky Creek*)	E,P	E
					■		Hairy quandong (*Elaeocarpus williamsianus)*	E,P	E
						■	*(Notelaea ipsviciensis)*	E	CE
						■	*(Phebalium distans)*	E	CE
			■				*(Cossinia australiana)*	E	E
			■			■	*(Planchonella eerwah)*	E	E
						■	*(Plectranthus habrophyllus)*	E	E
						■	*(Gossia gonoclada*)	E	E
						■	*(Leucopogon sp. Coolmunda D.Halford Q1635*)	E	E
						■	Swamp daisy (*Olearia hygrophila)*	E	E
Gastropod					■		Mitchell's rainforest snail (*Thersites mitchellae)*	E	CE
Amphibian	■				■		Green and golden bell frog (*Litoria aurea*)	E	V
					■		Stuttering frog (*Mixophyes balbus*)	E	V

Class	IBRA subregion						Species	Threatened species	Threatened species
	CL	CS	W	SR	RT	MB		State	EPBC
			■	■	■	■	Fleay's barred frog (*Mixophyes fleayi*)	E	E
			■				Mountain frog (*Philoria kundagungan*)	E	
			■				Loveridge's frog (*Philoria loveridgei*)	E	
			■				*(Philoria richmondensis)*	E	
	■	■	■	■	■	■	Giant barred frog (*Mixophyes iterates*)	E	E
						■	Wallum sedgefrog (*Litoria olongburensis*)	V	V
				■		■	Wallum rocketfrog (*Litoria freycineti*)	V	
				■			Cascade treefrog (*Litoria pearsoniana*)	V	
	■	■	■	■	■	■	Tusked frog (*Adelotus brevis*)	V	
Fish				■	■	■	Oxleyan pygmy perch (*Nannoperca oxleyana*)	E	E
						■	Murray cod (*Maccullochella peelii*)	V	
	■	■			■		Eastern freshwater cod (*Maccullochella ikei)*	E	E
				■		■	Purple-spotted gudgeon (*Mogurnda adspersa*)	E	
						■	Australian lungfish (*Neoceratodus forsteri*)	V	

E = Endangered; CE = Critically Endangered; V = Vulnerable; P = Protected; C =China Australia Migratory Bird Agreement; J = Japan Australia Migratory Bird Agreement; K = Republic of Korea Australia Migratory Bird Agreement
Because of large numbers of species, the table only shows the endangered species for birds and the nationally endangered for plants.
Source data: (i) New South Wales Bionet (NSW Environment and Heritage, 2013) – <www.bionet.nsw.gov.au/>, (ii) Qld Wildlife Online (Qld DEHP, 2013) – <www.ehp.qld.gov.au/wildlife/wildlife-online/> and (iii) Department of the Environment (2013a) <www.environment.gov.au/node/19448>.

1.1.7.3 Aquatic species and communities

The National Water Initiative looks to improve the efficiency and sustainability of water use and management with Paragraph 25 x focusing on identifying surface and groundwater systems of high conservation value to manage these systems to protect and enhance those values (Department of the Environment, 2004). The Australian National Aquatic Ecosystem Classification Framework (ANAE) was developed to support the classification of aquatic ecosystems and help identify High Ecological Value Aquatic Ecosystems (HEVAE), as well as support mapping aquatic ecosystems (Department of the Environment, 2013b). State management of water in the bioregion falls under Queensland's *Water Act 2000* and the New South Wales *Water Management Act 2000*. Environmental values and water quality objectives have also been established for riverine, estuarine, coastal waters and groundwater, within the South East Queensland Natural Resource Management area legislated under the Environmental Protection (Water) Policy 2009, and within New South Wales as guidelines in the New South Wales *Protection of the Environment Operations Act 1997*.

Wetlands

Wetlands are an essential component of natural hydrological cycles, storing and purifying water, catching sediments and nutrient recycling, providing coastal protection against ocean movement and providing habitat and nursery sites for fish communities (The State of Queensland Environmental Protection Agency, 1999). Wetlands have cultural values as well as associated tourism and recreation values and provide ecosystem services. They also provide habitat for a diverse number of plants and wildlife, including waders and shorebirds. Many of these wetlands are listed habitat for bird species connected to international migratory routes and have agreements set up within The Convention on the Conservation of Migratory Species of Wild Animals (e.g. The Japan Australia Migratory Bird Agreement, China Australia Migratory Bird Agreement and the Republic of Korea Australia Migratory Bird Agreement). Over 100 species are listed under these migratory bird agreements.

The Clarence-Moreton bioregion has an extensive system of wetlands (Figure 5). A process for identifying wetlands was developed by the Queensland Department of Environment Protection (DEHP, 2013b) from regional ecosystems data augmented by satellite imagery and topographic maps. Wetlands were categorised into different types. These include:

4. riverine wetlands – wetland and deepwater habitat within a channel with continuous or periodic moving water
5. lacustrine wetlands – large and open water–dominated systems (>8 ha), such as lakes
6. palustrine wetlands – vegetated non-channel habitat (<8 ha) with more than 30% emergent vegetation, such as swamps, bogs, springs and soaks
7. estuarine wetlands – inundated with seawater but can be diluted by freshwater runoff (DEHP, 2013j; WetlandInfo, 2013).

The riverine, palustrine and lacustrine wetlands are in the process of being assessed for conservation and biodiversity values, in accordance with the HEVAE process, using the Aquatic Biodiversity Assessment Mapping Method (AquaBAMM) (DEHP, 2013a).

The Moreton Basin IBRA subregion has approximately 800 lacustrine/palustrine wetlands (31.7 km^2) with 0.8 km^2 in estuarine and 142.2 km^2 in riverine wetland systems. The aquatic ecosystems in this subregion include floodplain and non-floodplain Melaleuca and Eucalyptus swamps, floodplain lakes and floodplain grass, sedge and herb swamps (DEHP, 2013f). The Scenic Rim IBRA subregion has approximately 24 lacustrine/palustrine wetlands (0.1 km^2) and 31.3 km^2 of riverine wetland system which all rely on surface water. The aquatic ecosystems in this subregion include floodplain Melaleuca and Eucalyptus swamps, and floodplain grass, sedge and herb swamps (DEHP, 2013h). Threats to wetlands in this bioregion are numerous and include agricultural expansion, and changed drainage patterns from construction of roads, drains and channels, particularly in expanding urban areas.

Two wetlands are listed as important (Environment Australia, 2001) in the Moreton Basin subregion. The Carbrook Wetlands Aggregation covers 3 km^2 and is made up of 88.8% palustrine wetlands, 10.8% estuarine wetlands and 0.3% lacustrine wetlands. The wetland complex consists of sub-coastal floodplain lakes, floodplain grass, sedge and herb swamps and sub-coastal tree swamps (DEHP, 2013c). Major floral species include *Melaleuca quinquenervia* closed/open forest and *Eucalyptus signata* and *E. intermedia* open forest/woodland. These wetlands are extensively used by waterbirds, including the threatened black-necked stork (*Ephippiorhynchus asiaticus*), painted snipe (*Roastratula benghalensis*) and the chestnut teal (*Anas castanea*). Many of the waders utilising the ephemeral grassy wetland areas are listed under the migratory acts (Department of the Environment, 2010).

The Karawatha Forest Park Wetlands consist of two lacustrine/palustrine wetlands (3.8% of area) and provide high connectivity value across remnant forests containing unconnected stream channels, marshes, pools and perennial backwaters. It has a sub-coastal floodplain tree swamp habitat with Melaleuca and Eucalyptus species. The wetland area contains diverse wildlife and a range of habitats which provide refugia to significant species (DEHP, 2013e). There are 13 vegetation communities (Kordas et al., 1993) which represent inland sub-coastal remnants of tall wet and open wet health and wallum. Eight Regional Ecosystems occur within the wetland area (Young and Dillewaard, 1999) of which two are endangered and five are ‘of concern’. The Queensland white stringybark (*E. tindalie*) with scribbly gum (*E. racemosa*) open forest and the narrow-leaved red gum (*E. seeana*), pink bloodwood (*Corymbia intermdia*) and *Angophora leiocarpa* woodland are endangered. Within the wetland area, six bird species are listed in international treaties. The wetlands are especially important to 26 frog species while the regent honeyeater (*Anthochaera phrygia*) is listed as endangered (Table 19).

The Upper Coomera River is classified as an important riverine wetland in the Richmond-Tweed Scenic Rim subregion, as are the Dalrymple and Blackfellow Creeks. The Upper Coomera River varies from warm subtropical notophyll to temperate microphyll rainforest and sclerophyll forest (Churchett, 1982) depending on elevation. Species-rich communities in the wetlands support a diverse range of fauna and uncommon plant communities. A number of vulnerable, rare and threatened species find refuge habitat within this wetland area. Six out of eight Regional Ecosystems are ‘of concern’ however none are endangered. Five endangered fauna species inhabit the wetland area: the cascade tree frog (*Litoria pearsoniana*), Fleay’s barred frog (*Mixophyes fleayi*), red goshawk *(Erythrotriorchis radiates*), eastern bristlebird (*Dasyornis brachypterus*) and Coxen’s parrot (*Cyclopsitta dipthalma coxeni*; Table 19). These species are also endangered in the Dalrymple and Blackfellow Creeks wetland area.

Dalrymple and Blackfellow Creeks consist of varied habitats in a montane environment including marsh environments with rainforest and riparian communities and montane creeks. The wetland has scenic and wildlife refuge value but is well known for its natural state and high integrity (Knight et al., 2002). Only lower reaches have been affected by clearing and grazing. Vegetation remnants provide high connectivity and refuge. Of the ten Regional Ecosystems, six are ‘of concern’. Unusual montane and submontane sclerophyllous forest exists and includes the rare Dunn’s white gum (*Eucalyptus dunnii*) and Bailey’s cypress (*Callitris baileyi*). Four bird species which frequent the wetlands are listed in international migratory treaties, including the great egret (*Ardea ibis*). Dalrymple Creek contains the largest assemblage of macroinvertebrate family taxa for a wetland in South East Queensland (Knight et al., 2002).

Estuaries in the Clarence-Moreton bioregion are dominated by mangrove communities (composed of *Avicennia marina, Aegiceras coniculatum, Exoecaria agallocha)* and saltmarsh species. Freshwater margins are occupied by swamp oak (*Casuarina glauca*) and paperbark (*Melaleuca* *quinquenervia*) while flooded gum (*Eucalyptus grandis*) grows on alluvial river flats. Banksia and bangalow palms are found in the dunes and heath and paperbark swamps occur behind the dunes and near the lagoons. Rare patches of rainforest species can be found even here where sufficient soil nutrients have accumulated.

Some significant wetlands have been identified in the north coast of New South Wales (National Land and Water Resources Audit, 2002). Clarrie Hall Dam supports several significant species, including the vulnerable comb-crested jacana (*Irediparra gallinacea*) and the endangered black-necked stork (*Ephippiorhynchus asiaticus*).

The Brunswick River Floodplain supports threatened species including the comb-crested black bittern (*Ixobrychus flavicollis*), freckled duck (*Stictonetta naevosa*), mangrove honeyeater (*Lichenostomus fasciogularis*) and the black-necked stork (*Ephippiorhynchus asiaticus*). Threatened flora on this section of floodplain includes the bakers wattle (*Acacia bakeri*) and the *Randia moorei* (National Land and Water Resources Audit, 2002).

Cumbebin Swamp provides habitat for the endangered black-necked stork (*Ephippiorhynchus asiaticus*) and Mitchell's rainforest snail (*Thersites mitchellae*). Other vulnerable species recorded are the bush hen (*Amaurornis olivaceus*), great knot (*Calidris tenuirostris*), grass owl (*Tyto capensis*) and the little bent-wing bat (*Miniopterus australis*). Cokora Lagoon supports a diversity of wetland birds including the vulnerable brolga (*Grus rubicundus*), pied oystercatcher (*Haematopus longirostris*) and the black-necked stork (*Ephippiorhynchus Asiaticus)* (National Land and Water Resources Audit, 2002).

Blue Lake is protected in Yuraygir National Park and provides habitat for the vulnerable brolga, the comb-crested jacana, the endangered black-necked stork and green and golden bell frog (*Litoria aurea*). The endangered little tern (*Sterna albifrons*) has also been recorded at the lake. The little tern is protected under both the Japan Australia Migratory Bird Agreement and China Australia Migratory Bird Agreement. Other vulnerable species include the glossy black cockatoo (*Calyptorhynchus lathami*), masked owl (*Tyto novaehollandiae*), rose-crowned fruit dove (*Ptilinopus regina*) and squirrel glider (*Petaurus norfolcensis*) (National Land and Water Resources Audit, 2002).

Much of the coastal wetlands in the major river basins of the bioregion have been significantly reduced, especially in the northern coastal area of New South Wales where an estimated loss of up to 85% of coastal wetlands has occurred (Goodrick, 1970; Pressey and Middleton, 1982). The main pressures currently or historically affecting parts of the rivers and wetlands downstream and estuaries in the bioregion can include:

- poor ecological health and water quality due to:
  - land clearing (as a result of agriculture and urban development)
  - stormwater runoff
  - sedimentation
  - waste water discharge
  - agricultural runoff
  - impacts associated with dredging and waterway structures

- bank erosion
- water regulation
- acid sulfate soils in some areas (especially along the coastal regions of north-east New South Wales)
- loss of riparian and intertidal vegetation
- depleted fish stocks
- invasive species
- high levels of human use (Byron Shire Council, 2013; University of NSW and NSW NPWS, 2006).

Clarence Lowlands Wetlands

The extensive Clarence Lowlands wetlands (520,500 ha) are of special conservation interest to state and federal governments (Clarence Lowlands Wetland Conservation Assessment, 2008). The Lowland wetlands cover parts of Richmond River and Clarence river basins and stretch from Ballina to Coutts Crossing, near the southern border of the Clarence-Moreton bioregion (Figure 30). The Clarence Lowlands supports saline basins, swamps and tidal delta flats in the main estuaries and meander plains, and back swamps, levees and terraces along the major drainage lines of the alluvial plain (Table 20). Nine wetlands are listed in *A Directory of Important Wetlands* in Australia. These include Alumy Creek/Bunyip Swamp, The Broadwater, Clarence River Estuary, Bundjalung National Park, Cowans Pond, Everlasting Swamp, Lower Bungawalbin Creek, Tuckean Swamp and Wooloweyah Lagoon (NSW Department of Environment and Climate Change, 2008).

There are over 70 threatened plant and animal species. These include the giant waterlily *(Nymphaea gigantean)*, the endangered weeping paperbark (*Melaleuca irbyana)*, *Hygrophila angustifolia* and the mangrove fern (*Acrostichum speciosum)*. The water plantain (*Alisma plantagoaquatica)* is at its most northern limit of distribution. Threatened species mainly dependent on wetlands, include the endangered spider orchid (*Dendrobium melaleucaphilum)*, the endangered southern swamp orchid (*Phaius australis)* and vulnerable *Maundia triglochinoides* (NSW Department of Environment and Climate Change, 2008). Many animals depend on the wetlands as habitat for breeding, foraging, and shelter, including birds, frogs, fish, reptiles and mammals. Threatened species that depend on these wetlands include the black-necked stork, comb-crested jacana, magpie goose and painted snipe.

The Clarence and Richmond Lowlands contain some acid sulfate soil areas. These are the result of naturally-occurring sediments and soils containing iron sulfides (especially pyrite) and/or their precursors or oxidation products (Clarence Catchment Management Committee, 1998). Acid sulfate soils occur if exposure of the sulfides to oxygen increase as a result of drainage or excavation of ground water that leads to the generation of sulfuric acid. Tulau (1999) identified several priority areas for acid sulfate soil management in the lower Clarence system including Everlasting Swamp, Shark Creek, Alumy Creek and the lower estuary.

The following impacts may be associated with acid sulfate soil runoff: habitat degradation, fish kills, fish disease outbreaks, reduced aquatic food resources, reduced migration potential of fish, reduced fish recruitment, altered water plant communities, weed invasion by acid-tolerant plants, secondary water quality changes, and reduced potability of water (Sammut et al., 1996; Sammut and Lines-Kelly, 1996).

The Healthy Rivers Commission (1998) and NSW DPI (2013b) noted that flood mitigation and drainage works have had significant detrimental impacts on the health of the Richmond and Clarence River. These include a reduction in the number and area of back swamp freshwater wetland areas, reduced areas of supratidal and intertidal saltwater wetlands, reduced areas of habitat for fish and other estuarine species, fish diseases and death due to acid discharge, and the alienation of agricultural land due to scalding. Floodgates have changed mangrove-fringed tributaries into drainage channels, and destroyed large areas of estuarine fish nursery and habitat (Pollard and Williams, 1997).

Acid discharges and reduction in fish habitat (Pollard and Hannan, 1994) have had a significant impact on the fishing and prawning industries in the Clarence Lowlands (Clarence Catchment Management Committee, 1998). Water quality requirements and tolerances for prawn species are outlined in Lancaster (1990). However, fish kills do not appear to be a common occurrence in the lower Clarence and its tributaries, possibly due to the generally high flushing of the Clarence River, although the effects of chronic exposure to poor quality water, such as red-spot disease, are common. New South Wales Fisheries has reported instances of fish kills and poor water quality flowing from Everlasting Swamp and tributaries that are blocked by floodgates, such as Sportsmans Creek, which also had a relatively low dissolved oxygen (Tulau, 1999).

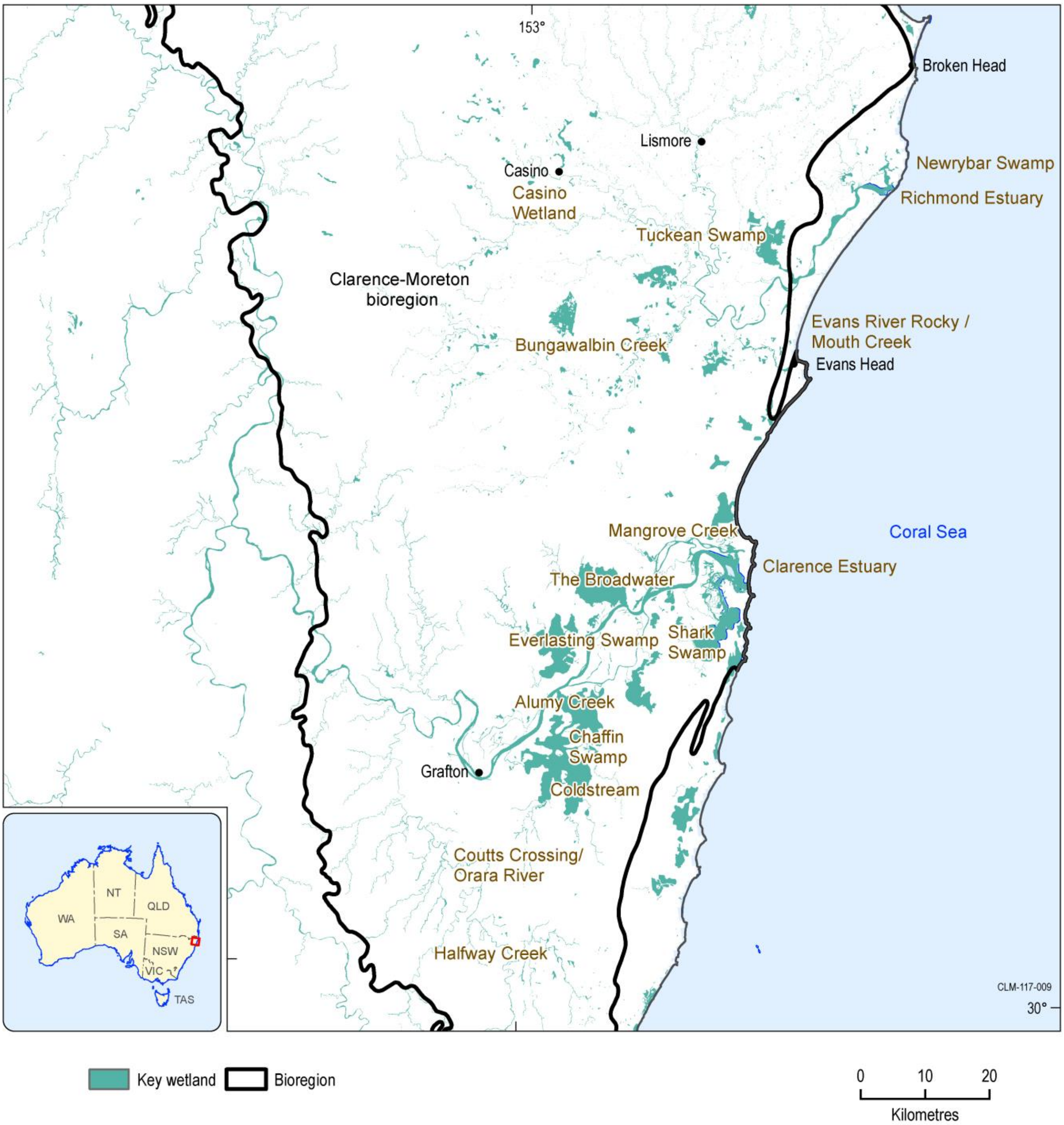

Figure 30 Key wetlands of the Clarence Lowland IBRA subregion

Table 20 Wetland clusters of Clarence Lowlands

Wetland cluster	Wetland type (TEC)	Threatened species	DIWA listed
Clarence river basin			
Alumy Creek / Bunyip Creek	Swamp Sclerophyll Forest Freshwater Wetland	Flora: 3 Fauna: 19 Migratory: 3	Yes
Chaffin Swamp	Swamp Sclerophyll Forest Freshwater Wetland	Flora: 2 Fauna:11 Migratory: 3	No
Clarence Estuary	Coastal Saltmarsh Swamp Oak Forest Swamp Sclerophyll Forest Mangrove	Flora: 3 Fauna: 44 Migratory: 6	Yes
Coldstream	Swamp Sclerophyll Forest Freshwater Wetland	Flora: 2 Fauna: 26 Migratory: 3	Yes
Coutts Crossing / Orara River	Swamp Sclerophyll Forest Freshwater Wetland	Flora: 3 Fauna: 32 Migratory: 8	No
Everlasting Swamp	Freshwater Wetland Swamp Sclerophyll Forest Swamp Oak Forest	Flora: Fauna: 26 Migratory: 7	Yes
Halfway Creek	Swamp Sclerophyll Forest Subtropical Coastal Floodplain Forest Freshwater Wetland	Flora: 2 Fauna: 26 Migratory: 2	No
Mangrove Creek*	Swamp Sclerophyll Forest Mangrove	Flora: 1 Fauna: 13 Migratory: 2	No
Shark Creek*	Swamp Sclerophyll Forest Swamp Oak Forest Subtropical Coastal Floodplain Forest Freshwater Wetland	Flora: 1 Fauna: 21 Migratory: 2	No
South Clarence	Freshwater Wetland Swamp Sclerophyll Forest	Flora: Fauna: 20 Migratory: 7	Yes
Tabbimoble	Swamp Sclerophyll Forest Subtropical Coastal Floodplain Forest Freshwater Wetland	Flora: 5 Fauna: 32 Migratory: 3	No
The Broadwater	Swamp Oak Forest Swamp Sclerophyll Forest Freshwater Wetland Mangrove Saltmarsh	Flora: 2 Fauna: 20 Migratory: 11	Yes

Wetland cluster	Wetland type (TEC)	Threatened species	DIWA listed
Richmond river basin			
Bungawalbin	Swamp Oak Forest Paperbark Forest Freshwater Wetland Swamp Box and Mahogany Forest	Flora: 13 Fauna: 39 Migratory: 2	Yes
Casino	Freshwater wetland	Flora: 4 Fauna: 20 Migratory: 9	No
Evans River/Rocky mouth Creek	Swamp Sclerophyll Forest Swamp Oak Forest Freshwater Wetland Saltmarsh	Flora: 8 Fauna: 23 Migratory: 3	No
Newrybar	Dry Sclerophyll Forest Swamp Sclerophyll Forest Wallum sedgelands Wet Heath	Flora: 11 Fauna: 22 Migratory: 2	No
Richmond Estuary	Swamp Sclerophyll Forest Saltmarsh Swamp Oak Forest Mangrove	Flora: 13 Fauna: 38 Migratory: 7	No
Tuckean	Paperbark Forest Freshwater Wetland	Flora: 16 Fauna: 26 Migratory: 3	Yes
Wardell	Swamp Sclerophyll Forest Riparian Rainforest Wallum sedgelands	Flora: 3 Fauna: 27 Migratory: 2	No

Source data: Department of Environment and Climate Change NSW (2008)
Conservation assessment of wetlands in the Clarence Lowlands IBRA subregion. p.6, Appendix 3.
TEC = Threatened Ecological Community; DIWA = Directory of Important Wetlands of Australia; Migratory = listed in international migratory agreements; * = not surveyed extensively

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