Australian Government

BIOREGIONAL ASSESSMENTS

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

Observations analysis, statistical analysis and interpolation for the Clarence-Moreton bioregion

Product 2.1-2.2 from the Clarence-Moreton Bioregional Assessment

6 October 2016

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

The Bioregional Assessment Programme

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

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

Department of the Environment and Energy

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

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Authorship is listed in relative order of contribution.

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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 (IESC, 2015).

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

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

The Bioregional Assessment Programme

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

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

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

- the Sydney Basin bioregion
- the Gippsland Basin bioregion.

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

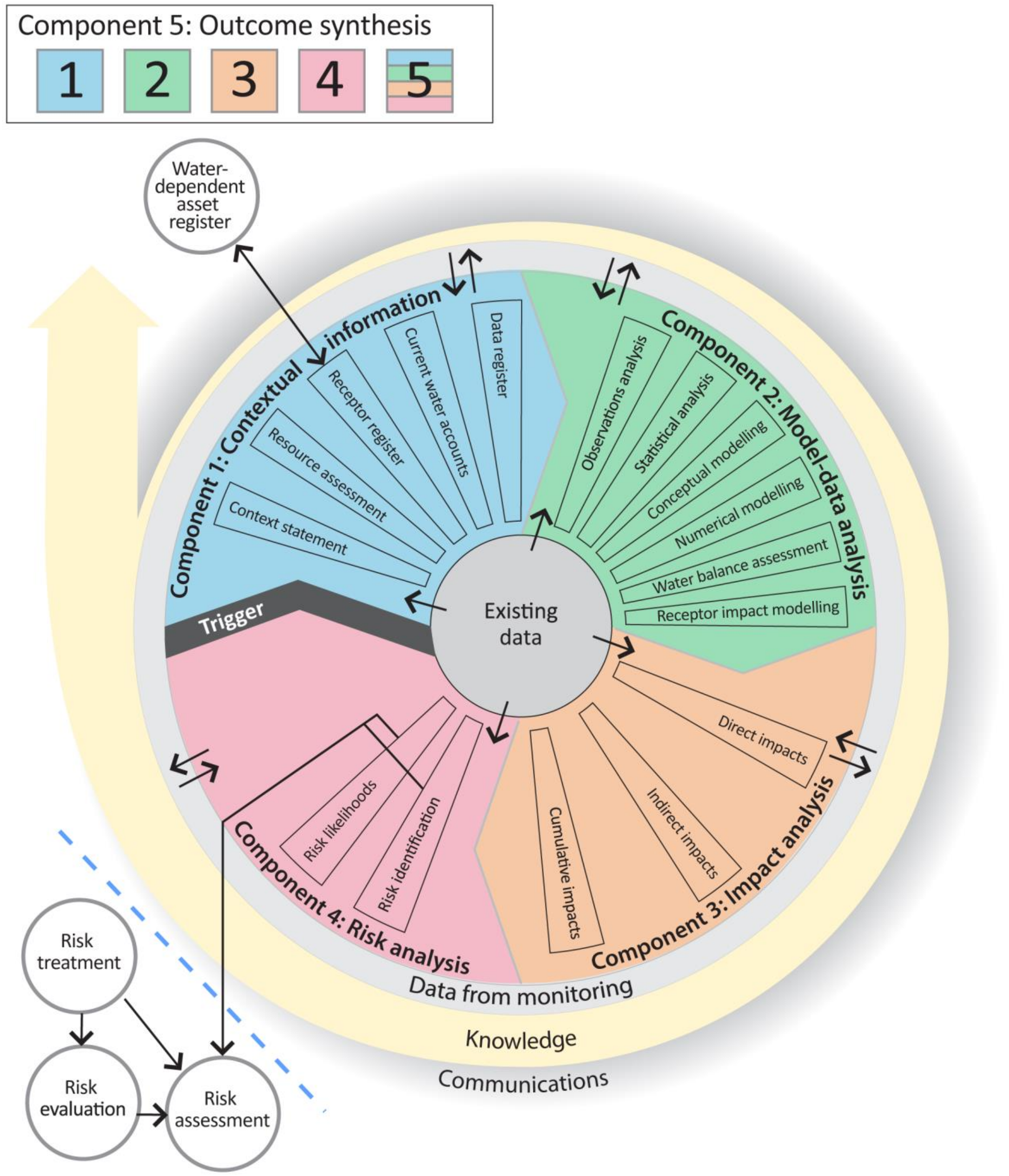

Figure 1 Schematic diagram of the bioregional assessment methodology

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

Methodologies

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

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

Table 1 Methodologies

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

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

Technical products

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

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

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

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

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

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

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

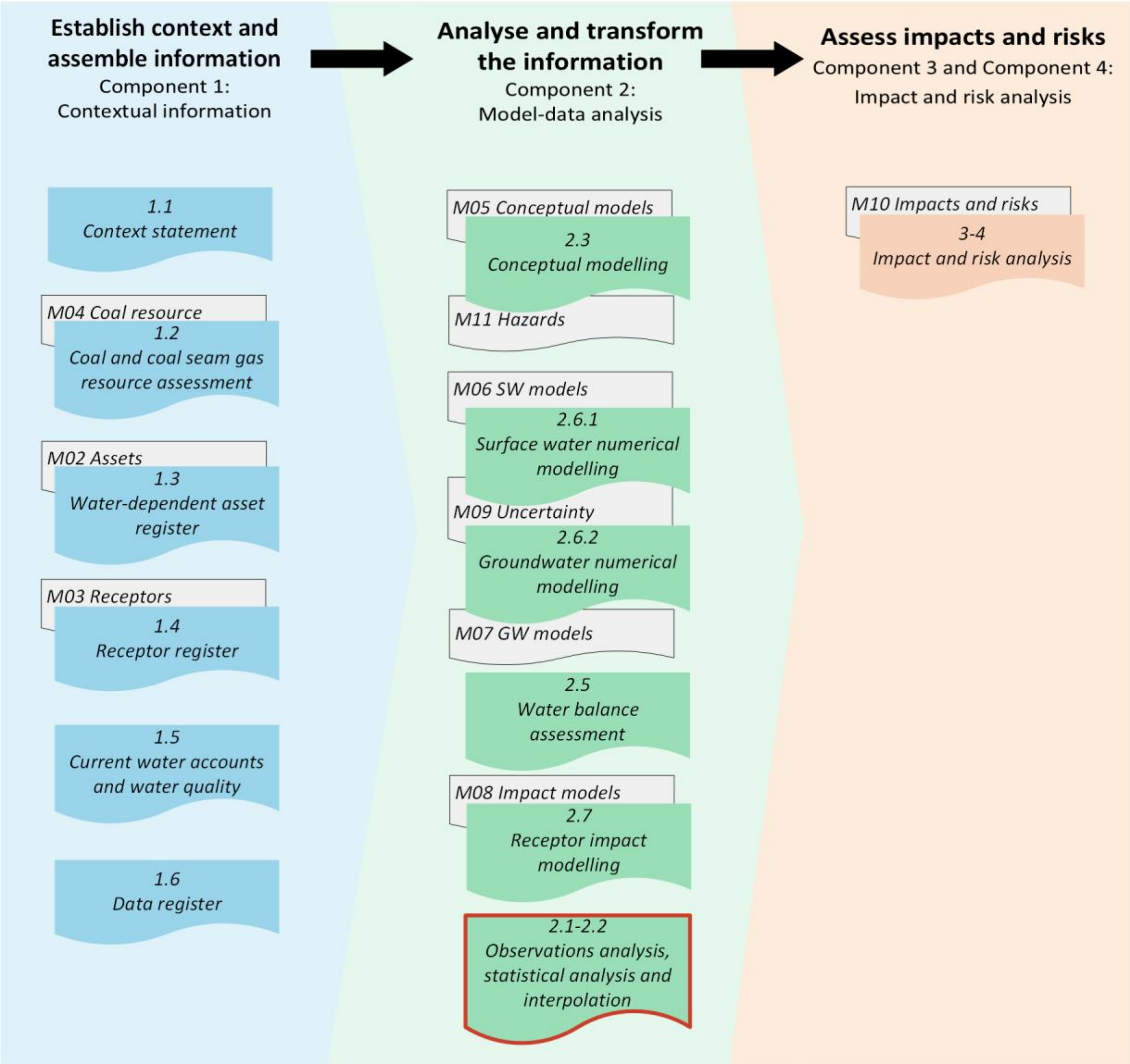

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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

Table 2 Technical products delivered for the Clarence-Moreton bioregion

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

Component	Product code	Title	Section in the BA methodology[b]	Type[a]
Component 1: Contextual information for the Clarence-Moreton bioregion	1.1	Context statement	2.5.1.1, 3.2	PDF, HTML
	1.2	Coal and coal seam gas resource assessment	2.5.1.2, 3.3	PDF, HTML
	1.3	Description of the water-dependent asset register	2.5.1.3, 3.4	PDF, HTML, register
	1.5	Current water accounts and water quality	2.5.1.5	PDF, HTML
	1.6	Data register	2.5.1.6	Register
Component 2: Model-data analysis for the Clarence-Moreton bioregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2	PDF, HTML
	2.3	Conceptual modelling	2.5.2.3, 4.3	PDF, HTML
	2.5	Water balance assessment	2.5.2.4	PDF, HTML
	2.6.1	Surface water numerical modelling	4.4	PDF, HTML
	2.6.2	Groundwater numerical modelling	4.4	PDF, HTML
	2.7	Receptor impact modelling	2.5.2.6, 4.5	Not produced
Component 3 and Component 4: Impact and risk analysis for the Clarence-Moreton bioregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	Not produced
Component 5: Outcome synthesis for the Clarence-Moreton bioregion	5	Outcome synthesis	2.5.5	PDF, HTML

[a]The types of products are as follows:

- 'PDF' indicates a PDF document that is developed by the Clarence-Moreton Bioregional Assessment using the structure, standards and format specified by the Programme.
- 'HTML' indicates the same content as in the PDF document, but delivered as webpages.
- 'Register' indicates controlled lists that are delivered using a variety of formats as appropriate.
- 'Not produced' indicates that the product was not developed. A webpage explains why and points to relevant submethodologies (Table 1).

About this technical product

The following notes are relevant only for this technical product.

- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 151.0° East for the Clarence-Moreton bioregion and two standard parallels of –18.0° and –36.0°.
- Contact bioregionalassessments@bom.gov.au to access metadata (including copyright, attribution and licensing information) for all datasets cited or used to make figures in this product. At a later date, this information, as well as all unencumbered datasets, will be published online.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived datasets, the created date is used.

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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 20 December 2016, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

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2.1 Observations analysis for the Clarence-Moreton bioregion

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

The data are categorised according to the following disciplines:

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

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

The statistical analysis and interpolation aims to develop a quantitative understanding of the Clarence-Moreton subregion by analysing the observed data and – where required – interpolating into locations where data are sparse.

This product also provides advice on data gaps. More information on data gaps will be reported in later products.

This product concludes with a detailed description of water management for coal resource developments. Only that information required for numerical modelling (in product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling)) is included.

2.1.1 Geography

Summary

This section provides an analysis of the errors associated with the climate data used for the water balance modelling. To characterise errors of the input climate data, the long-term monthly values of precipitation (P), and maximum (T_{max}) and minimum (T_{min}) temperatures were calculated along with root-mean-square error (RMSE) mean values for the same variables for the period January 1980 to December 2009. Results showed relative errors of 47.5%, 2%, and 8% in P, T_{max}, and T_{min}, respectively (where relative error is calculated by dividing the monthly RMSE mean grid by the monthly mean grids).

2.1.1.1 Observed data

The basic geographic data for the Clarence-Moreton bioregion were reported in the companion product 1.1 for the Clarence-Moreton bioregion (Rassam et al., 2014).

2.1.1.2 Statistical analysis and interpolation

All geographic data specific to the Clarence-Moreton bioregion were obtained from state or national datasets. This means no statistical analysis or interpolation was performed to generate any of the geographic datasets. However, to characterise errors of the input climate data used for the water balance modelling, some bioregion-specific spatial analysis was performed. This is a useful characterisation to better understand the limitations of the input data. This analysis is outlined in this section.

In addition to generating daily and monthly grids of meteorological variables (P, T_{max} and T_{min}), the Bureau of Meteorology (Jones et al., 2009) also generate daily and monthly root-mean-square error (RMSE) grids of the same variables. These daily and monthly RMSE grids are a combined measure of the observational error and geostatistical error. The latter is a function of the interpolation algorithm, density of isolated station observations and degree of spatial autocorrelation of the process(es) driving the spatial variance captured in the data being interpolated.

To characterise errors of the input climate data the long-term (from January 1980 to December 2009) monthly mean values for P, T_{max} and T_{min} were calculated. Also calculated were the long-term monthly RMSE mean values for the same variables for the same time period. Relative error, expressed as a percent, was calculated by dividing the monthly RMSE mean grid by the monthly mean grids (i.e. RMSE grid/mean grid for each meteorological variable).

The spatially-averaged long-term monthly mean P for the Clarence-Moreton bioregion is 110 mm/month, and the associated P RMSE mean for the bioregion is 45 mm/month (see Figure 3a and Figure 3b, respectively). This results in a relative error of 47.5% in the input P grids (Figure 3c). The relatively high error is due, in part, to P being a highly spatially variable process (it has low spatial autocorrelation).

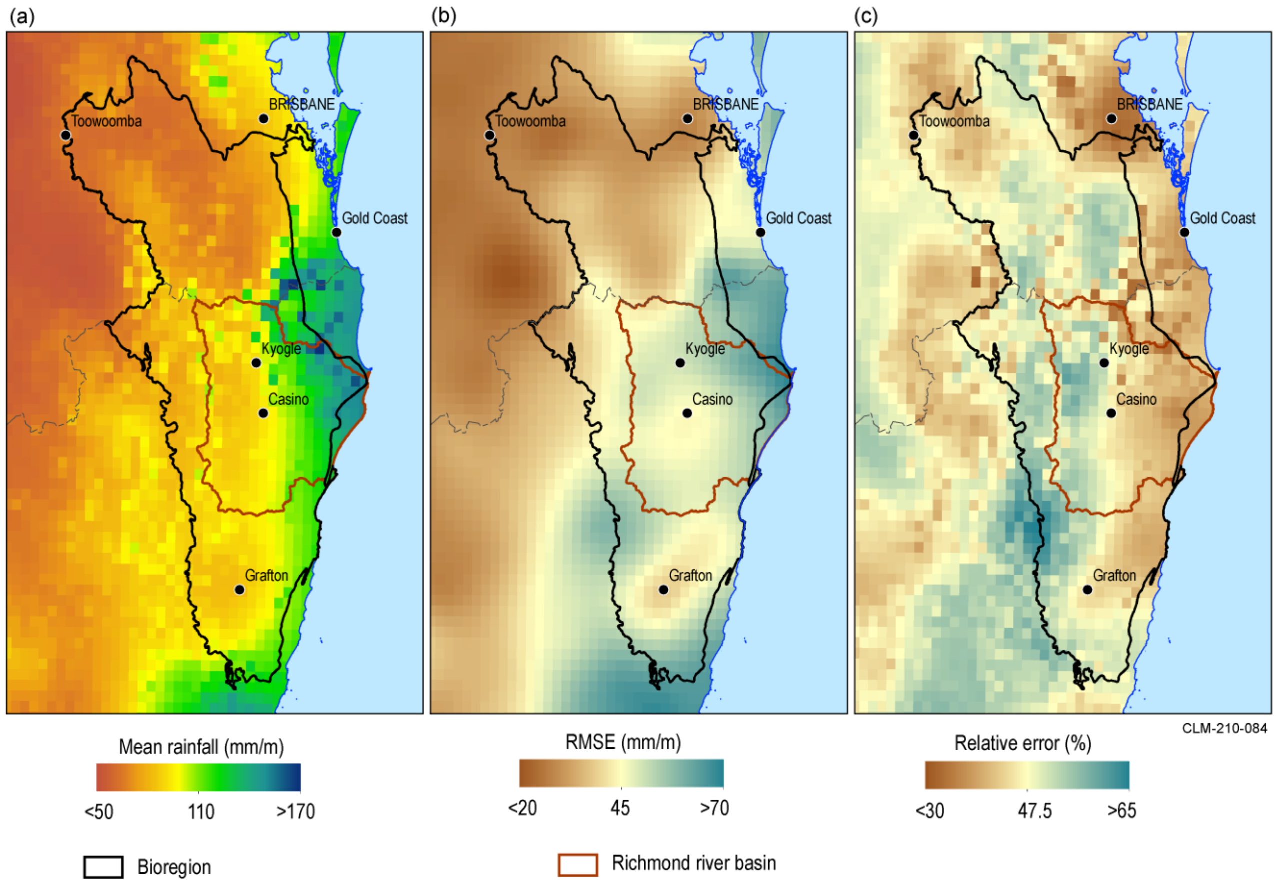

Figure 3 Spatial variation of precipitation from 1980 to 2009 (a) monthly mean precipitation (b) monthly mean rootmean-square error (RMSE) of monthly mean precipitation and (c) monthly mean precipitation relative error for the Clarence-Moreton bioregion and proximal surface water basins

Data: Bioregional Assessment Programme (Dataset 1)

For air temperatures, a meteorological field that has higher spatial autocorrelation than P, regional distribution is governed by topography and distance from the ocean. The T_{max} spatially-averaged long-term monthly mean is 22 °C for the Clarence-Moreton bioregion (Figure 4a). The associated RMSE is approximately 0.47 °C (Figure 4b), which leads to a relative error of 2% for T_{max} (Figure 4c). For T_{min} in the Clarence-Moreton bioregion, there are similar spatial patterns, with the spatially-averaged long-term monthly mean being 12.5 °C (Figure 5a) and the associated RMSE being approximately 0.69 °C (Figure 5b), which leads to a relative error of 8% for T_{min} (Figure 5c).

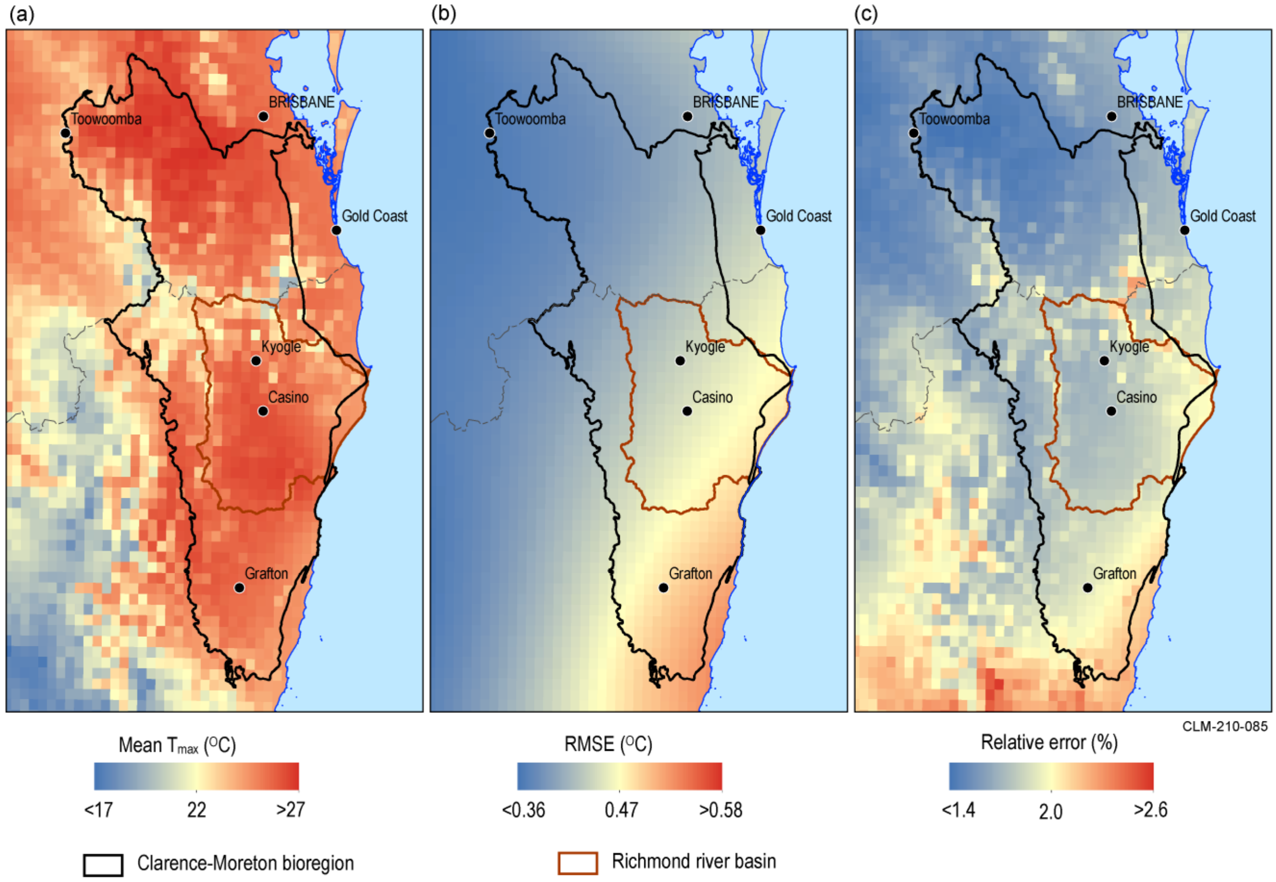

Figure 4 Spatial variation of maximum air temperature (T_{max}) from 1980 to 2009 (a) monthly mean T_{max} (b) root-mean-square error (RMSE) of monthly mean T_{max} and (c) monthly mean T_{max} relative error for the Clarence-Moreton bioregion and proximal surface water basins

Data: Bioregional Assessment Programme (Dataset 1)

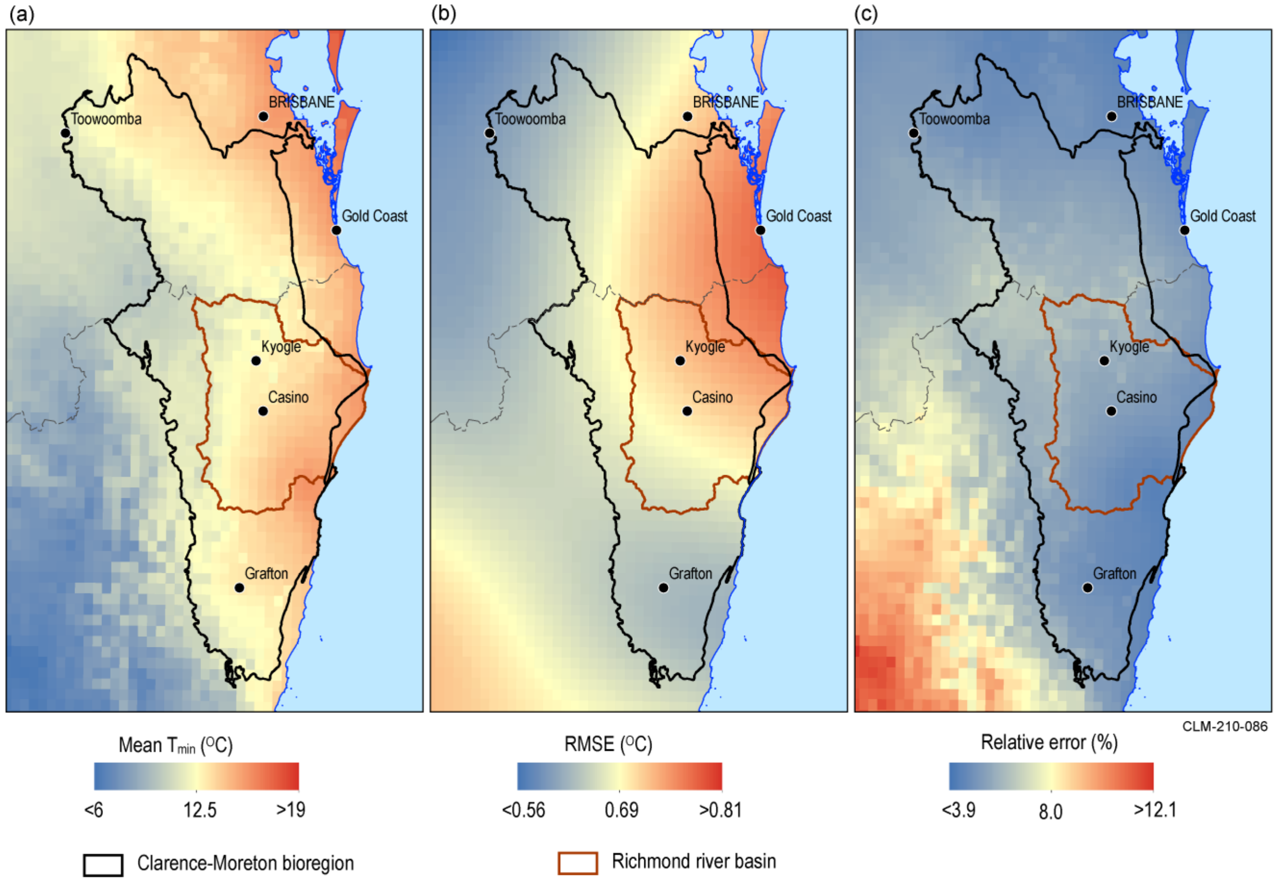

Figure 5 Spatial variation of minimum air temperature (T_{min}) from 1980 to 2008 (a) monthly mean T_{min} (b) root-mean-square error (RMSE) of monthly mean T_{min} and (c) monthly mean T_{min} relative error for the Clarence-Moreton bioregion and proximal surface water basins

Data: Bioregional Assessment Programme (Dataset 1)

2.1.1.3 Gaps

The characterisation of input data errors suggests that having a denser network of official Bureau of Meteorology stations recording climate data has the potential for improved water-related modelling in the Clarence-Moreton bioregion. For precipitation, while the greatest RMSE values are in the higher rainfall area to the north-east of Kyogle, the greatest relative errors are in the lower rainfall areas further west.

References

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Dataset 1 Bioregional Assessment Programme (2015) BILO Climate Relative Error Grids V01. Bioregional Assessment Derived Dataset. Viewed 07 August 2015, http://data.bioregionalassessments.gov.au/dataset/c0c139f5-3648-4e0f-9acf-a884b7cc859b.

2.1.2 Geology

Summary

This section describes the datasets that have been obtained and compiled for the development of the three-dimensional geological model of the Clarence-Moreton bioregion. This section also describes the workflow used to build the three-dimensional geological models. The geological data described in this product inform the development of multiple three-dimensional geological models of surface water basins within the Clarence-Moreton bioregion.

Prior to this bioregional assessment, no three-dimensional geological models existed for most areas within the Clarence-Moreton bioregion (for example, no models existed for the Clarence-Moreton bioregion in Queensland). Furthermore, although pre-existing grids were available for selected sedimentary bedrock hydrostratigraphic units such as the Walloon Coal Measures (the primary target of coal seam gas (CSG) exploration) in NSW, no three-dimensional representations of alluvial or volcanic aquifers and shallower bedrock units existed anywhere in the Clarence-Moreton bioregion. The three-dimensional geological models developed during this bioregional assessment therefore substantially contribute to the understanding of the geometry and architecture of sedimentary bedrock units, volcanic aquifers and alluvial aquifers in the Clarence-Moreton bioregion.

Section 2.1.2.1 introduces the data types that underpinned the three-dimensional geological model. They include lithological and stratigraphic logs from groundwater bores and exploration and deep stratigraphic wells, airborne geophysical data, remotely sensed data, seismic data and geological structure information. ArcGIS and GoCAD were used to determine the extent of major stratigraphic units at the surface and in the subsurface by integrating and visualising all the associated data.

The major geological data sources in the Clarence-Moreton bioregion are geological maps, lithological and stratigraphic data from the Queensland and NSW groundwater databases, stratigraphic records from exploration wells and geophysical data. In addition, interpolated surfaces of selected geological contacts (i.e. interfaces between different sedimentary bedrock stratigraphic units) provided by Metgasco Limited and the NSW Department of Trade and Investment helped to inform the development of the three-dimensional geological models.

The Clarence-Moreton bioregion includes six major alluvial aquifer systems, which are likely to directly support many of the groundwater-dependent assets. These alluvial systems are the Lockyer Valley, the Bremer river basin and Warrill creek basin, the Logan-Albert river basin, the Richmond river basin, and the Clarence river basin. These alluvial aquifers overlie the bedrock stratigraphic units of the geological Clarence-Moreton Basin and the basalts of the Main Range Volcanics and Lamington Volcanics.

Data from groundwater bores underpin the characterisation of the interface between the alluvial aquifer systems and the underlying sedimentary and volcanic bedrock, which is crucial in determining how shallow and deep aquifer systems interact hydraulically. There are more

than 12,000 registered groundwater bores with lithological information throughout the different river basins of the bioregion. However, only approximately 40% of these bores have stratigraphic information, and the stratigraphic information is often incomplete (i.e. not continuous for the entire bore length) or incorrect. When possible, the lithological logs were converted into stratigraphic logs, and these were subsequently used to define the contacts between the alluvium and the underlying sedimentary or volcanic bedrock. The spatial interpolation of the groundwater stratigraphic data shows that these different alluvial aquifer systems within the bioregion are very different with regards to their sediment thickness, the width of the alluvial plains and the shape of the valleys. However, there are also some common characteristics. For example, most alluvial systems in the bioregion are relatively narrow and deeply incised into the bedrock in their headwaters, with a typical thickness of approximately 10 to 15 m, and although the thickness distribution within each alluvial system is highly variable, all systems have a maximum thickness of approximately 30 to 35 m.

The subsurface geometry of the bedrock stratigraphic units of the Clarence-Moreton Basin within the Clarence-Moreton bioregion is generally very complex. The Clarence-Moreton Basin consists of several sub-basins, and within each sub-basin, multiple depositional centres exist where sediment thicknesses of more than 2500 m have been intersected or are inferred. In addition, as demonstrated by seismic data, tectonic activity has resulted in significant vertical displacements of bedrock units along faults.

The definition of the boundaries between the deeper volcanic and sedimentary bedrock units in the bioregion is based on the following principal sources: groundwater bore data; deep stratigraphic wells; CSG, petroleum and coal exploration wells; and seismic interpretation provided by Metgasco Limited and the NSW Department of Trade and Investment.

Overall, the spatial coverage with deep stratigraphic and exploration wells in the Clarence-Moreton bioregion is comparatively poor in relation to the structural complexity and compared to other sedimentary basins such as the neighbouring Surat Basin. However, the spatial coverage has considerably improved during the last 10 to 15 years due to the drilling of new exploration wells. Nevertheless, in some parts of the bioregion, such as where the Clarence-Moreton Basin underlies the Bremer river basin in south-east Queensland, there is still a substantial lack of knowledge on the depth of the sedimentary basin as most wells do not intersect the deeper stratigraphic units below the Walloon Coal Measures (the primary target for CSG) here.

In addition, the spatial resolution of reliable well log and seismic data is not sufficient everywhere to model how faults vertically displace bedrock units.

The three-dimensional geological models developed using the data sources and workflows described in this product form the basis for the development of a conceptual hydrogeological model that describes how geology, hydrogeology and hydrology are linked (described in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016)). It also forms the basis for the development of a groundwater model (described in companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016)).

2.1.2.1 Methods

The primary aim of the compilation of the geological datasets described in this product is to inform the development of three-dimensional geological models of the Clarence-Moreton bioregion. In many traditional sedimentary basin geological and hydrogeological investigations, the primary aim of developing three-dimensional models is to characterise the aquifer geometry of deep sedimentary bedrock layers to facilitate the development of petroleum resources or characterise deep groundwater resources. Shallower aquifer systems such as alluvial systems or volcanic aquifers are often inadequately represented in these models or lumped together as ‘alluvium’ or ‘overburden’. To account for the fact that most water-dependent assets in the Clarence-Moreton bioregion are associated with shallow aquifers or surface water, three-dimensional geological models developed during this bioregional assessment aim to accurately describe the geometry of both shallow and deep aquifers in the Clarence-Moreton bioregion. In particular, the geological datasets and the three-dimensional geological models aim to characterise the geological contacts between the alluvium, the Main Range and Lamington volcanics and sedimentary bedrock. Understanding the geometry of these interfaces is critical to help with the conceptualisation of groundwater dynamics and surface water – groundwater interaction. It will also underpin the development of causal pathways that link coal resource developments to water-dependent assets described in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016). Furthermore, it also provides the layer structure for a numerical groundwater flow model, which is developed to assess the potential impacts of CSG development on water resources in the Clarence-Moreton bioregion (Cui et al., 2016).

The three-dimensional geological models developed as part of the Clarence-Moreton Bioregional Assessment (the Assessment) are developed in GoCAD/SKUA (Paradigm Geophysical Pty Ltd®) and described in detail in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016). They depict the main stratigraphic units of the Clarence-Moreton bioregion (Figure 6), but do not represent variations in lithological composition (lithofacies or rock types). Furthermore, although the current three-dimensional geological models represent important structural features, fault displacements are not modelled in the current set of three-dimensional geological models (see Section 2.1.2.1.5 and Section 2.1.2.4).

2.1.2.1.1 Lithological and stratigraphic data

Bore logs or well logs (also commonly known as drill logs) are the main source of data used to construct the three-dimensional geological model, and to reliably assign screened intervals (corresponding to the interval where the casing is slotted to allow intake from the aquifer) to discrete stratigraphic units (e.g. Quaternary alluvium or Walloon Coal Measures in the Clarence-Moreton bioregion). In this product, ‘bore’ or ‘bore log’ is used where a reference is made to groundwater bores, whereas ‘well’ is used with regards to exploration wells or deep stratigraphic wells. Groundwater bore logs and associated groundwater level measurements are also essential for constructing potentiometric surface maps that show groundwater flow direction and for characterising spatial and/or temporal water chemistry patterns within aquifers.

The major bore/well log data sources used in the Assessment are:

- groundwater bores, sourced from the Queensland Department of Natural Resources and Mines (DNRM) groundwater database (Queensland Department of Natural Resources and Mines, Dataset 1) and the National Groundwater Information System (NGIS) groundwater database (Bureau of Meteorology, Dataset 2)
- deep stratigraphic wells, sourced from publications, including O'Brien and Wells (1994)
- exploration wells, including CSG exploration wells, coal exploration wells, mineral exploration and petroleum exploration wells, sourced from company well completion reports accessed through the Queensland DNRM Interactive Resource and Tenure Maps (IRTM) system and the NSW Digital Imaging Geological Systems (DIGS®).

Geotechnical wells exist in the eastern part of the basin, but have not been used to date as they are mostly shallow and only record lithological rather than stratigraphic information.

A typical bore/well log includes the following information:

- a registration number that uniquely identifies the well
- a location (easting and northing, or longitude and latitude)
- the total depth
- bore/well type (e.g. groundwater, exploration, appraisal or production)
- an elevation of the natural ground surface or the top of the casing
- lithological and stratigraphic descriptions with their associated depth intervals.

Typically, this information is collected by drillers (for groundwater bores) and/or geologists (for exploration wells) when the bore/well is first installed, and then passed on to state agencies for archiving in an electronic database.

While the different bore and well log data are very useful, there are some challenges associated with the use of data from multiple bore/well types in regional-scale syntheses such as the Bioregional Assessment Programme. For example, there is often limited consistency in the ways in which bores/wells are completed, there is no generally adopted standard template, and different companies have different style sheets and purposes. In addition, the groundwater bores and exploration wells were drilled over a very long time period (more than 100 years), and terminology and standards have changed substantially over time. Three-dimensional geological models, potentiometric surface maps and many other geological, hydrochemical or hydrogeological applications are dependent on the accuracy and consistency of the input data from which they are developed. The quality of the bore log data in the groundwater databases in Queensland (tables 'Stratlogs' and 'Stratigraphy' in Queensland Department of Natural Resources and Mines (Dataset 1)) and NSW (tables 'Drillers logs' and 'Geologist logs' in Bureau of Meteorology (Dataset 2)) is highly variable and often very poor, particularly for bores which were drilled several decades ago when drillers had little or no experience in geological logging.

Some common problems with lithological and stratigraphic descriptions in these databases are:

- no lithological and/or stratigraphic information available for many bores or wells

- omission of important information such as the colour of sandstones
- use of incorrect geological terms
- no depth information
- misspellings.

Consequently, all well log data were subjected to extensive data quality checks prior to use in construction of the three-dimensional geological model or for hydrogeological or hydrochemical applications.

Data preparation

The main steps and procedures used to check, simplify and unify lithological bore log data descriptions were:

- **Consistent use of terminology and spelling**. The first stage of checking the bore log data involved editing the lithological and stratigraphic descriptions to ensure consistent use of terminology and spelling. This was done for each individual bore log and also across the entire dataset. For example, superseded stratigraphic unit names (e.g. Helidon Sandstone instead of Woogaroo Subgroup) are common in the Queensland groundwater database (Queensland Department of Natural Resources and Mines, Dataset 1). Furthermore, in the NSW groundwater database (Bureau of Meteorology, Dataset 2), descriptions such as 'blue metal' or 'metal' are used to describe basalts. The use of such terms to describe basalts is widely known in geology, and they can therefore be converted to 'basalt'. Spelling mistakes were also corrected, e.g. replacement of 'course sandstone' with 'coarse sandstone'.
- **Identification of geological inconsistencies or geological errors.** In the second stage of data checking, the bore log data were examined for geological inconsistencies that may have represented errors in the lithological descriptions. Table 3 shows a hypothetical example where 'granite' is reported to occur below and above sandstone. The lithological description, 'granite', is very common in the database, but granites are generally absent within the extent of the Clarence-Moreton bioregion (although present outside the Clarence-Moreton bioregion at the basin margins) (Rassam et al., 2014). This description is therefore geologically unlikely, and thus it was assumed with a high level of confidence that the original description refers to another bedrock type such as shale. The description was corrected in the database to 'sedimentary bedrock'. The cause of such errors may be related to poor geological knowledge of the logger or difficulties in distinguishing different rock types from cuttings. Other typical geological errors for basalt in the lithological descriptions in the NSW and Queensland groundwater databases include:
  - Basalt is incorrectly described as 'sandstone', 'hard', 'shale', 'black shale', 'red shale' or 'volcanic shale' or simply described as 'rock'.
  - Basalt is commonly included in bore log descriptions in areas where basalts are likely to be absent according to geological maps or the lack of magnetic anomalies in geophysical data.
  - Sandstone is often described as 'shale', 'soft shale', 'hard' or 'rock'.

- **Verification of bore elevation data**. The source and accuracy of elevation information in a bore log database are generally unknown. For example, this can be because many of the bores contained in the database were drilled a long time ago and methods to determine the elevation have evolved significantly since then. Hence, a digital elevation model (DEM) was used to provide independent verification of the ground elevation reported for each individual bore log. As the source of ground elevation reported in bore logs is often unknown, the elevation estimate from the DEM was generally favoured to ensure consistency across the whole dataset. The DEM used in the Assessment has an approximate resolution of 1 arc second or 30 m, which is derived from the Shuttle Radar Topography Mission (SRTM) dataset (Geoscience Australia and CSIRO Land and Water, 2010). Data for the ground surface elevation of each bore were extracted from the DEM in Global Mapper™.
- **Simplification of lithological logs**. Due to the size of the dataset (>30,000 Excel rows), with hundreds of different lithological descriptions, the dataset was simplified into a smaller subset of lithological descriptions. These lithological descriptions formed the basis for the preliminary assessment into simple units such as 'alluvium', 'sedimentary bedrock' or 'basalt'.
- **Conversion of lithological logs into stratigraphic logs**. No stratigraphic information exists for the bores in the NSW groundwater database, and only nine bores out of several thousand bores within the Clarence-Moreton bioregion in NSW have an aquifer assigned in the National Groundwater Information System (Bureau of Meteorology, Dataset 2). The three-dimensional geological model depicts stratigraphic units, rather than lithological data, as it is not possible to model lithological variation at the scale of the entire bioregion. Furthermore, many of the stratigraphic units in the Clarence-Moreton bioregion are composed of variable sequences of sandstone, mudstone, siltstone or other rock types. As a result, rock types are not necessarily characteristic markers of different formations, and the modelling of the three-dimensional distribution of the different units in the subsurface is based on stratigraphy rather than rock types. Without stratigraphic information, it would not be possible to determine the stratigraphy at the screened intervals of groundwater bores. This severely limits the usefulness of groundwater level measurements or hydrochemical data for further use in the BA. To overcome this limitation, an attempt to assign stratigraphy based on lithology was done based on geological knowledge and the expert scientific judgment of the Assessment team. An example of the procedure is shown in Table 3. In this example, the Koukandowie Formation is the shallowest bedrock unit and the bore is located in an area where the alluvium is present. Consequently, the shallow sandstone at this location is considered to be the Koukandowie Formation. The terms 'black clay' and 'sandy clay' are common lithological descriptions of alluvial sediments, and the sediments which overlie the sandstone are therefore likely to be alluvium. Therefore, the lithological description of granite from 12 to 15 mBGL (metres below ground level) is likely to be incorrect. For deeper bores that are likely to intersect multiple bedrock stratigraphic units, it is often impossible to differentiate with sufficient confidence between the stratigraphic units in the vertical column based on the lithological records as descriptions are often ambiguous. For example, sandstone or shale can occur in different units. In such cases, the term 'unknown' was assigned to the respective depth interval.

Table 3 Example of a hypothetical bore log showing the cleaning and simplification procedure used to convert lithological logs to stratigraphic logs

Bore ID	Bore depth (mBGL[a])	From (mBGL)	To (mBGL)	Lithological log	Corrected and simplified lithological description	Shallowest bedrock geological unit[b]	Surface geological unit[b]	New stratigraphic log
99999	48.7	0	1.2	Black clay	Alluvium	Within Koukandowie	Within alluvium	Alluvium
99999	48.7	1.2	4	Sandy clay	Alluvium	Within Koukandowie	Within alluvium	Alluvium
99999	48.7	4	12	Rock	Sandstone	Within Koukandowie	Within alluvium	Koukandowie
99999	48.7	12	15	Granite	Sedimentary bedrock	Within Koukandowie	Within alluvium	Koukandowie
99999	48.7	15	48.7	Sandstone	Sandstone	Within Koukandowie	Within alluvium	Koukandowie

[a]mBGL corresponds to metres below ground level
[b]When a bore is located within the extent of the alluvium, the bedrock unit underlying the alluvium is also considered. In this example, the bore is located within the alluvium, and the bedrock unit underlying the alluvium is the Koukandowie Formation.

- **Data validation using geological judgment and reasoning.** Although the data checking procedure starts prior to the development of the three-dimensional geological model, considerable ambiguity may still remain. However, it often becomes evident that certain bore log observations or stratigraphic assignments contradict those of neighbouring bores when the lithological logs are viewed in three dimensions using a package such as GoCAD (Paradigm®). For example, a frequent observation in NSW was that rocks are commonly described as ‘basalt’ in lithological logs in areas where basalts are not present on geological maps and not shown as magnetic anomalies on airborne geophysical images. This becomes very evident when all bores are displayed together in three dimensions, and in such cases, the original data in the database were revisited and consequently corrected. This process will be ongoing throughout the three-dimensional geological model development.

2.1.2.1.2 Airborne geophysical data

Airborne geophysical data, including radiometric, magnetic and gravity data, can be very useful to identify geological structures such as faults, folds and dykes in sedimentary basins. Airborne geophysical data were sourced from Queensland and NSW Government agencies. For NSW, much of the available airborne geophysical data has been assessed and compiled by FROGTECH on behalf of the NSW Department of Primary Industries and is now included in the ‘Clarence-Moreton SEEBASE^{TM} and GIS project’ product (Sommacal et al., 2008) (NSW Department of Primary Industries, Dataset 3). No reprocessing of airborne geophysical data was conducted in the Assessment.

2.1.2.1.3 Remotely sensed data

Various remote sensing applications (e.g. ASTER, Landsat and MODIS systems) can be very useful for different geoscientific applications. One such use is identifying surface expression of faults by assessing differences in variations in key mineralogical groups or vegetation. Due to time constraints, it was not possible to use remote sensing data in this BA, but their usefulness to identify surface expression of faults will be further explored as part of a CSIRO strategic project ('Next generation methods and capability for multi-scale cumulative impact assessment and management' sub-theme 'Tracer-based improvement of groundwater model conceptualisation and predictability').

2.1.2.1.4 Seismic data

Seismic data are a valuable data source for three-dimensional geological modelling, particularly in assessing how faults may juxtapose different geological units. Seismic reflection data (processed seismic sections or grids which incorporate seismic data) were sourced from the Division of Resources and Energy of the NSW Office of Trade and Investment and from Metgasco Limited (Metgasco). The depth information in seismic sections is generally reported in travel time rather than metres below ground surface. For the data to be used in three-dimensional geological modelling, the seismic data need to be converted from travel time to depth. This is beyond the scope of the BA, however, seismic picks from processed seismic data and seismic interpretations which incorporate seismic data were provided by Metgasco (Metgasco Limited, Dataset 4) and the NSW Department of Trade and Investment (Dataset 5).

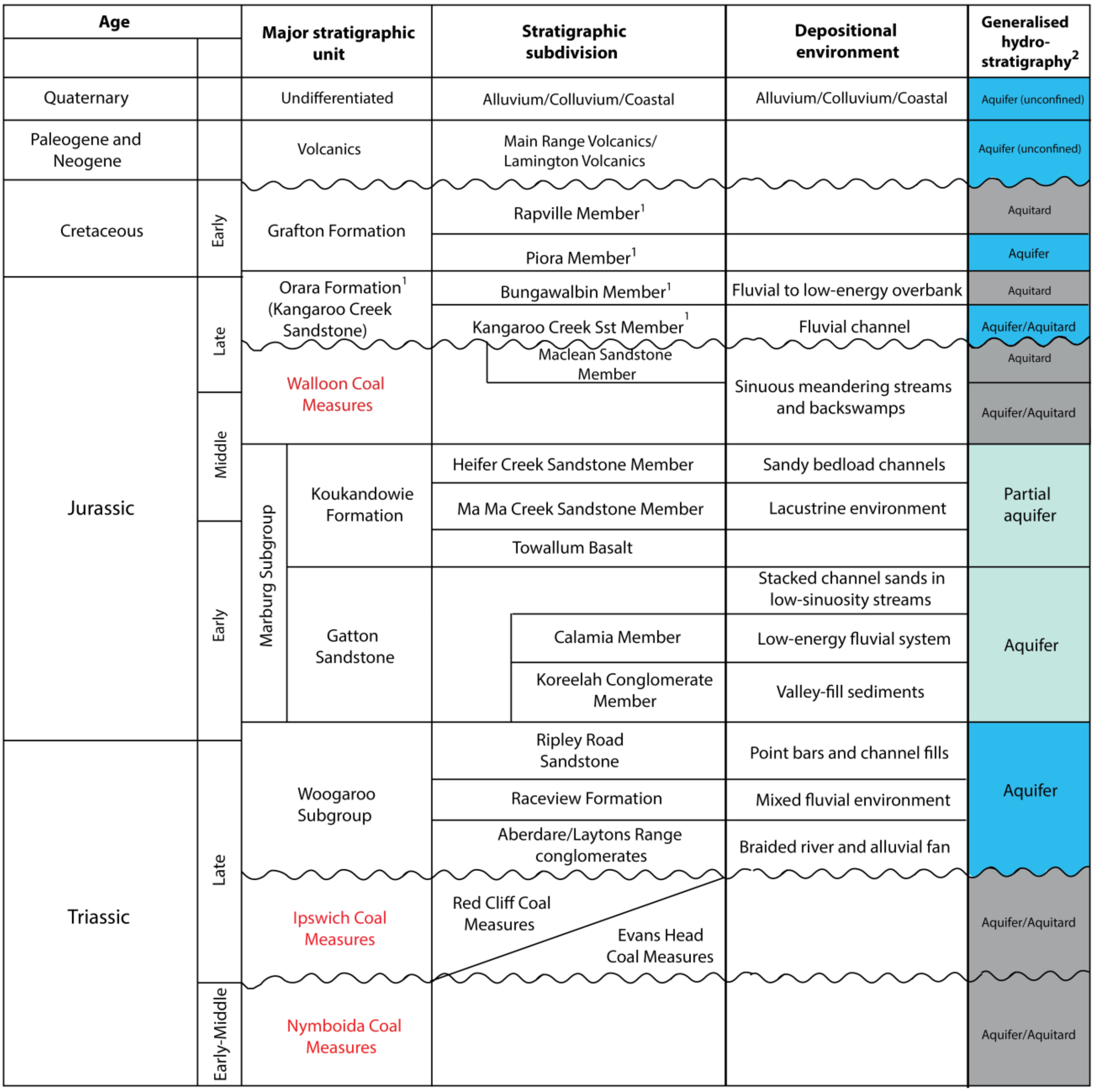
2.1.2.1.5 Geological structures

The spatial surface distribution of geological structures (e.g. faults) was collated from different data sources, including geological maps, geoscientific datasets from the Queensland and NSW geological survey and the 'Clarence-Moreton SEEBASE™ and GIS project' product (Sommacal et al., 2008) (NSW Department of Primary Industries, Dataset 3). In addition, seismic images were used to qualitatively assess the presence and influence of faults in the subsurface. In seismic images, the upper part of the section (approximately 100 m) is often 'noisy', and it is therefore not well understood from this data source if faults extend to the surface.

2.1.2.1.6 Extent of major stratigraphic units at the surface and in the subsurface

The extent of the major stratigraphic units within the Clarence-Moreton bioregion (Figure 6) was constructed in ArcGIS and GoCAD using all available geological information. Geological maps only display the extent of geological units at the surface, but for the development of three-dimensional geological models, shapefiles represent the extent at both surface and in the subsurface and are helpful to guide model development. The recent revision of the stratigraphy of the youngest stratigraphic units within the Clarence-Moreton Basin in NSW proposed by Doig and Stanmore (2012), and adopted by the Geological Survey of NSW, means that the boundaries of some of the younger units have changed. A preliminary new map (not yet officially published) has been provided by the Geological Survey of NSW (Geological Survey of NSW, Dataset 6), and has been used in the Assessment. Additional data sources were used where bedrock stratigraphic units of the Clarence-Moreton Basin (e.g. Walloon Coal Measures) are buried underneath Neogene volcanic rocks (e.g. Lamington Volcanics). Lithological and stratigraphic data from groundwater bores, deep stratigraphic wells, existing two-dimensional cross-sections (e.g. Ingram and Robinson, 1996) and exploration wells were integrated with geological interpretations (e.g.

through the construction of many additional cross-sections) in three-dimensional space in GoCAD to determine the likely extent of the stratigraphic units both at the surface and subsurface.



[1]proposed stratigraphic revision by Doig and Stanmore (2012)

[2]generalised hydrostratigraphy is modified from Radke and O'Brien (2012)

Figure 6 Stratigraphic table of the Clarence-Moreton Basin

This figure is based on Rassam et al. (2014), Doig and Stanmore (2012), Radke and O'Brien (2012) and O'Brien and Wells (1994)

2.1.2.2 Observed data

2.1.2.2.1 Lithological and stratigraphic data

Groundwater bores

Groundwater bores from the Queensland and NSW groundwater databases are an important source of information on lithological data and have underpinned the development of the three-dimensional geological model. More than 12,000 registered groundwater bores have lithological information in the Clarence-Moreton bioregion (Table 4). The Lockyer Valley in south-east Queensland has the highest density of groundwater bores with lithological information from more than 5000 bores (Figure 7 and Table 4). The Richmond river basin in NSW has more than 3000 bores with lithological data. The spatial coverage in other river basins such as the Bremer river basin and Warrill creek basin, the Logan-Albert river basin and in particular the Clarence river basin is much poorer, which is attributed to different land uses and/or a stronger reliance on surface water.

Table 4 Groundwater bores with lithological information in the Clarence-Moreton bioregion

River basin	Number of groundwater bores with lithological information	Number of groundwater bores with stratigraphic information in database	Median depth of groundwater bores with stratigraphy (m)
Lockyer Valley (part of Brisbane river basin)	5362	2914	27.4
Bremer river basin (part of Brisbane river basin)	862	225	18
Logan-Albert river basin	1550	220	19.8
Mid- and Lower Brisbane river basin	964	161	na
Richmond river basin	3309	6	na
Clarence river basin	474	0	na

na = data not applicable
Data: Bioregional Assessment Programme (Dataset 7, Dataset 8)

Information from the groundwater bores is critical to characterise the contact between the alluvium and the underlying volcanic and sedimentary bedrock. However, its usefulness for developing the formation tops of deeper aquifers is mostly limited. This is indicated by the shallow depths of most groundwater bores. For example, groundwater bores with lithological data in the Lockyer Valley have a median depth of only 27.4 m in comparison to the depth of the Clarence-Moreton Basin which exceeds 2000 m in many parts of Queensland and NSW.

In addition to this depth limitation, there is also a substantial lack of stratigraphic information associated with the groundwater bores. For example, less than half of all bores with lithological data also have stratigraphic data (where depth horizons are assigned to stratigraphic layers) in the DNRM groundwater database (Table 4 and Figure 7), and only six bores have stratigraphic information in the NSW part of the bioregion (Table 4). Bores that lack stratigraphic data are of limited use for the purpose of building the three-dimensional geological model. As this poses a severe limitation, considerable effort has been made by the Assessment team to improve the lithological data, and where possible, stratigraphic data were assigned to the bores. This was possible for most bores in NSW, and the interface between alluvium and underlying bedrock can therefore be well defined in most areas. However, in many cases, ambiguity remains with regards to the assignment of the stratigraphic units for deeper groundwater bores. Following that process, all bores were imported into GoCAD for further data quality assessments, thus paving the way to commence the development of the interface between the alluvial aquifers and the underlying bedrock aquifers. During the development of the three-dimensional geological model, this classification was further improved iteratively.

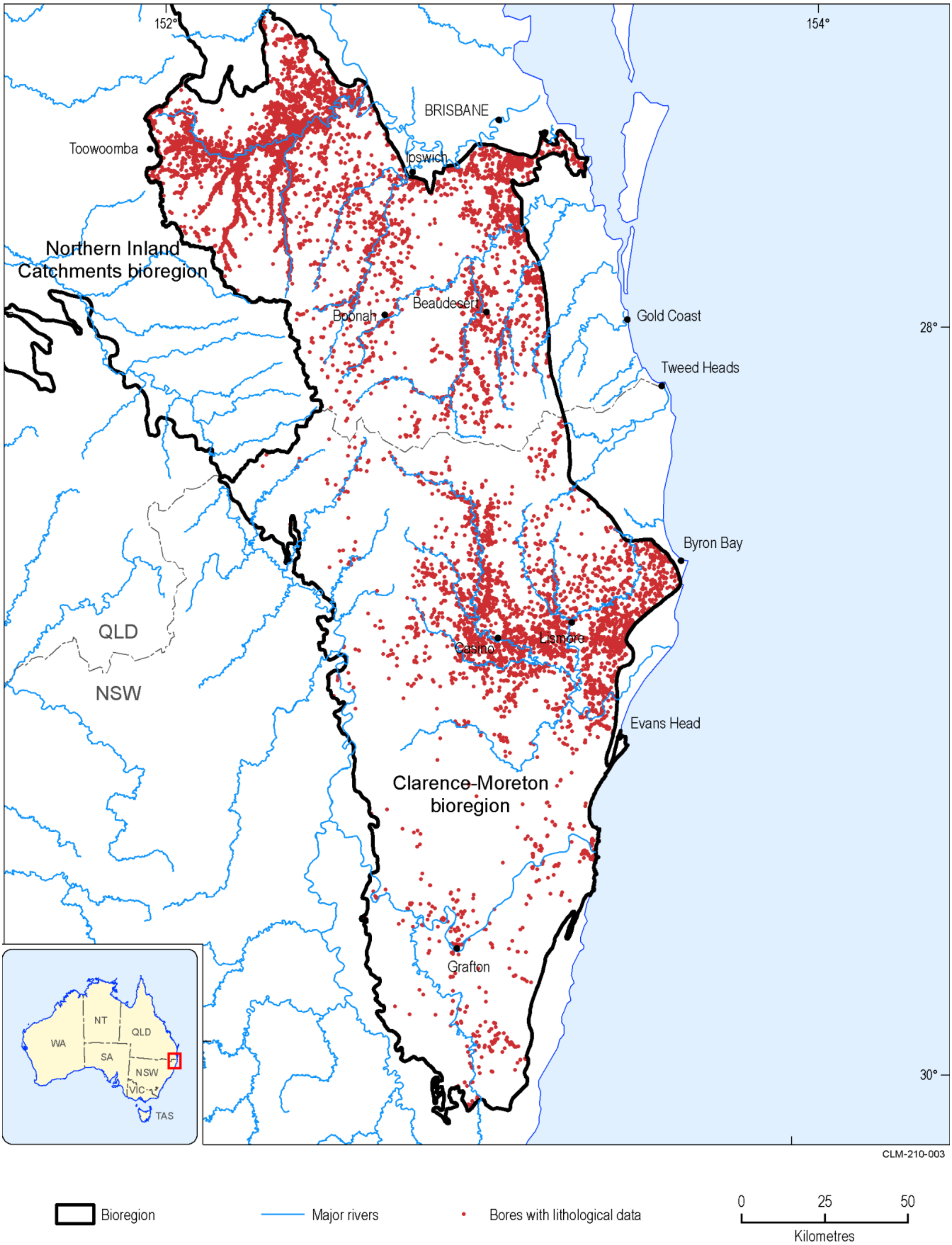


Figure 7 Groundwater bores with lithological data in the Clarence-Moreton bioregion

Data: Bioregional Assessment Programme (Dataset 7)

Stratigraphic wells

In addition to the groundwater bores, there are also 22 stratigraphic wells in the bioregion (Bioregional Assessment Programme, Dataset 9). These were drilled as part of a programme to improve the understanding on the character and depth of the sedimentary sequences in the Clarence-Moreton Basin as described in O'Brien and Wells (1994). With a maximum depth of more than 1000 m and a mean depth of more than 400 m (Table 5), these wells are substantially deeper than most groundwater bores. In addition, the quality of the stratigraphic information from these wells is much better than the quality of groundwater bore log descriptions, and several of these deep stratigraphic wells penetrate the entire sedimentary sequence of the Clarence-Moreton Basin and intersect the underlying basement. These data therefore provide an important source of information on the subsurface distribution and thickness of the stratigraphic units of the Clarence-Moreton Basin.

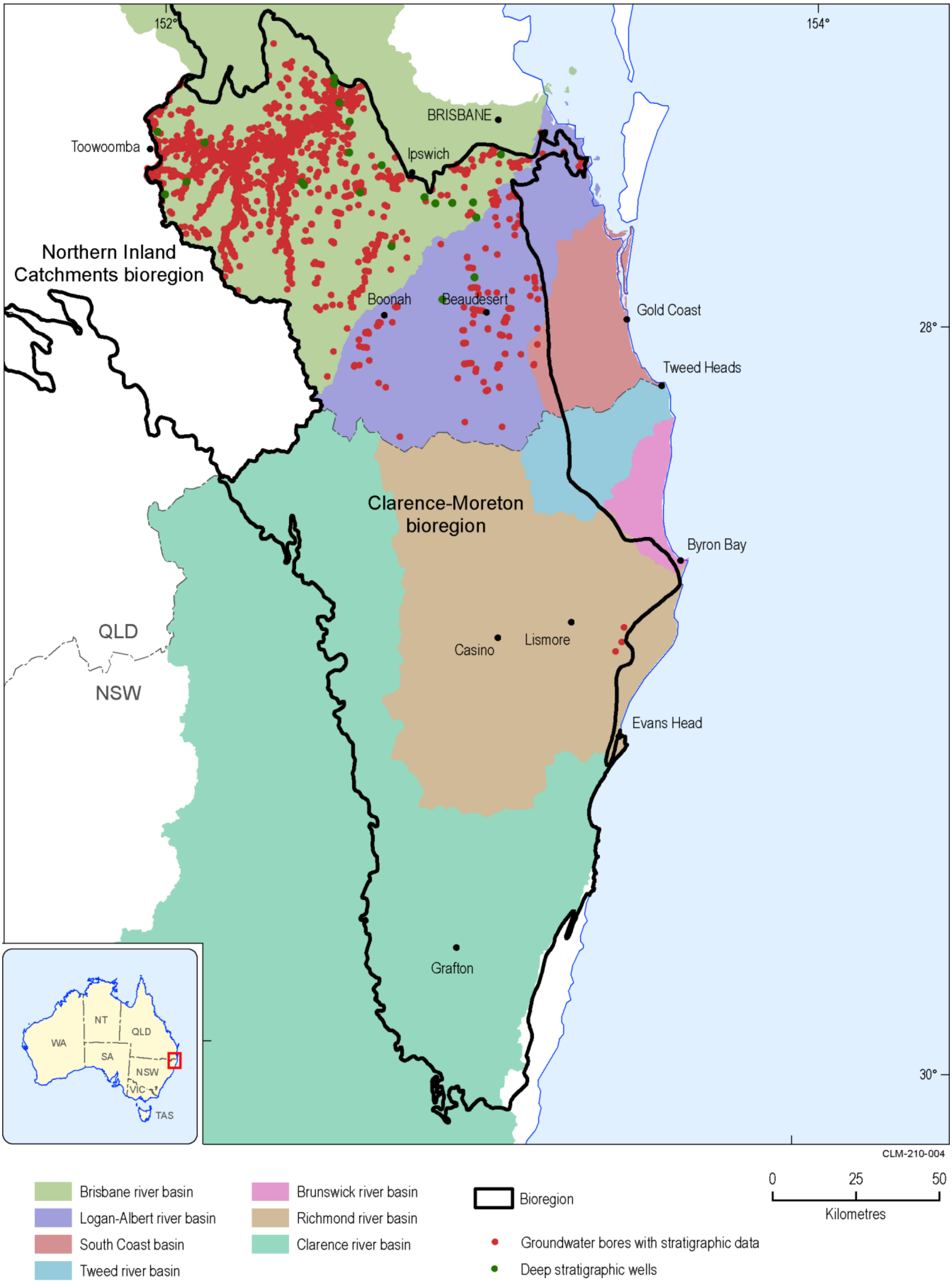


Figure 8 Groundwater bores with stratigraphic data and deep stratigraphic wells in the Clarence-Moreton bioregion

Data: Bioregional Assessment Programme (Dataset 8, 9)

Exploration wells

In addition to the stratigraphic wells mentioned above, exploration wells are another important data source for the construction of the formation tops that have underpinned the development of the three-dimensional geological model.

The different exploration well types in the bioregion are:

- CSG exploration, trial or pilot wells
- petroleum or conventional gas exploration wells
- coal exploration wells
- mineral exploration wells.

Coal seam gas exploration wells

Stratigraphic data were collated from wells that originated from various sources. There are 39 CSG wells in the Queensland part of the Clarence-Moreton bioregion and 74 in the NSW part (Bioregional Assessment Programme, Dataset 10), with most wells drilled in the last 10 to 15 years predominantly by Metgasco and Arrow Energy Pty Ltd (Arrow Energy). Well completion reports were downloaded from the DNRM QDEX database and the NSW Department of Trade and Investment DIGS®database. In addition, unpublished well completion reports were provided by Metgasco. With mean depths of 551 m and 782 m, and maximum depths of 1052 m and 1522 m in Queensland and NSW, respectively, these wells significantly enhance the understanding of the subsurface geometry. Resulting from the new data from CSG exploration wells, there has also been a revision of the stratigraphy of the youngest bedrock units of the Clarence-Moreton Basin in NSW (Doig and Stanmore, 2012). Most of these CSG exploration wells have targeted CSG resources within the Walloon Coal Measures, but some wells were also drilled to explore the CSG potential of the older Ipswich Coal Measures (Figure 9). In addition to the data from the CSG well completion reports, a spreadsheet with formation tops re-interpreted to account for the revised stratigraphy was provided by Metgasco, forming one of the key data sources for the development of the three-dimensional geological model (Metgasco Limited, Dataset 11).

Petroleum and conventional gas exploration wells

Petroleum and conventional gas exploration in the bioregion commenced decades ago. There are currently 26 petroleum/conventional gas exploration wells in Queensland (most of which were drilled prior to 1990) and 24 in NSW (Bioregional Assessment Programme, Dataset 10). Despite being fewer than the CSG exploration wells, they are considered an important source of information for understanding subsurface aquifer geometry. Due to the considerable depth of some of those wells (Table 5) that extend as deep as 2490 m in NSW at Kyogle 1, and together with seismic data, they are considered the most important data source for constructing formation tops of the deeper stratigraphic units in the Clarence-Moreton Basin (e.g. Gatton Sandstone and Woogaroo Subgroup).

Table 5 Exploration and stratigraphic wells in the Clarence-Moreton bioregion in Queensland

	Count	Minimum depth (mBGL)	Mean depth (mBGL)	Maximum depth (mBGL)
CSG (exploration, trial or pilot)	39	84	551	1052.5
Petroleum exploration (conventional gas or oil)	26	34	464	2490
Coal exploration	576	na	na	na
Mineral resources exploration	na	na	na	na
Stratigraphic wells	22	36	450	1238

na = data not applicable
Data: Bioregional Assessment Programme (Dataset 9, Dataset 10, Dataset 12). In addition, information from publications (e.g. O'Brien and Wells (1994) and Ingram and Robinson (1996)) is also considered.

Table 6 Exploration and stratigraphic wells in the Clarence-Moreton bioregion in NSW

	Count	Minimum depth (mBGL)	Mean depth (mBGL)	Maximum depth (mBGL)
CSG (exploration, trial or pilot)	74	204	782	1522
Petroleum exploration (conventional gas or oil)	24	393	1493	2490
Coal exploration	94	na	na	na
Mineral resources exploration	na	na	na	na
Stratigraphic bores	na	na	na	na

na = data not applicable
Data: Bioregional Assessment Programme (Dataset 9, Dataset 10, Dataset 13) . In addition, information from publications (e.g. O'Brien and Wells (1994) and Ingram and Robinson (1996)) is also considered.

Coal exploration wells

There are 670 coal exploration wells in the bioregion, of which 576 are in Queensland (Bioregional Assessment Programme, Dataset 12) and 94 in NSW (Bioregional Assessment Programme, Dataset 13) (Table 5 and Table 6). In comparison to the CSG, petroleum and conventional gas exploration wells, these are considered less useful for developing the three-dimensional geological model because:

- They are typically shallower and most of them only target the uppermost 50 to 100 m of the Walloon Coal Measures or Ipswich Coal Measures at the shallow margins of the Clarence-Moreton Basin.
- For most of them, there are only lithological data with no stratigraphic descriptions available.
- They often only target one formation and do not intersect the underlying formation, hence, the only useful information that can be derived is the minimum depth of the target formation.
- The quality of the well completion reports is poorer compared to those for CSG and petroleum wells, with no digital records of logs.

Nevertheless, the well completion reports for the coal exploration wells were obtained from the DNRM QDEX and the NSW Department of Trade and Investment DIGS® databases and, with a focus on the deeper coal exploration wells, any useful information was extracted.

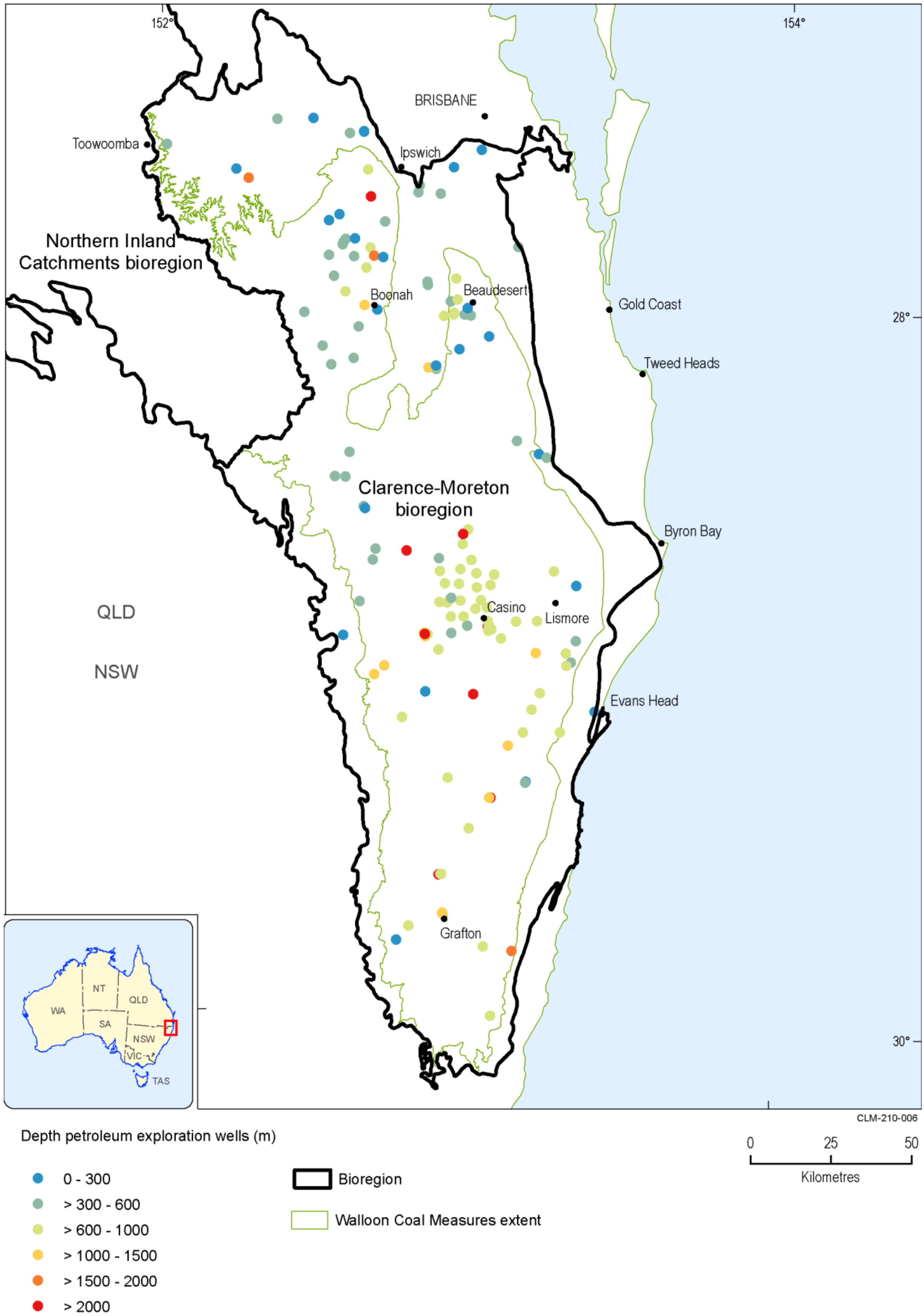


Figure 9 Spatial distribution and depth of coal seam gas and petroleum exploration wells

Wells drilled outside the boundary of the Walloon Coal Measures target the deeper and older coal of the Ipswich Coal Measures

Data: Bioregional Assessment Programme (Dataset 10)

Mineral exploration wells

In contrast to CSG, petroleum and coal bores, there are no geographic information system (GIS) datasets available from the Queensland IRTM system or NSW Geoscience Information Services that show the location and depth of the mineral exploration bores in the bioregion. Instead, there is a shape file that shows all mineral exploration projects within a specified area. It was therefore necessary to assess each project report individually to search for useful data. Most of the mineral exploration data in the bioregion appeared to be of limited use due to the shallow depth of the bores and/or the lack of stratigraphic descriptions. However, a final report on Exploration Licence 4430 by BHP Minerals (Darby, 1993; Torr, 1994) contained very useful lithological logs of approximately 113 shallow bores in the Bungawalbin Creek in the southern Richmond river basin, an area that has little data in the NSW groundwater database. These data were then manually entered into the database (Bioregional Assessment Programme, Dataset 14) and combined with the groundwater bore dataset to improve the definition of the interface between the alluvial aquifer and the underlying bedrock.

2.1.2.2.2 Geological maps

There are many geological maps for the bioregion that range in scale from 1:100,000 to 1:1,000,000.

Geological maps used in the Assessment are:

- South-East Queensland geology (Bioregional Assessment Programme, Dataset 15): this dataset contains 1:100,000 digital map sheets for the entire bioregion in Queensland. This map is used to define the surface geology extent for the three-dimensional geological modelling in Queensland
- Warwick-Tweed Heads 1:250,000 dataset (Brunker et al., 1972): covers the northern part of the bioregion in NSW
- Surface geology map of Australia: 1:1,000,000 geological maps (compiled at a 1:250,000 scale) that cover the entire bioregion (Bioregional Assessment Programme, Dataset 16)
- NSW Coastal Quaternary Geology (1:25,000 and 1:100,000 scales): detailed geological maps of the Quaternary geology in the coastal region of the bioregion in NSW.
- An unreleased GIS dataset of the revised bedrock geology in NSW (Geological Survey of NSW, 2014). One of the challenges in this project is that a change in the stratigraphic classification of the Clarence-Moreton Basin sedimentary sequences has been proposed by Doig and Stanmore (2012) based on the newly available data from CSG exploration wells. This proposed revision has been adopted by the Geological Survey of NSW. A new (preliminary) GIS dataset of the boundaries of the bedrock stratigraphic units in the bioregion in NSW has been developed by the Geological Survey of NSW (Geological Survey of NSW, 2014) and provided for the purpose of the Assessment (Geological Survey of NSW, Dataset 6).

Apart from the larger-scale (1:1,000,000 or 1:2,000,000) geological maps which generally do not show enough differentiation between formations (e.g. between the Gatton Sandstone and the Koukandowie Formation in many areas), there is no single geological map that covers the entire bioregion. As a result, and also to account for the revision of the stratigraphy of the Clarence-Moreton Basin in NSW, a new composite geological map which combines different datasets was developed for the Assessment (Figure 10). To serve the purpose of the three-dimensional geological modelling, this composite geological map needed to be further simplified as only limited complexity can be captured by the three-dimensional geological model due to computational limitations.

To achieve this simplification, stratigraphic units were combined where possible (e.g. different intrusive rocks were combined into a single class) and the alluvial aquifer boundaries were changed to exclude small alluvial tributary systems with widths of less than 200 m.

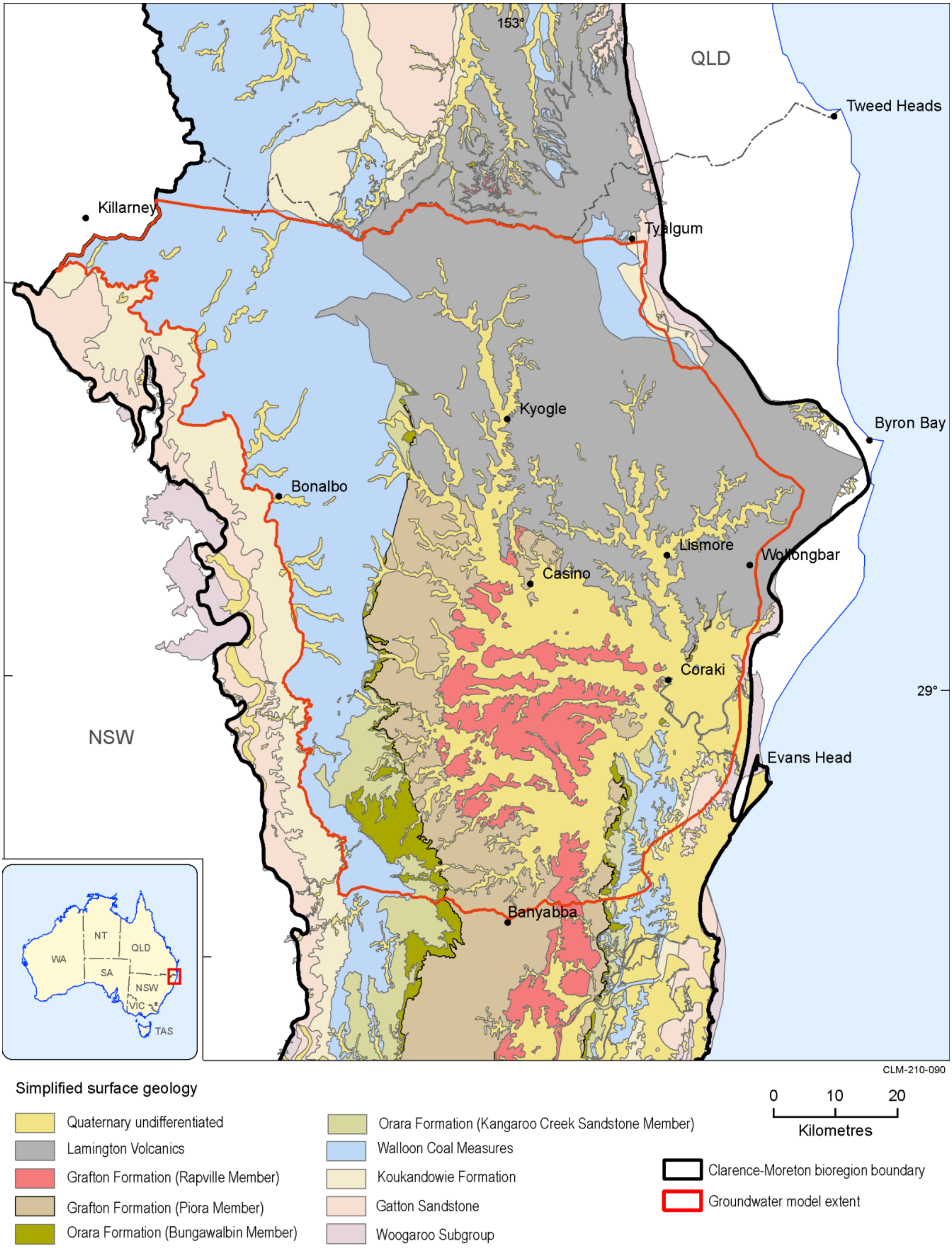


Figure 10 New geological map derived from different pre-existing maps and showing the revised stratigraphy in New South Wales

This map adopts the revised stratigraphic classification proposed by Doig and Stanmore (2012).
Data: (i) Surface geology map of Australia 1:1,000,000 (Bioregional Assessment Programme, Dataset 16), (ii) Geological Survey of NSW (Dataset 6), (iii) Geological survey of Queensland (Bioregional Assessment Programme, Dataset 15)

2.1.2.2.3 Geophysical data

The national geophysics dataset fully covers the Clarence-Moreton bioregion with magnetic, radiometric and gravity datasets. However, the usefulness of these geophysical datasets for this project is limited to the identification of regional-scale geological structures due to the coarse resolution. Apart from these national geophysical survey datasets, the Clarence-Moreton bioregion has some of the poorest coverage of site-specific airborne geophysical data in Queensland with only one available survey. In NSW, the Grafton – Tenterfield Airborne Geophysical Survey was released in 2012. In addition to the gridded geophysical datasets downloaded from the Geophysical Archive Data Delivery System (GADDS), more geophysical data compilations are available for the bioregion in NSW. Data packages containing geophysical data that were obtained from the Geological Survey of NSW (NSW Office of Trade and Investment) and are used in the Assessment are:

- Onshore Clarence-Moreton Basin – Petroleum Data Package
- Clarence-Moreton Basin – Geophysical Data Compilation
- Clarence-Moreton SEEBASE^{TM} and Structural GIS Project (NSW Department of Primary Industries, Dataset 3)
- Clarence-Moreton Basin Seismic Survey 2008
- Grafton – Tenterfield Airborne Geophysical Survey.

Geophysics (magnetic, radiometric and gravity)

Figure 11 shows the airborne geophysical data in the Clarence-Moreton bioregion. The geophysical data available for the bioregion include numerous sets of magnetic, gravity and radiometric data. Overall, the usefulness of some of these datasets for building the three-dimensional geological model or the identification of new additional structural features seems to be limited due to their coarse resolution. However, the recent Grafton – Tenterfield airborne geophysical survey which covers the northern part of the bioregion in NSW has a considerably finer resolution. It has collected magnetic, gamma-ray and digital terrain data within parts of the mineral-prospective New England Orogen and the Clarence-Moreton Basin. This survey allows, for example, the differentiation of the Lamington Volcanics that are visible as a magnetic anomaly.

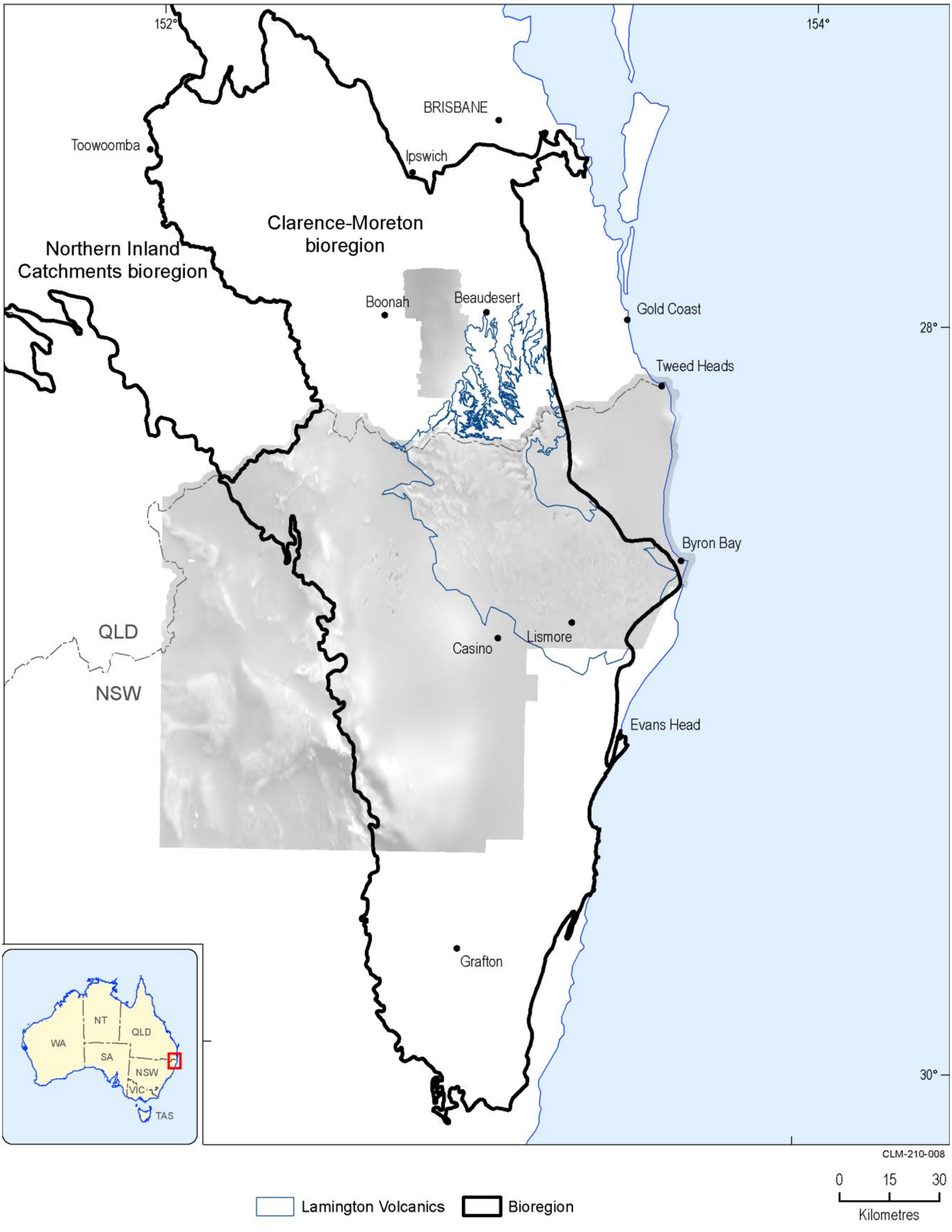


Figure 11 Airborne magnetic surveys in the Clarence-Moreton bioregion showing the extent of the Lamington Volcanics and structural features

Data: Bioregional Assessment Programme (Dataset 17)

Geophysics (seismic reflection)

Apart from the stratigraphic data from exploration bores and stratigraphic bores, seismic data are the most important source of information underpinning the geometry of aquifers in the subsurface. In addition, seismic data allow the determination of vertical displacements of stratigraphic units along faults. Seismic data can also provide information on the internal architecture and disposition of sedimentary rock formations in the subsurface. Seismic data are available in the Clarence-Moreton bioregion as follows:

- There are 706 km of seismic lines acquired as part of nine individual seismic surveys in the bioregion in Queensland (Figure 12) (Bioregional Assessment Programme, Dataset 18). Most of these were collected during the 1960s to 1980s and would require substantial reprocessing prior to any use in this project. However, seismic data for the most recent survey (‘Boonah’, acquired by Arrow Energy in 2000) have been acquired from the Geological Survey of Queensland.
- There are 249 seismic lines with a total line length of 2471 km in NSW (Figure 12) (Bioregional Assessment Programme, Dataset 19). As in Queensland, many of these seismic surveys were conducted in the 1960s to 1980s. However, there are also more recent surveys conducted by Metgasco in addition to reprocessing the results of older datasets.

In combination with the stratigraphic records from exploration and stratigraphic wells, grids which incorporate seismic interpretations provided by Metgasco (Metgasco Limited, Dataset 4) and the NSW Department of Trade and Investment (Dataset 5) for the NSW part of the Clarence-Moreton bioregion were used as data inputs to build the three-dimensional geological model in NSW (Figure 8). In particular, this helped to understand aquifer geometry and understand the extent and type of structural disruption, which may cause direct stratigraphic contact between aquifers and aquitards.

These two datasets included grids of the following layers (covering all or parts of the Clarence-Moreton bioregion in NSW):

- Metgasco Limited formation top grids (Dataset 4): top of the Kangaroo Creek Sandstone, top of the Richmond coal seams (i.e. the top of the coal seams in the Walloon Coal Measures), top of Koukandowie Formation (only partially covering the NSW part of the Clarence-Moreton bioregion) and Gatton Sandstone (only partially covering the NSW part of the Clarence-Moreton bioregion).
- NSW Department of Trade and Investment formation top grids (Dataset 5): top Walloon Coal Measures (i.e. top of the Richmond coal seam), top Gatton Sandstone, top Ripley Road Sandstone (part of the Woogaroo Subgroup), top Ipswich Coal Measures, top Nymboida Coal Measures and top of Basement.

No pre-existing formation top grids or seismic interpretations or picks existed for any of the shallower layers in NSW (i.e. any stratigraphic units younger than the Kangaroo Creek Sandstone) or for any stratigraphic units in Queensland. More detail on how these existing layers were used to inform the three-dimensional geological model is shown in Figure 8 and Section 2.1.2.3.3.

2.1.2.2.4 Remotely sensed data and digital elevation models

The ground surface elevation has been extracted from the 1-second Shuttle Radar Topography Mission (SRTM) DEM data (Geoscience Australia, 2008), which has a resolution of 28.6 m x 28.3 m. From the original SRTM data, CSIRO and Geoscience Australia have produced the smoothed 1-second DEM dataset with buildings and vegetation removed (Geoscience Australia and CSIRO Land and Water, 2010) (Geoscience Australia, Dataset 20). This SRTM DEM was re-sampled at a lower resolution (200 m) to allow use in the three-dimensional geological models (Bioregional Assessment Programme, Dataset 21). This is the primary source of elevation data used in the Assessment. However, particularly in low-lying areas such as the Richmond river basin or Clarence river basin, the use of lidar data would be beneficial, as there is only very limited topographic relief where small errors in the DEM potentially have a large influence on the conceptual and numerical models. Lidar data exist for most of the Clarence-Moreton bioregion in Queensland and for part of the bioregion in NSW, and are owned by Queensland and NSW state agencies. However, these data have not been obtained due to their very considerable cost.

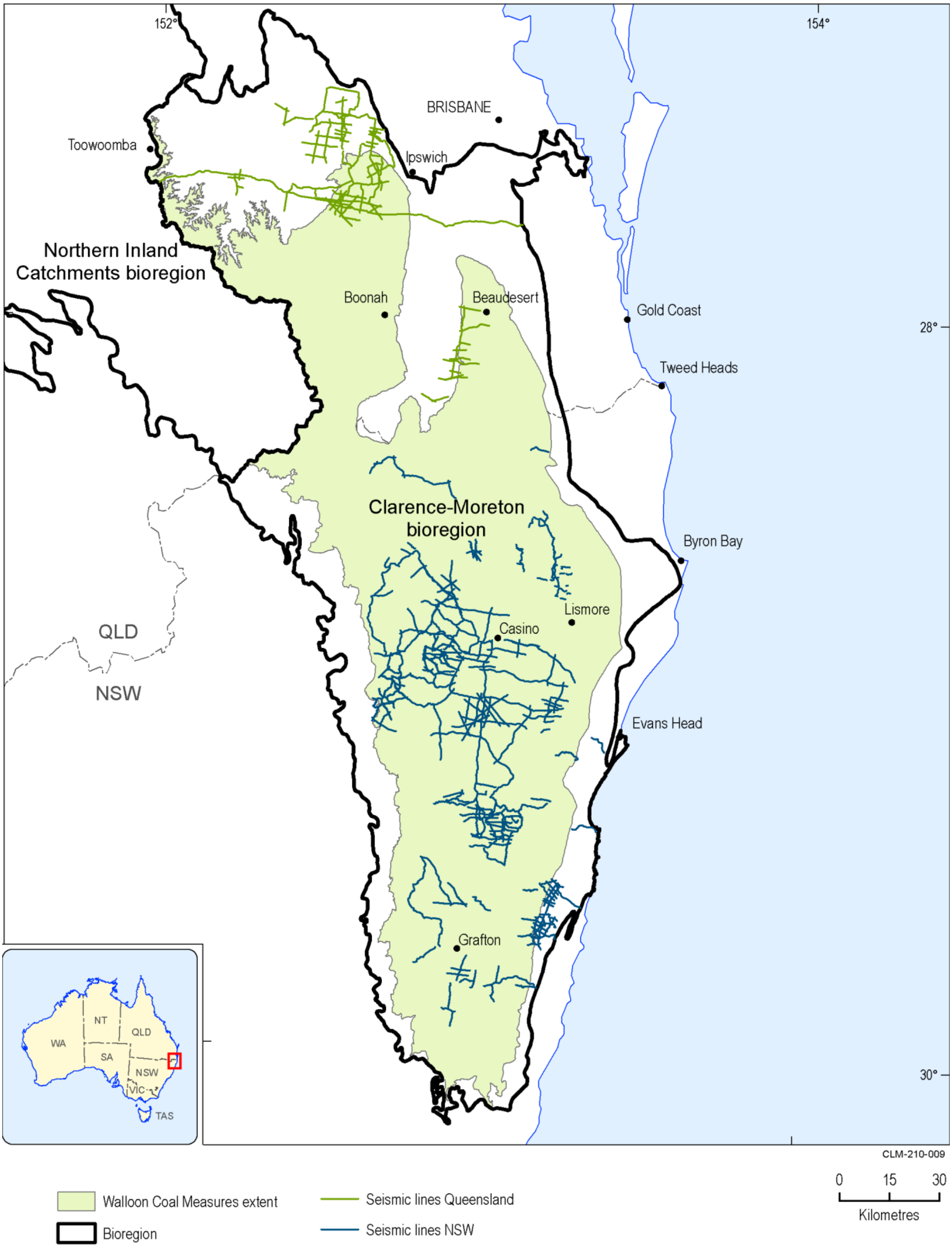


Figure 12 Seismic surveys in Clarence-Moreton bioregion

Data: Bioregional Assessment Programme (Dataset 18, Dataset 19, Dataset 22, Dataset 26)

2.1.2.2.5 Geological structure

There is a range of datasets (GIS data and publications) available on the geological structure of the Clarence-Moreton Basin, including:

- Clarence-Moreton SEEBASE^{TM} and Structural GIS Project (Geological Survey of NSW) (NSW Department of Primary Industries, Dataset 3). The SEEBASE data provide an indication of the entire depth to basement across the entire Clarence-Moreton bioregion, but the reliability of the depth estimate is highly variable
- seismic data (previously mentioned)
- Queensland geology and structural framework (Geological Survey of Queensland) (Geological Survey of Queensland, Dataset 23)
- Petroleum prospectivity of the Clarence-Moreton Basin in NSW (Ingram and Robinson, 1996)
- Geology and petroleum potential of the Clarence-Moreton Basin, NSW and Queensland (O'Brien and Wells, 1994)
- Metgasco fault mapping (derived from reprocessed seismic data, provided in commercial confidence by Metgasco) showing faults that are present in different stratigraphic formations

2.1.2.3 Statistical analysis and interpolation

This section focuses on the development of the three-dimensional geological model, which is based on the data sources introduced in the previous section. Multiple three-dimensional geological models were developed from the data sources described above, including four regional models of the following river basins:

- Brisbane river basin (i.e. Lockyer Valley, Bremer river and Warrill creek basins)
- Logan-Albert river basin
- Richmond river basin
- Clarence river basin.

In addition, one bioregion-wide model has been developed based on the four regional models. The reason for developing regional finer-scale models first was that considerable trial and error is involved in the development of three-dimensional geological models, and the computing time required to develop the bioregion-wide model is very long. Furthermore, the regional-scale models all have a finer resolution, which allows better assessment of the link between geology and hydrological processes in specific regions.

The datasets utilized for the different regional three-dimensional geological models are shown in Table 8.

2.1.2.3.1 Three-dimensional geological model workflow

This section briefly describes the workflow used to develop the three-dimensional geological models of the subsurface stratigraphic architecture of the Clarence-Moreton bioregion. The models were developed using SKUA® three-dimensional geological modelling software (Paradigm Geophysical Pty Ltd, version 14.1).

2.1.2.3.2 Definition of the stratigraphic column

A three-dimensional geological model is generally composed of a series of units (layers) that are assembled with respect to their chronology and structural relationships. These units are defined by a set of boundary horizons, which represent the geological contacts between the different formations; a critical step in the modelling workflow is to determine the number of boundary horizons needed and identify their location in three-dimensional space (Raiber et al., 2012). During this step, the horizons that represent each geological layer are added to the model in chronological order, and the types of contacts between the different layers are defined. The decision on which layers are included in the three-dimensional geological model is underpinned by geological knowledge. Table 7 shows the layers that were included in the regional and/or bioregion-wide models. For example, the Grafton Formation and the Orara Formation (Bungawalbin Member and Kangaroo Creek Sandstone) are absent in the Brisbane river basin, therefore there was no need to include layers representing these units in the Brisbane river basin three-dimensional geological model. Another example is the inclusion of the MacLean Sandstone (the upper part of the Walloon Coal Measures) as a separate layer in the Richmond river basin three-dimensional geological model. In this area, there are sufficient data to differentiate it from the coal seams of the Walloon Coal Measures, whereas there are insufficient data elsewhere within the Clarence-Moreton bioregion. In addition, the relationships between the different horizons are defined during this step. In simple three-dimensional geological models of sedimentary basins (often referred to as 'layer-cake models'), the relationships between the different sedimentary bedrock units of a sedimentary basin are usually modelled as conformable or unconformable contacts (where the base of each geological layer is represented by the top surface of the underlying layer) or as baselaps (where layers terminate along the lower boundary of a depositional sequence). However, the inclusion of the alluvium and the volcanic aquifers in the three-dimensional geological models of the Clarence-Moreton bioregion adds significantly more complexity, as the contacts between the alluvium and the underlying Lamington or Main Range volcanics or sedimentary bedrock, as well as the contact between the Lamington or Main Range volcanics and the underlying sedimentary bedrock, are eroded. Furthermore, unlike in simple 'layer-cake models', the alluvium and volcanic units overlie many different sedimentary bedrock units, and consequently, rather than representing them as formation tops, they are represented in the three-dimensional geological model as the 'base of alluvium' and 'base of basalt', respectively.

Table 7 Stratigraphic units included in the regional and bioregion-wide three-dimensional geological models

'Y' denotes that a layer is included in a three-dimensional geological model.
'N' denotes that the layer is present in the specific region, but that it is not included as a model layer.
Superscript 'a' indicates that there are sufficient data available to differentiate the Maclean Sandstone from the coal seams of the Walloon Coal Measures.
Superscript 'b' indicates that the different layers of the Bundamba Group (i.e. Koukandowie Formation, Gatton Sandstone and Woogaroo Subgroup) are not differentiated.

	Brisbane river basin	Logan-Albert river basin	Richmond river basin	Clarence river basin	Bioregion wide
Quaternary undifferentiated	Y	Y	Y	Y	Y
Main Range Volcanics/Lamington Volcanics	Y	Y	Y	Y	Y
Intrusions	Y	Y	N	N	Y
Grafton Formation	Not present	Y	Y	Y	Y
Bungawalbin Member	Not present	Y	Y	Y	Y
Kangaroo Creek Sandstone	Not present	Y	Y	Y	Y
Walloon Coal Measures (MacLean Sandstone)	Not differentiated[a]	Not differentiated[a]	Y	Not differentiated[a]	Not differentiated[a]
Walloon Coal Measures (coal seams)	Y	Y	Y	Y	Y
Koukandowie Formation	Y	Y	Not differentiated[b]	Y	Y
Gatton Sandstone	Y	Y	Not differentiated[b]	Y	Y
Woogaroo Subgroup	Y	Y	Not differentiated[b]	Y	Y
Basement undifferentiated	Y	Y	Not differentiated	Y	Y

2.1.2.3.3 Selection of input datasets

The major datasets used for the development of different regional and for the bioregion-wide three-dimensional models are listed in Table 8. A 'tick' denotes that a dataset was used for the development of a specific three-dimensional geological model, whereas a cross indicates that it was not used for this model.

The selection of datasets is primarily based on geographic area. However, it is important to note that datasets that represent an area outside a specific regional three-dimensional modeling domain but borders this area were in many instances still used for the development of a model to avoid model artefacts at the boundary of the model domain. For example, datasets from the Richmond river basin three-dimensional geological model were used to inform the model of the Logan-Albert river basin (and vice versa).

The selection is also related to the decision which hydrostratigraphic units are present in a particular area, and which units should be included in a specific model (Section 2.1.2.3.2). For example, a decision was made by the Assessment team not to include layers below the Walloon

Coal Measures into the groundwater model of the Richmond river basin. The reason for this decision was that the Gatton Sandstone and the Koukandowie Formation are low-yielding aquitards or partial aquifers which contain highly brackish to saline groundwater, and no or very few groundwater bores are screened in these units (Figure 27 in Section 2.1.3 and companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016)). Therefore, these deeper layers below the Walloon Coal Measures were not represented in the three-dimensional geological model of the Richmond river basin, as the primary purpose of this model was to provide the layer structure for the numerical model. However, all major layers are represented in the bioregion-wide three-dimensional geological model.

Finally, another important criterion for the dataset selection was the timing when datasets became available for use in the Assessment. Some datasets, even though they are considered useful for the development of a specific regional three-dimensional model, were not available at the time when the model was developed. However, all datasets listed in Table 8 were integrated to inform the bioregion-wide three-dimensional geological model.

Table 8 Key datasets and references used in the development of regional and bioregion-wide three-dimensional geological models

A ‘Y’ indicates that a dataset (or a reference) was used for a particular model, whereas an ‘N’ indicates that it was not used.

Dataset name/description	Dataset number	Richmond river basin	Bioregion-wide model	South-East Queensland[a]	Logan-Albert river basin	Clarence river basin
Clarence-Moreton SEEBASE & Structural GIS Project	3	Y	Y	Y	Y	Y
Metgasco Limited formation top grids	4	Y	Y	N	N	Y
NSW Tade and Investment formation top grids	5	N	Y	N	N	Y
NSW Geological Survey - geological units DRAFT line work	6	Y	Y	N	Y	Y
Metgasco Limited formation top re-interpretations	11	Y	Y	N	N	Y
CLM - Coal Bore Holes in QLD	12	N	Y	N	N	N
CLM - Coal Bore Holes in NSW	13	Y	Y	N	N	Y
BHP mineral exploration wells stratigraphy	14	Y	Y	N	N	N
CLM - QLD Surface Geology Mapsheets	15	Y	Y	Y	Y	N
CLM - Geology NSW and QLD combined	16	Y	Y	Y	Y	Y
CLM - Lamington Volcanics extent	17	Y	Y	N	Y	N
Digital Elevation Model (re-sampled at a 200 m resolution)	21	Y	Y	Y	Y	Y
CLM - Walloon Coal Measures extent	22	Y	Y	Y	Y	Y
CLM - Kangaroo Creek Sandstone extent	24	Y	Y	N	Y	Y

Dataset name/description	Dataset number	Richmond river basin	Bioregion -wide model	South-East Queensland[a]	Logan-Albert river basin	Clarence river basin
Queensland well completion reports	25	N	Y	Y	Y	N
CLM - Woogaroo Subgroup extent	26	N	Y	Y	Y	Y
NSW coal seam gas well completion reports	27	Y	Y	N	Y	Y
Fault surfaces	28	Y	Y	Y	Y	Y
Interpolated base of alluvial systems	29	Y	Y	Y	Y	Y
CLM - Lockyer Valley groundwater bore stratigraphy	30	N	Y	Y	Y	Y
CLM - Logan-Albert river basin groundwater bore stratigraphy	31	Y	N	N	N	N
CLM - Bremer river basin groundwater bore stratigraphy	32	N	Y	Y	Y	N
Richmond river basin groundwater bore stratigraphy	33	Y	Y	N	Y	Y
NSW CSG wells stratigraphy	34	Y	Y	N	Y	Y
Queensland CSG wells stratigraphy	35	N	Y	Y	Y	N
CLM - Gatton Sandstone extent	36	N	Y	Y	Y	Y
CLM - Alluvia extent	37, 38, 39, 40, 41	Y	Y	Y	Y	Y
CLM - Main Range Volcanics extent	42	Y	Y	Y	Y	Y
CLM - Koukandowie Formation extent	43	Y	Y	Y	Y	Y
CLM - Piora Member extent	44	Y	Y	N	Y	Y
CLM - Bungawalbin Member extent	45	Y	Y	N	Y	Y
O'Brien and Wells, 1994	na	Y	Y	Y	Y	Y
Ingram and Robinson, 1996	na	Y	Y	Y	Y	Y

[a]the model domain covers the Lockyer Valley, Bremer river basin and the Warrill Creek catchment
na = not applicable, and these rows refer to reports which provided critical input in the development of the three-dimensional geological models

2.1.2.3.4 Representation of structural elements in the three-dimensional geological model

Geological structures such as faults can have a significant influence on groundwater flow. They can, for example, lead to compartmentalization of aquifer/aquitard systems or form preferential pathways for inter-aquifer connectivity (discussed in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016)).

In the three-dimensional geological models of the Clarence-Moreton bioregion, knowledge related to the presence of major structural elements has been used to inform the geometry of depositional centers such as the Casino Trough and Grafton Trough. For this purpose, major faults were imported into the three-dimensional model framework as surfaces and this was particularly useful to guide the placement of additional control points to avoid model artefacts in areas of poor data density.

However, modelling vertical displacements (i.e. juxtaposition) of stratigraphic units along faults is associated with many challenges; even in data-rich sedimentary basins such as the linked Surat Basin (and despite more than 10 years of on-going research by many stakeholders), no adequate publicly available basin-wide faulted three-dimensional geological model currently exists.

Key challenges that are associated with the inclusion of faults in basin-wide three-dimensional geological models are:

- Limited or inadequate fault mapping
- Lack of data and understanding on the three-dimensional structure, dip, depth, throw and displacement of faults to inform the model
- Conceptual uncertainties on the role of faults: evaluation of existing data reveals considerable remaining ambiguity, suggesting that there is considerable conceptual uncertainty. This uncertainty is unlikely to be resolved by a single structural model, and this highlights the need to develop multiple structural models (as suggested, for example, by Ye et al. (2010)).
- Computational time: the integration of alluvial, volcanic bedrock and sedimentary bedrock hydrostratigraphic units in the Clarence-Moreton three-dimensional geological models results in very long computational times; the inclusion of faults adds considerably to computational run times.

With the exception of the central Richmond river basin, the density of deep wells with good stratigraphic records and the coverage by seismic surveys is relatively poor in most parts of the Clarence-Moreton bioregion (Figure 9 and Figure 12) compared to other sedimentary basins such as the linked Surat Basin. Furthermore, fault mapping particularly in the Queensland part of the Clarence-Moreton bioregion is extremely limited. This means that for most areas within the Clarence-Moreton bioregion, there are insufficient data to model fault displacements. The only area where there may be sufficient data to develop a faulted three-dimensional geological model is the Richmond river basin. As a result of these challenges and within available time and resources, no faulted three-dimensional geological model could been developed.

To further enhance the understanding of the hydraulic role of faults, the impact of faults on predictions in the context of regional groundwater modelling will be modelled stochastically as part of a CSIRO strategic project for the central Richmond river basin (‘Next generation methods and capability for multi-scale cumulative impact assessment and management’; sub-theme ‘Tracer-based improvement of groundwater model conceptualisation and predictability’).

2.1.2.3.5 Characterisation of binding horizons of shallow aquifers (alluvium and basalt)

The data sources used for the three-dimensional geological model have been described in previous sections. A certain surface may be well constrained in some parts of the model domain but poorly constrained or even absent in others due to a lack of data. To overcome this limitation, the depth maps created using kriging (Figure 13 to Figure 17) were used in data-poor areas such as the Clarence river basin and in the headwaters of alluvial systems where the data coverage is generally sparse to represent the 'base of alluvium' horizon in the three-dimensional geological models. In data-rich areas such as the Lockyer Valley or the central Richmond River floodplain, additional control points were digitised in GoCAD™ (Paradigm Geophysical Pty Ltd, version 2009.4) using regular sets of cross-sections (constructed using the GoCAD add-on module 'Mining Utilities' from Mira Geosciences) to avoid model artefacts and to guide the shape of the horizon.

Richmond River alluvium

As shown in Table 4, there are 3309 groundwater bores with lithological data in the Richmond river basin. After cleaning these data and converting the lithological data into stratigraphic logs where possible, these data were used to create a surface that represents the depth to the base of the alluvium, and thus, the interface with the underlying bedrock. This can then be converted to a surface representing the elevations that underpin the three-dimensional geological model by relating it to the topography (derived from the SRTM data). Figure 13 shows that the depth of the Richmond River alluvial system is mostly less than 30 m in the centre of the alluvium of the Richmond River drainage line, with local thicknesses of up to approximately 45 m.

The headwater alluvial systems within the Lamington Volcanics as well as smaller tributary systems in the southern part of the Richmond river basin are typically thinner and mostly less than 15 to 20 m. The shape of these smaller systems (usually v-shape) also differs from the wider central drainage line of the Richmond River (u-shaped).

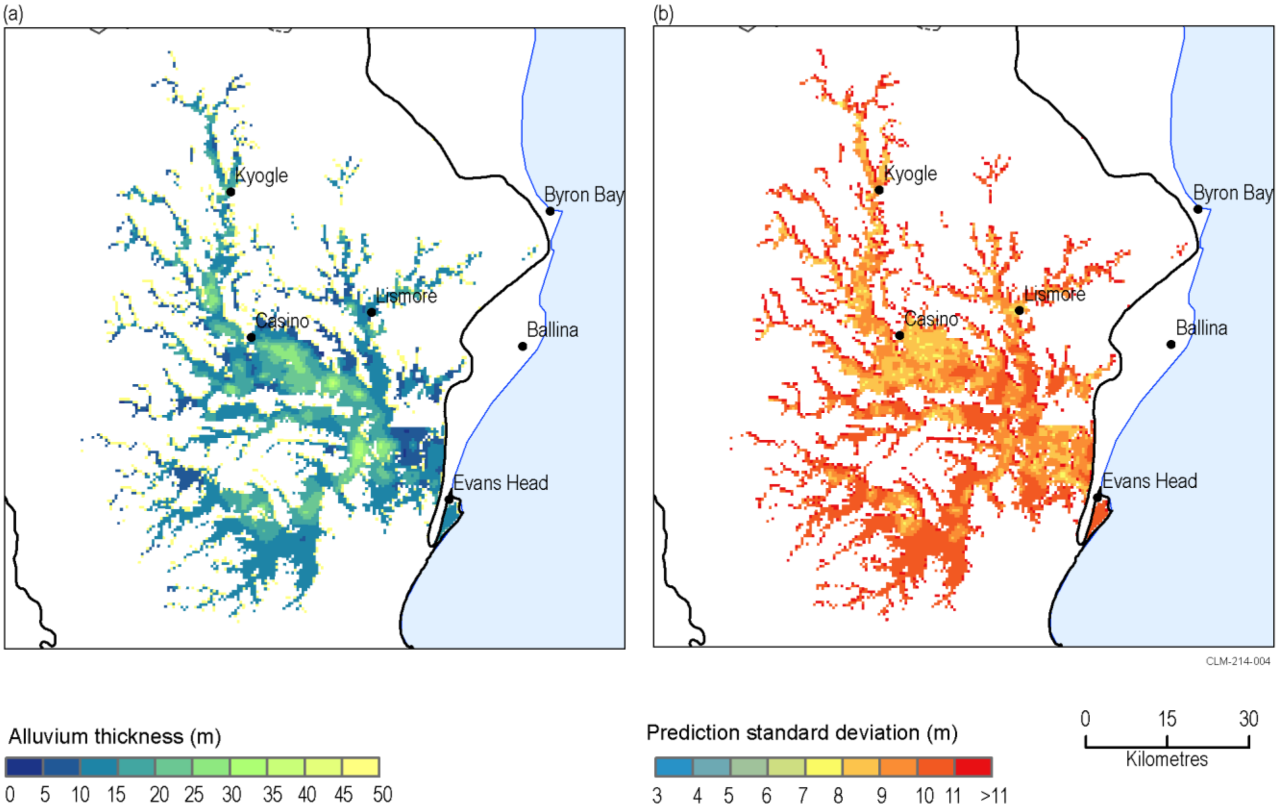


Figure 13 Depth to the base of the Richmond River alluvial system and standard deviation associated with the prediction

Data: Bioregional Assessment Programme (Dataset 29)

Clarence River alluvium

As outlined in Section 2.1.2.2.1, there are 474 groundwater bores with lithological data and no groundwater bores with stratigraphic data available in the Clarence river basin. Consequently, the uncertainty associated with the spatial interpolation is very high in the Clarence river basin (Figure 14), as indicated by a standard deviation of nearly 50% of the thickness of the alluvium. Based on this limited knowledge, the Clarence River alluvium appears to be considerably thinner than the Richmond River alluvium.

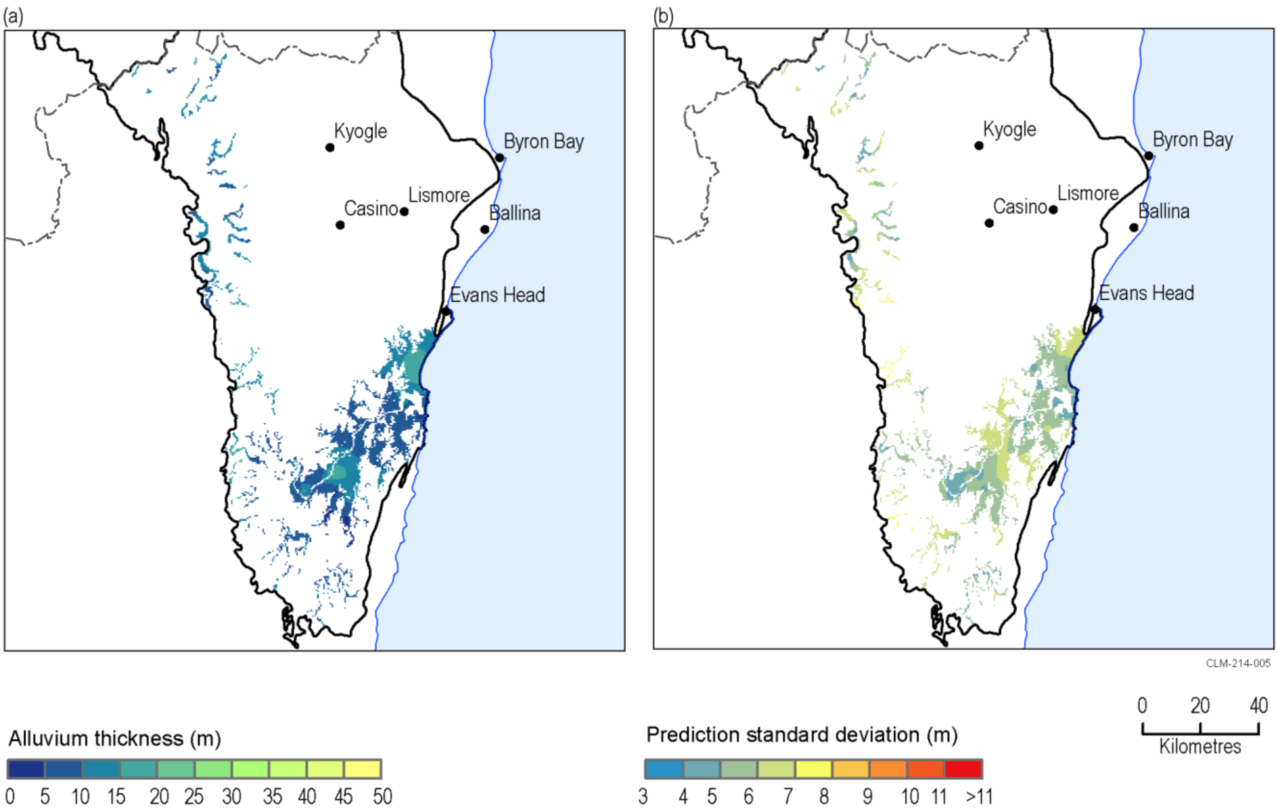


Figure 14 Depth to the base of the Clarence River alluvial system and standard deviation associated with the prediction

Data: Bioregional Assessment Programme (Dataset 29)

Lockyer Valley alluvium

With lithological logs available for more than 5000 groundwater bores, the Lockyer Valley alluvial system is the best constrained alluvial system in the bioregion. Accordingly, the standard deviation associated with the spatial interpolation is considerably smaller relative to the thickness of the system compared to other alluvial systems such as the Clarence River alluvium (Figure 15).

The thickness of the Lockyer Valley alluvial system generally varies between 20 to 35 m throughout much of the central drainage line of Lockyer Creek. Towards the edges, the alluvium is thinner. In major tributary systems such as Laidley Creek and the lower reaches of other creeks such as Tenthill Creek, the thickness of the alluvial systems is similar (20 to 30 m). In the headwaters, most tributary systems of Lockyer Creek have considerably thinner and narrower alluvial systems, generally ranging from approximately 5 to 15 m.

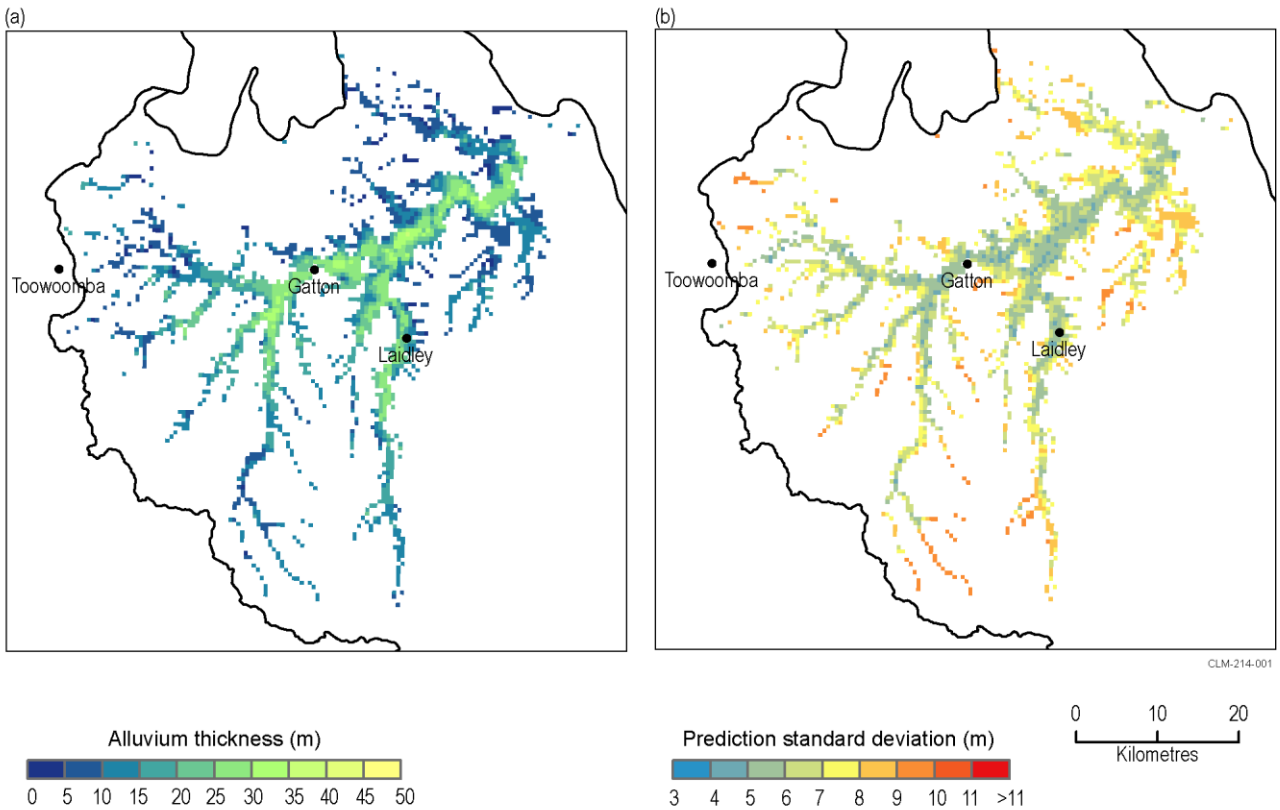


Figure 15 Depth to the base of the Lockyer Valley alluvial system and standard deviation associated with the prediction

Data: Bioregional Assessment Programme (Dataset 29)

Logan-Albert alluvium

The depth to the base of the Logan-Albert alluvial system is based on 1550 groundwater bores (Table 4). The thickness of the Logan-Albert alluvial system (Figure 16) is more variable than the Lockyer Valley or the Richmond River alluvial systems. Where the floodplain is widest in the central part of the river basin, the alluvial sediments reach a thickness of approximately 30 m. However, throughout much of the Logan-Albert river basin, the thickness of the alluvial sediments typically ranges between 5 to 20 m. Due to the large size of the catchment and the relatively small number of data points, the standard deviation associated with the kriging interpolation is comparatively high.

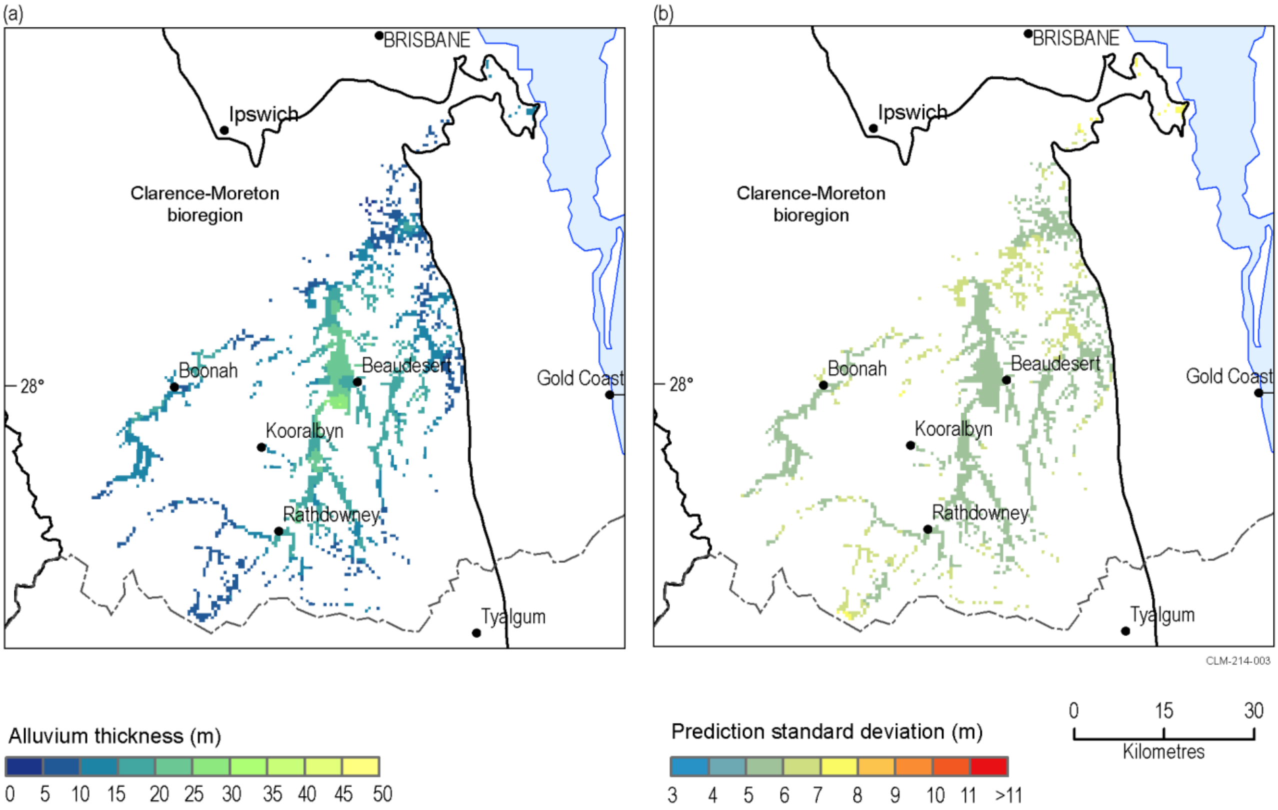


Figure 16 Depth to the base of the Logan-Albert River alluvial system and standard deviation associated with the prediction

Data: Bioregional Assessment Programme (Dataset 29)

Bremer River alluvium

The surface of the depth to the base of the Bremer River and Warrill Creek alluvial system is based on 862 groundwater bore lithological logs (Table 4). In comparison to the neighbouring Lockyer Valley, the uncertainty associated with the prediction is higher in the Bremer river basin (Figure 17) as indicated by a higher standard deviation relative to the thickness of the alluvium. The wider parts of the floodplain of the Bremer River and Warrill Creek alluvial systems are up to about 25 to 30 m thick. No distinct thinning of the alluvial aquifer systems can be observed towards the edge of the alluvium, indicating that the interface between the alluvium and the underlying bedrock is relatively steep. The alluvial systems of the Bremer River and Warrill Creek are relatively wide in comparison to other systems such as those in the Lockyer Valley. This is probably a reflection of the topography, which is typically flat or gently undulating throughout most of the Bremer river basin. Similar to other alluvial systems in south-east Queensland and north-east NSW, the alluvial aquifer systems in the Bremer river and Warrill creek basins are typically less than 15 m thick.

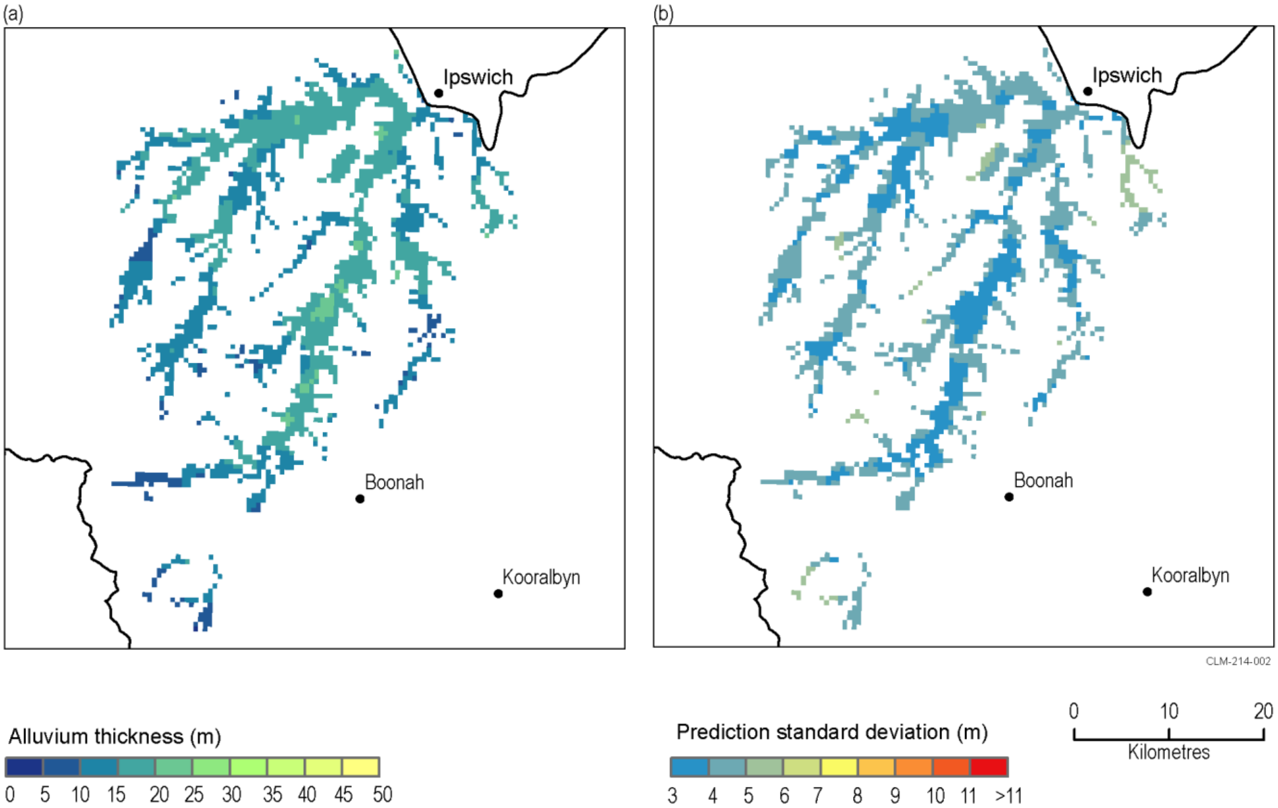


Figure 17 Depth to the base of the Bremer River alluvial system and standard deviation associated with the prediction

Data: Bioregional Assessment Programme (Dataset 29)

Comparison of alluvia within the Clarence-Moreton bioregion

Overall, this analysis indicates that the thickness of the alluvial systems in the Clarence-Moreton bioregion varies within a relatively small margin, whereas the width of the floodplain is highly variable. In effect, in all alluvial systems in the bioregion, the maximum thicknesses that have been observed from bore logs are approximately 30 to 40 m. This is in strong contrast to other alluvial systems further to the west, for example the Condamine River alluvium, which is approximately 130 m thick (Dafny and Silburn, 2014).

Base of basalt horizon

The primary data used to develop the 'base of basalt' horizon (representing the base of the Lamington Volcanics and the Main Range Volcanics) are picks from groundwater bore or exploration well data where the interface between the basalt and the underlying sedimentary bedrock was intersected. As these picks are very sparse in some areas, additional control points were digitised along regular sets of cross-sections to avoid model artefacts and horizon cross-overs.

2.1.2.3.6 Characterisation of the bedrock stratigraphic units in the Clarence-Moreton bioregion

The challenges associated with the development of the sedimentary bedrock formation tops are very different from those related to defining the base of the alluvium and basalts. In contrast to the alluvium-bedrock interface, there are far fewer points where the interfaces between different bedrock units are intersected. As outlined in Section 2.1.2.1.1, stratigraphic information from the deeper stratigraphic bores together with information derived from exploration bores and seismic data are the main sources of information.

In addition to the lack of data points, the considerable geological complexity as influenced by structural features such as different depositional centres and the presence of faults, folds or dykes make this task difficult.

A comparison of a previously developed isopach map of the Walloon Coal Measures (Ingram and Robinson, 1996) with the Walloon Coal Measures thickness observed at some more recently drilled exploration bores (Figure 18) demonstrates that the newly obtained information will result in considerable changes of the isopach maps in some areas. Similarly, other formation tops will change, although most newly drilled exploration bores do not extend beyond the top of the Koukandowie Formation. As a result, while the thickness and geometry of all Clarence-Moreton Basin bedrock units from the youngest formation (Grafton Formation) to the top of the Koukandowie Formation will change, the formation tops of the deeper formations still primarily rely on the same data as presented by O'Brien and Wells (1994) and Ingram and Robinson (1996), complemented by seismic data provided by the NSW Department of Primary Industry. However, it is important to note that where formation boundaries are conformable, the geometry of the contacts between deeper formations is also informed by the geometry of shallower formation boundaries.

The horizons of the tops of the different sedimentary basin stratigraphic units are represented by the well log data and picks from seismic lines aided by the grids provided by Metgasco (Dataset 4) and the NSW Department of Trade and Investment (Dataset 5). Where required, control points were digitised in GoCAD™ (Paradigm Geophysical Pty Ltd, version 2009.4) as additional constraints for each horizon using regular sets of cross-sections to avoid model artefacts and prevent horizon crossings. This was required particularly in regions where only few wells intersect the deepest sedimentary basin stratigraphic units and where no seismic data exist (e.g. Brisbane river basin or at the boundary between the Richmond river basin and the Logan-Albert river basin).

The three-dimensional geological models were then developed using the stratigraphic and structural modeling workflow in SKUA® (Paradigm Geophysical Pty Ltd, version 2014.1) petroleum reservoir engineering software. The following steps taken to characterise the bedrock stratigraphic units in the Clarence-Moreton bioregion are:

- **Assignment of input data to geological horizons**. Objects such as curves that represent the extent of each model unit or formation top picks derived from cross-sections are assigned to each horizon. Following this, the role of each object is defined (e.g. curves representing the extent of model units are defined as non-erosional outlines).
- **Definition of the three-dimensional geological model domain.** The horizontal and vertical extent of the model domain, also referred to as the 'volume of interest' (VOI), is defined during this step. This task is required because it defines the volume which 'seals' the model. The horizontal extent is determined from a polygon that represents the surface water basin boundaries (for the regional models) or the boundary of the Clarence-Moreton bioregion for

the bioregion-wide model. The vertical extent is based on the inferred elevation of the horizons, which will be included in the models.

- **Modelling of horizons.** A surface is fitted to the input data, taking into account the location and extension of the other horizons, the stratigraphic column and the defined relationships between different horizons (e.g. erosional contact versus conformable contact). Horizons are first previewed, and then iteratively improved. This procedure, for example, includes the detection of horizons that are crossing and the computation of the mismatch between the input data and the previewed horizons. After all critical issues are resolved, the horizons are developed.
- **Honouring of well log data.** During this workflow step, the consistency of the built horizons is compared with the well input data. A mismatch table shows the vertical distance between the horizons and the markers. Where the computed mismatch is considerable, this might indicate that there are errors with the well marker, and the original well logs are then revisited. After checking the mismatch table and revisiting the original well logs where required, the horizons are fit to the input well markers.
- **Building the three-dimensional geological model grid.** In the last step of the workflow, the three-dimensional geological grid is built from the horizons representing the stratigraphic units in accordance with the stratigraphic column within the entire VOI.

2.1.2.3.7 Isopach maps, depth to formation top and depth to base of formation

Following the development of the three-dimensional geological models, isopach maps can be developed to illustrate the spatial variability of the thickness of the stratigraphic units. Isopach maps and/or depth to the 'formation top' maps have been presented by O'Brien and Wells (1994) and Ingram and Robinson (1996). However, due to the available new data, particularly from CSG exploration wells, these existing maps do not represent the latest state of knowledge in some areas, as shown by the discrepancy between previously developed isopaches and the thickness indicated by more recent exploration well records (Figure 18).

The three-dimensional geological models developed during this BA will be discussed in detail in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016).

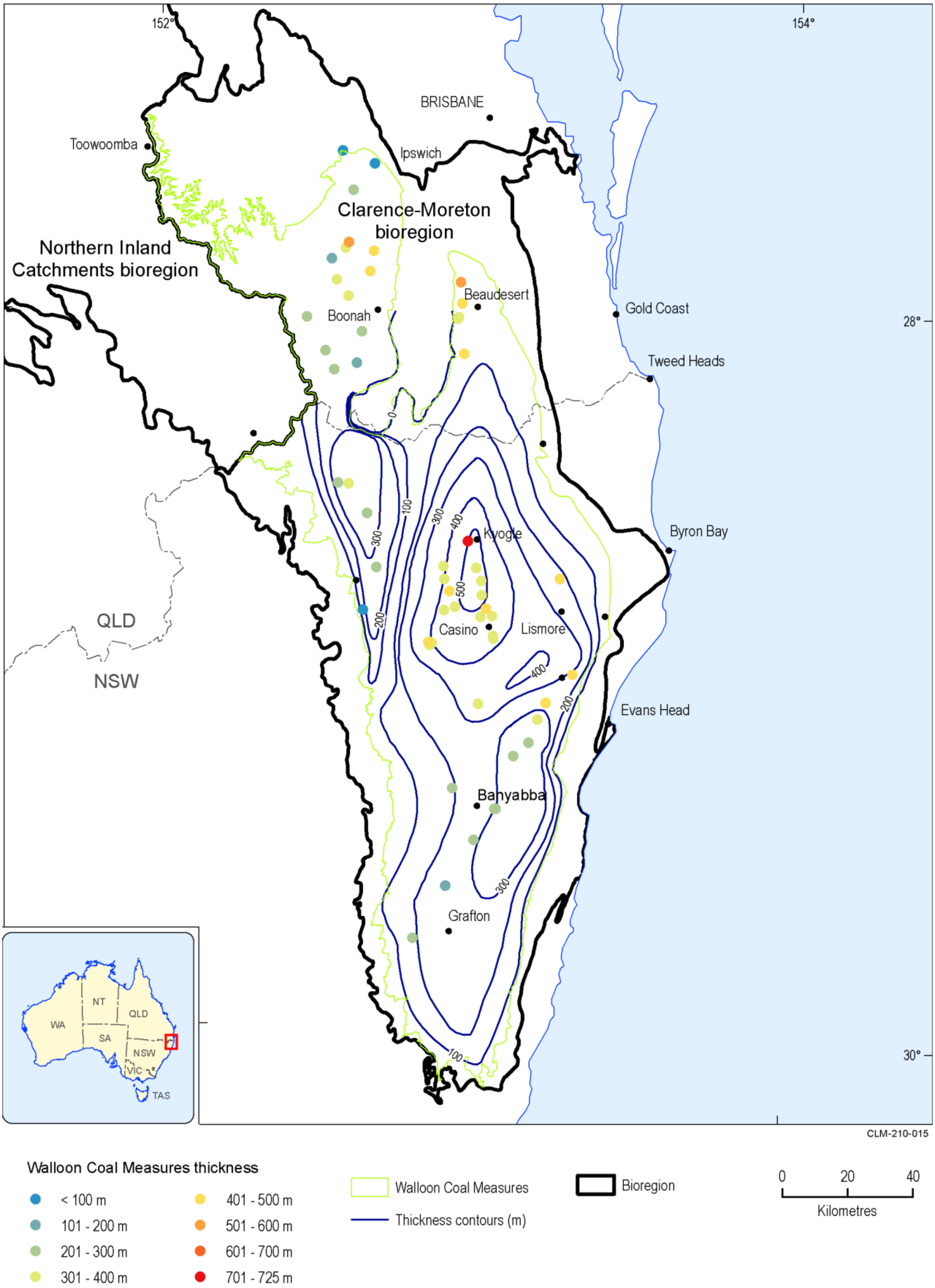


Figure 18 Isopach map showing the thickness of the Walloon Coal Measures

Only wells where the full sequence of the Walloon Coal Measures (i.e. where the formation underneath the Walloon Coal Measures (Koukandowie Formation)) has been intersected are shown.
Data: Bioregional Assessment Programme (Dataset 46), derived from Ingram and Robinson (1996) in relation to the thickness of the Walloon Coal Measures at exploration wells drilled since 1996 (Bioregional Assessment Programme, Dataset 47)

2.1.2.4 Gaps

CSG exploration wells drilled during the past 10 to 15 years together with newly acquired or reprocessed seismic data help considerably in improving understanding of the geometry of the bedrock stratigraphic units in the Clarence-Moreton bioregion.

Despite the new data, knowledge gaps that will translate into uncertainties on the subsurface stratigraphic architecture represented by the three-dimensional geological model still remain. The gaps and uncertainties will be discussed in more detail as part of companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016). Major knowledge gaps include:

- lack of shallow bores in the Clarence river basin, meaning that the interface between the alluvial and underlying bedrock aquifers is poorly constrained
- lack of understanding on fault displacements in many parts of the Clarence-Moreton bioregion
- lack of stratigraphic wells and stratigraphic information in groundwater bores in many areas of the bioregion such as the northern part of the Richmond river basin near the border to Queensland
- lack of understanding of the depth of the Clarence-Moreton Basin underneath the Bremer river basin with no well intersecting the top of the basement underneath the Clarence-Moreton Basin
- lack of understanding of the vertical boundaries between different formations underneath the Main Range Volcanics (particularly at the boundary of the Bremer and the Condamine river basins) and the Lamington Volcanics (particularly near the border of Queensland and NSW)
- poor coverage of high-resolution airborne geophysical imagery.

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Dataset 44 Bioregional Assessment Programme (2014). CLM – Grafton-Piora bedrock Bioregional Assessment Derived Dataset. Viewed 04 March 2016, http://data.bioregionalassessments.gov.au/dataset/59addbea-b8a5-4409-9c36-da260efe81f1.

Dataset 45 Bioregional Assessment Programme (2014) CLM – Orara-Bungawalbin bedrock Bioregional Assessment Derived Dataset. Viewed 04 March 2016, http://data.bioregionalassessments.gov.au/dataset/c5f52b4d-5a3e-4772-97f9-171b875e32dc.

Dataset 46 Bioregional Assessment Programme (2014) CLM - Walloon Coal Measures isopach thickness contours. Bioregional Assessment Derived Dataset. Viewed 04 March 2016, http://data.bioregionalassessments.gov.au/dataset/871fecc0-e7b2-4237-b249-0de112fcfe63.

Dataset 47 Bioregional Assessment Programme (2014) CLM - Walloon Coal Measures thickness well points. Bioregional Assessment Derived Dataset. Viewed 07 March 2016, http://data.bioregionalassessments.gov.au/dataset/13cab8c0-2e28-4000-ae8b-ddd5fa3ab20f.

2.1.3 Hydrogeology and groundwater quality

Summary

This section details various statistical techniques to assess the spatial and/or temporal variability of four hydrogeological datasets: groundwater levels, hydraulic parameters, groundwater quality and allocations (Section 2.1.3.2 and Section 2.1.3.3). The objective of this study is to collate, process and analyse the pre-existing hydrogeological and hydrochemical data to support the development of a conceptual model of causal pathways and a numerical groundwater model in the context of coal mining and coal seam gas (CSG) extraction.

For example, groundwater bores were assigned to major aquifers by comparing their screen intervals to relevant aquifer boundaries. Water levels were standardised to the Australian Height Datum (AHD) using a 1-second DEM to enable contour maps to be generated. The TGUESS approach was adopted to derive transmissivities from pumping tests available in the state databases. Subsequently, hydraulic conductivities were derived from the transmissivities and available bore screen information. The process of aquifer assignment allowed the grouping of available bore data into aquifers. Section 2.1.3.1.5 briefly describes the chloride mass balance method, which was used for estimating groundwater recharge, and presents the resulting recharge estimates for the bioregion.

A brief description of different observation data groups, their sources and their spatial distributions is given in Section 2.1.3.1. Water level time series data analysis is reported in Section 2.1.3.3.1 for a 13-year period (2000 to 2012), with the period 2000 to 2007 representing drought conditions. The period from 2008 to 2012 reflects how groundwater levels have changed following the break of the drought and severe flooding. Mean groundwater levels and depths to groundwater and the associated uncertainties were determined for various aquifers of the Clarence-Moreton bioregion including the alluvial aquifers, the Walloon Coal Measures, the Gatton Sandstone and the Woogaroo Subgroup. Generally, mean water levels and flow directions in the alluvial aquifers follow the topographic gradient. They follow a predominantly north-easterly direction in the Queensland part of the Clarence-Moreton bioregion, and an easterly direction in the NSW part. However, in some areas of the Clarence-Moreton Basin, the groundwater flow direction differs from these patterns, highlighting the complex nature of groundwater dynamics in this sedimentary basin. The temporal variability in water levels was assessed by two statistical metrics: the Mann-Kendall tau statistic and the Sen's slope estimate. The alluvial aquifers exhibited a rapid response to the break of the drought in 2008. In contrast, the response of water levels in the bedrock aquifers to rainfall events and the break of drought was more subdued.

The spatial variability of transmissivities and hydraulic conductivities in the alluvial aquifers are reported in Section 2.1.3.3.2. Alluvial aquifers have higher transmissivities than the bedrock formations. Mean hydraulic conductivity estimates for the Lockyer and the Bremer alluvial aquifer systems were generally higher than for their counterparts in the Logan-Albert and Richmond river alluvia. The hydraulic properties exhibited considerable spatial variability within and across different alluvial systems.

The results of the analysis of water chemistry data are presented in Section 2.1.3.3.3. Multivariate statistical analysis was used to identify patterns within the large datasets, based on groundwater chemistry records from several thousand bores. The multivariate statistical analysis of water chemistry patterns in the sedimentary and volcanic bedrock showed that some of the stratigraphic units have distinct patterns that allow differentiation from other units. However, the analysis also showed that there is considerable variability within the stratigraphic units, suggesting complex processes of groundwater hydrochemical evolution and recharge. The water chemistry analysis of the alluvial aquifer systems in the different regions confirmed that groundwater recharge processes (e.g. stream recharge) and the groundwater hydrochemistry in the underlying bedrock are the major controls on groundwater quality in the alluvial aquifer systems. In the headwaters where alluvial aquifers overlie volcanic bedrock, groundwater quality is generally good, whereas higher salinities are often observed in floodplain environments and particularly at the edge of alluvial aquifer systems

Groundwater recharge, one of the most important input parameters for the groundwater numerical model, was estimated using chloride mass balance for the volcanic and sedimentary bedrock units and the relationship of soil, vegetation and rainfall for the alluvial aquifers.

A gap analysis of the hydrogeological data is provided in Section 2.1.3.4. The data gap analysis highlights that sufficient hydrogeological and hydrochemical data for analysis of temporal patterns only exist for some alluvial aquifer systems (i.e. Lockyer Valley, Bremer river basin and Logan-Albert river basin), whereas limited groundwater monitoring data are available for the Richmond and Clarence river basins. Additionally, the major data gap identified is that very limited information exists relating to groundwater heads, flow directions and hydraulic properties in deeper bedrock formations.

This section provides a comprehensive hydrogeological assessment for the Clarence-Moreton bioregion. It informs the conceptualisation (see companion product 2.3 of the Clarence-Moreton bioregion (Raiber et al., 2016)) that underpins the numerical groundwater model for the Richmond river basin (see companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016)). The relevant hydrogeological datasets sourced from NSW and Queensland state agencies underwent a rigorous process of standardisation to guarantee the integrity of this process and to ensure that they are fit for modelling purposes.

Mean groundwater levels and depths to groundwater and the associated uncertainties were determined for various aquifers of the Clarence-Moreton bioregion including the alluvial aquifers, the Walloon Coal Measures, the Gatton Sandstone and the Woogaroo Subgroup. This information is crucial to the identification of recharge/discharge areas and associated groundwater flow systems, as well as for the development of the groundwater balance for the bioregion. The inferred flow directions provide an insight into groundwater dynamics and aid preliminary identification of areas that can potentially be impacted by CSG and coal mining development. The temporal variability in water levels represented by the Mann-Kendall tau statistic and the Sen’s slope estimate analysis illuminates system dynamics and highlights how shallow groundwater and deep aquifers respond to contrasting climate conditions. Hydraulic parameters provide critical input into the numerical groundwater model – the identification of uncertainties in the hydraulic parameter fields is essential as they can contribute significantly to the overall uncertainty associated with the modelling of impacts.

The multivariate statistical analysis identifies patterns within thousands of groundwater chemistry records that inform critical hydrological processes such as recharge/discharge and the complex processes of groundwater hydrochemical evolution. It also helps to explain how geological structures influence aquifer connectivity and enables the identification of areas where surface water – groundwater interactions occur.

The gap analysis provides an overall assessment of data availability in the three-dimensional space, that is, spatially and across aquifers of various depths. This knowledge constitutes a crucial, first-step input that informs the modelling capability that can be conducted in the Clarence-Moreton bioregion. Informed decisions can then be made on crucial aspects such as model complexity, as represented by the extent of the domain and its temporal and spatial resolution, and the ability to refine a model in certain areas where CSG or coal mining developments are likely to occur.

2.1.3.1 Methods

2.1.3.1.1 Aquifer assignment

Assigning a bore to a specific aquifer is underpinned by the screened interval data and the aquifer boundaries. In many cases, it is impossible to assign the screened interval of a bore to a single aquifer as bores are either screened across different aquifers or there is insufficient information on stratigraphy and screened intervals. The National Groundwater Information System (NGIS) groundwater database (Bureau of Meteorology, Dataset 1) contains only limited stratigraphic data for groundwater bores in the Clarence-Moreton bioregion. Therefore, an independent assessment of the stratigraphy boundary was conducted during the Clarence-Moreton Bioregional Assessment (the Assessment) (as described in Section 2.1.2.2.1). Following this stratigraphic assessment for the Clarence-Moreton bioregion in NSW, and after a quality check of the data from the Queensland groundwater database (Bioregional Assessment Programme, Dataset 2), bores were assigned to aquifers by comparing their screen intervals and depth with aquifer boundary data. Furthermore, a code was used for each bore to indicate the spatial relationship between the source aquifer and screen intervals.

The following steps were followed during the aquifer assignment:

Queensland

- **Determine the boundary of the aquifer of interest.** The ‘Aquifer’ table in the Queensland Department of Natural Resources and Mines (DNRM) database registers aquifers that a bore intersects when it is drilled and records the upper and lower extents of aquifers. This information was used to identify the aquifer boundary at any specific location. When boundary information was missing the ‘Stratigraphy’ table was used to identify aquifer boundaries instead.

- **Determine the screen interval of bores.** The 'Casing' table contains the screen information for most bores in the database. The codes 'PERF' (perforated), 'SCRN' (screen) and 'ENDD' (open end pipe considered as an entry point) in the column 'MATERIAL' indicate water entry locations. The code 'OPEN' indicates that a bore is uncased at some depths; if bores intersect an aquifer, then they are considered as water supply points. These codes were used to find the screen interval of a bore. When multiple screens exist, the bore is assumed to be screened across the entire length of the individual screens.
- **Determine the screen code.** A bore may tap into an aquifer in four ways depending on its screen location in aquifers. Four codes (I, T, B and E; abbreviations are explained in the figure caption of Figure 19) were used to indicate the different spatial relationships of a bore with its targeted aquifer (Figure 19). When screen information is lacking, bores with their lower ends located in an aquifer are assumed to be tapped to that aquifer and were assigned a screen code 'BOI' (Figure 19).

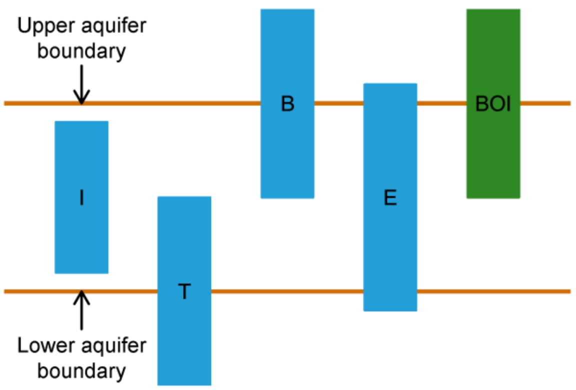

Figure 19 Diagram showing the spatial relationship between aquifer boundaries and screen intervals

(I) the screen interval is within the aquifer; (T) the top of the screen interval is within the aquifer; (B) the bottom of the screen interval is within the aquifer; (E) the bore screen penetrates the entire aquifer; (BOI) there is no screen information in the database, but the bore bottom is located within the aquifer

- **Filter bores for a specific area using a shape file or coordinates.** If only a part of the aquifer is of interest, then the bores can be filtered based on their locations.
- **Cross-check the final datasets against expert knowledge and spatial context of aquifers.** Any errors that remain following extensive data quality checks can be highlighted during data interpretation and visual representation and can subsequently be corrected through an iterative process.

New South Wales

- Assess the boundaries of aquifers as outlined in Section 2.1.2.1.6.
- **Determine the screen intervals of bores.** The screen information was extracted from the 'Construction' table in the Bureau of Meteorology (Dataset 1) groundwater data archive. The keywords 'OPENING' and 'HOLE' were used to calculate screen intervals. For example, for the bores in Table 9, GW102905, GW004084 and GW410337 have screen intervals of 12 to 30 mBGL, 80.7 to 115.7 mBGL and zero to 3.05 mBGL, respectively. The bore depth

information was extracted from the NSW Water Data Transfer Format (WDTF), Hydstra, and the Bureau of Meteorology (Dataset 1) dataset. For bores without depth information in these databases, the bore depth calculations were based on the construction information.

- Filter bores for a specific area using a shape file or coordinates.
- Cross-check the final datasets against expert knowledge, the spatial context of aquifers and the 3D geological model.

Table 9 Sample data to show the algorithm used to determine the screen interval

Work No	Component	Type	From depth (mBGL)	To depth (mBGL)
GW102905	Casing	PVC class 9	0.5	30
GW102905	Hole	Hole	0	30
GW102905	Opening	Slots	12	30
GW004084	Opening	Slots – vertical	100.5	115.7
GW004084	Opening	Slots – vertical	80.7	80.9
GW004084	Casing	Threaded steel	0	61.5
GW004084	Casing	Threaded steel	0.3	152.4
GW410337	Hole	Hole	0	3.05

mBGL refers to metres below ground level
Data: Bureau of Meteorology (Dataset 1)

2.1.3.1.2 Water levels

Queensland

Water level data for the Queensland part of the Clarence-Moreton bioregion were obtained from the DNRM groundwater database (Bioregional Assessment Programme, Dataset 2). The 'water level' information in the database refers to the distance from the natural ground surface or reference point to the water surface in a groundwater bore. When the water level is above a reference point, it has a positive value, otherwise it is negative. If there is no record, then this is indicated by a zero. The 'Elevation' table records the elevation of natural ground surface around a bore or the reference point based on AHD or state datum (STD). When two elevation records for the same bore appeared, the most recent record was used. Thus, the water level represented as AHD is the sum of the water level in the 'Water level' table and the corresponding elevation in the 'Elevation' table. For the data to be deemed useful in the statistical analyses, they needed to be referenced relative to one datum. In this case, the AHD was used. Due to inconsistencies in data (being referenced to AHD, STD, and assumed datum (ASS)) and unknown quality and source of the elevations, the Australian 1-second DEM was used for referencing all elevation data.

New South Wales

Water level data for the NSW part of the Clarence-Moreton bioregion were obtained from the National Groundwater Information System (NGIS) groundwater database (Bureau of Meteorology, Dataset 1). Additionally, nine Metgasco monitoring bores with water level records from 2004 to 2006 were merged into the collated database (Metgasco, 2007). The sign convention for water level records in NSW is opposite to that used in the DNRM database (Bioregional Assessment

Programme, Dataset 2). The water level in the NSW database is represented as the depth of water below the ground surface; a positive value was used for water level below the reference point. Elevations of bores are missing for many bores. To make the converted water level more consistent, all the elevations of bores were derived from the Australian 1-second DEM.

2.1.3.1.3 Hydraulic parameters

The state groundwater databases contain limited pumping test data, which usually include the date and duration of the test, initial water level, pumping rate, and maximum drawdown. The transmissivity of relevant aquifers was estimated based on the pumping test data adopting the TGUESS approach, where transmissivity is estimated from specific capacity based on the Cooper-Jacob approximation to the Theis equation (Bradbury and Rothschild, 1985). Hydraulic conductivity was computed from the derived transmissivity data where screen interval data were available. However, where hydraulic conductivity or transmissivity was available in the original state database, this value was kept as the primary value for the statistical analysis. When multiple hydraulic conductivity or transmissivity records were present, the median was used for the statistical analysis.

2.1.3.1.4 Groundwater quality

Multivariate statistical analyses were used in the Assessment to identify spatial patterns of groundwater chemistry that may be related to processes such as:

- groundwater recharge
- surface water – groundwater connectivity
- aquifer connectivity
- evolution of groundwater within different aquifers along the flow paths.

Piper plots were then used to compare the results of multivariate statistical analysis.

Historical water chemistry data were collated from these tables in the Queensland and NSW groundwater databases:

- ‘Water analysis’ in the DNRM groundwater database (Bioregional Assessment Programme, Dataset 2)
- ‘Groundwater quality’ in the National Groundwater Information System (NGIS) groundwater database (Bureau of Meteorology, Dataset 1).

Data quality validation

Prior to use in multivariate statistical analyses, all water chemistry major ion data used in the Assessment were subjected to standard quality checks such as charge balance calculations. The common exclusion criterion for water chemistry data is a charge balance error (CBE) of ±5% (Freeze and Cherry, 1979). However, due to the poor spatial coverage of sampling points in some parts of the Clarence-Moreton bioregion, and in agreement with other authors (e.g. Guggenmos et al., 2011; Güler et al., 2002; King et al., 2014), a CBE of ±10% was chosen in the Assessment to ensure that only samples with significant charge imbalances were excluded.

Multivariate statistical procedure

Hierarchical Cluster Analysis (HCA) is a multivariate statistical technique that incorporates a combination of any number of user-defined chemical and physical constituents including non-numerical parameters (Güler et al., 2002; Raiber et al., 2012). This method is commonly adopted in groundwater hydrochemical studies to identify certain patterns within a dataset to further understand the physical and chemical processes that underpin groundwater evolution (e.g. Stetzenbach et al., 1999; Güler et al., 2002; Thyne et al., 2004; Daughney and Reeves, 2006; O'Shea and Jankowski, 2006; Cloutier et al., 2008; Menció and Mas-Pla, 2008; Woocay and Walton, 2008; Daughney et al., 2011; Raiber et al., 2012).

The number of variables used in an HCA should be sufficiently large to ensure an accurate depiction of groundwater quality while a representative subset of those variables is sought to reflect the spatial variability of groundwater chemistry and the processes that control it. Nine variables were selected for the HCA of the Clarence-Moreton bioregion, namely, Ca, Mg, Na, K, HCO_3, Cl, SO_4, electrical conductivity and pH. Except for the latter, all variables were log-transformed to ensure that they closely follow a normal distribution.

The HCA presented in this work was carried out using the StatGraphics Centurion software (Manugistics Inc., USA) with two different linkage rules implemented. Firstly, the nearest neighbour linkage rule was used to identify monitoring sites having significantly different hydrochemical signatures compared to other sites (i.e. outliers that were placed as residuals in a separate group). Secondly, the Ward's linkage rule was adopted to generate distinct clusters based on an analysis of variance used to group all non-residuals into separate clusters (i.e. each site in a cluster is more similar to other sites in the same cluster than to any site from a different cluster). The square of the Euclidean distance (E) was used in the HCA as a measure of similarity, which was performed over all variables included in the analysis. In previous studies (e.g. Güler et al., 2002; Daughney and Reeves, 2006; Cloutier et al., 2008; Daughney et al., 2011; Raiber et al., 2012), the outlined transformations of the input data, linkage rules and similarity measure were identified as the most appropriate techniques for classifying hydrochemical data. The outcome of this procedure is a dendrogram (e.g. Cloutier et al., 2008).

HCA is considered to be a semi-objective technique since an element of judgment is still required in the crucial step of determining the appropriate number of clusters that best represents the sample population. In this study, a step-wise procedure was conducted, which involved the visual inspection of the dendrogram (Cloutier et al., 2008; Raiber et al., 2012) and the comparison of centroid concentrations (represented by the median) for the different input variables for different clusters at different separation thresholds. The median was deemed to be a better indicator of central tendency as it is less sensitive to extreme values compared to the mean (Helsel and Hirsch, 2002).

2.1.3.1.5 Groundwater recharge

Groundwater recharge sourced from rainfall is a crucial input into numerical groundwater models. There have not been previous estimates of recharge in the Clarence-Moreton bioregion at a scale suitable for the numerical modelling that will be carried out in this bioregion. Hence, recharge was estimated using the chloride mass balance method (Anderson, 1945). This simple and costeffective method for estimating recharge is the most commonly used method in Australia due to the availability of data that supports it (Crosbie et al., 2010).

The assumptions that underpin the chloride mass balance method may be summarised as follows (Wood, 1999):

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

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

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

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

For the Clarence-Morton bioregion these assumptions have an impact on the ability to estimate recharge. In alluvial areas, additional chloride originating from streams as well as upward flow from deeper aquifers violates the first assumption. Similarly, recharge could not be estimated where the screen was not in the same aquifer as the surface geology due to potential leakage from overlying stratigraphic units. Bores in these areas were excluded from further analysis. There is no evidence of any halite or other significant mineral deposits of chloride so the second assumption is valid. There is not enough information on the temporal characteristics of chloride deposition to determine if the deposition is in steady state, but the effects of land use change could cause some issues. As the area was cleared over a century ago, and the bores used for the chloride mass balance estimation are shallow, it is assumed that the groundwater samples are representative of the current land use. Areas identified as being under irrigation were excluded due to the recycling of chloride which would violate the fourth assumption. Direct runoff from the surface was not accounted for in the recharge estimations; this will lead to an overestimation of recharge. The enhanced deposition of chloride on tall vegetation (trees) was also not accounted for, resulting in an underestimation of recharge. Although neither process has been accounted for, they are expected to be of the same order of magnitude in error (10–30%) in opposing directions. As they could not be quantified they have not been included in the uncertainty in the recharge estimates.

The chloride deposition over the Clarence-Moreton bioregion extracted from the national dataset at a resolution of 0.05° (Leaney et al., 2011) shows that chloride deposition is much greater near the coast compared to inland areas (Figure 20). Within the Clarence-Moreton bioregion, there were approximately 4000 points with chloride data available where it was possible to assign the bore to an aquifer based on the screen location (Figure 19). After excluding those bores in alluvial and confined areas, there were only 374 valid point estimates of recharge which were not uniformly distributed across the spatial extent of the bioregion (Figure 20).

As the numerical model requires a continuous surface of recharge estimates, the point estimates derived from the chloride mass balance needed to be upscaled. It has been shown by Crosbie et al. (2010) that annual average rainfall, soil type and vegetation type are the key determinants of recharge and had been previously used to upscale point estimates (Crosbie et al., 2013). However, the paucity of data in this region led to using annual average rainfall across three different classes of surface geology as co-variates. Those classes were chosen because: Cenozoic volcanics have higher recharge rates for a given rainfall compared to other rock types; Walloon Coal Measures are of interest as their outcrop areas recharge and replenish the aquifer following the cessation of CSG pumping; all other rock types were combined due to a lack of data needed to distinguish between them.

A log-linear relationship was adopted for estimating annual average recharge from annual average rainfall. This is similar to relationships developed previously from both field and modelled data (Crosbie et al., 2013; Crosbie et al., 2010). At the higher end of the rainfall spectrum (especially when extrapolated beyond the range of the field data), the log-normal relationship can predict recharge rates that are much greater than rainfall. To prevent this happening, a global maximum recharge rate equal to half the rainfall has been imposed; this is approximately the highest recharge estimated from the point scale chloride mass balance estimates. As the chloride mass balance method was not appropriate for alluvial areas, empirical relationships developed from historical field data to predict recharge using average annual rainfall, soil clay content and vegetation were used (Wohling et al., 2012).

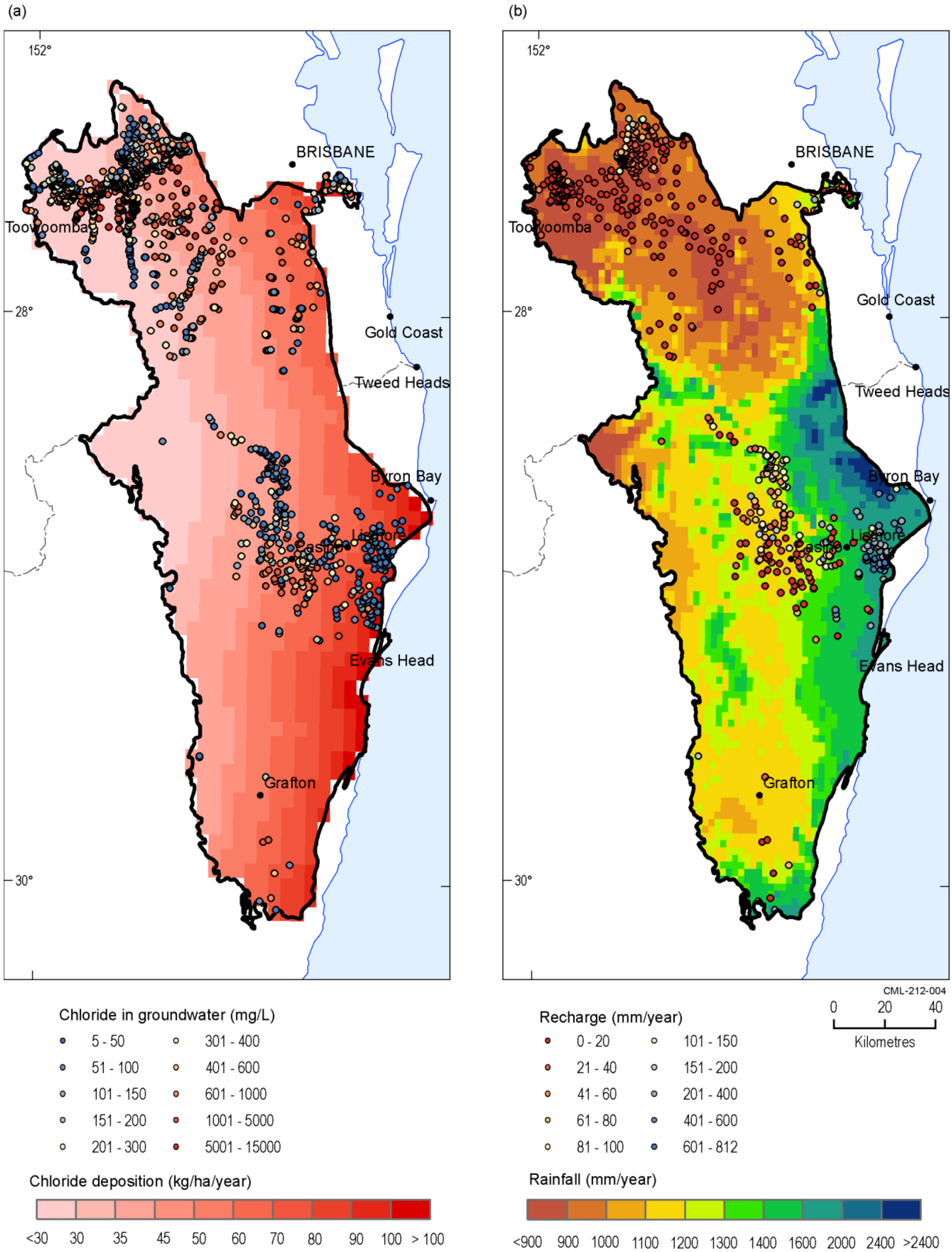

Figure 20 Inputs into the chloride mass balance method

Left panel (a) showing the chloride deposition and the chloride concentration of the groundwater over the surface geology type and the right panel (b) showing the annual average rainfall and the point estimates of recharge (excluding points on alluvium)
Data: Bioregional Assessment Programme (Dataset 2)

2.1.3.2 Observed data

The observed data for the Clarence-Moreton bioregion are mainly from the Queensland and NSW state groundwater databases (Bioregional Assessment Programme, Dataset 2; Bureau of Meteorology, Dataset 1; NSW Hydstra and NSW WDTF) collected by the Bureau of Meteorology. As data collection ceased in November 2013, data received after November 2013 were not included in the analysis. Only bores with enough data to determine screen intervals or bore depth were used in the analysis (Table 10) as these data are necessary to assign a bore to particular aquifers. In the absence of bore screen data, the bore was assigned to an aquifer based on the depth of the bore if this information was deemed reliable and plausible. Seven screen codes are used to indicate different bores in terms of their spatial relationship with a particular aquifer. They are:

- **I**: bores with screen intervals inside the aquifer
- **T**: bores with a screen top inside the aquifer
- **B**: bores with a screen bottom within the aquifer
- **E**: bores with screen intervals penetrating the entire aquifer
- **BOI**: bores with their bottom inside the aquifer although without screen information in the database
- **DS**: aquifer assignment for a bore sourced directly from the state database where the bore is only open to a single aquifer
- **DM**: aquifer assignment for a bore sourced directly from the state database where the bore is screened to multiple aquifers.

The alluvium, Main Range / Lamington Volcanics and Woogaroo Subgroup represent the three most targeted aquifers with 3536, 921 and 868 associated bores, respectively. The mean of bore depths is less than 50 m and the 90th percentile of bore depth is around 120 m (Figure 21). Therefore, most bores in the Clarence-Moreton bioregion are relatively shallow with respect to the basin basement depth (2–4 km). Most bores are screened to either the alluvium or the outcrops of underlying bedrock aquifers. The shallow reach of bedrock bores is also demonstrated by their spatial distribution along the aquifer boundary. Figure 22 to Figure 28 display the spatial distribution of bores with construction information in major aquifers.

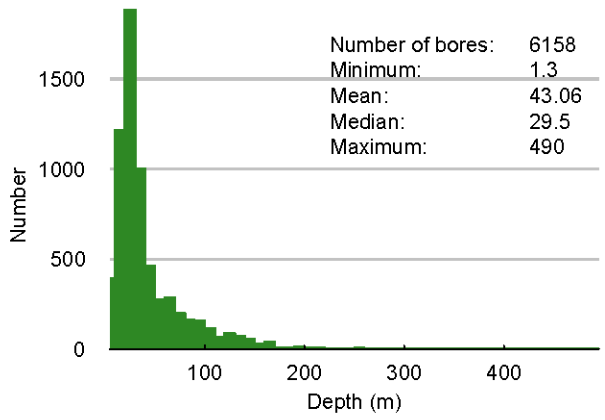

Figure 21 Histogram showing the distribution of bore depths in the Clarence-Moreton bioregion

The inset shows the corresponding statistical summary. Three bores RN22500, RN75903 and RN124727, with respective depths of 1202 m, 805 m and 518 m, have been excluded from the plot for increased figure resolution.
Data: Bureau of Meteorology (Dataset 1), Queensland Department of Natural Resources and Mines (Dataset 3)

Table 10 Number of bores with screen and/or depth information grouped by aquifers

The depth column presents the depth range of bores associated with a specific aquifer. Bores with different screen codes have been counted separately.

Major stratigraphic unit	Number of bores: I	Number of bores: T	Number of bores: B	Number of bores: E	Number of bores: BOI	Number of bores: DS	Number of bores: DM	Total	Depth range (m)
Alluvium	568	260	30	173	89	2380	36	3536	1.3–45
Main Range / Lamington Volcanics	610	75	35	126	0	74	1	921	3.5–186
Grafton Formation: Rapville Member	75	2	19	25	0	0	0	121	9.8–168
Grafton Formation: Piora Member	134	11	10	31	0	0	0	186	9.1–490
Orara Formation: Bungawalbin Member	13	0	1	3	0	0	0	17	16–111
Orara Formation: Kangaroo Creek Sandstone Member	23	0	3	5	0	0	0	31	10.3–97
Walloon Coal Measures	70	3	7	17	1	243	12	353	3.7–518
Marburg Subgroup (undifferentiated)	0	0	0	1	0	40	6	47	14–261
Marburg Subgroup: Koukandowie Formation	30	10	1	3	0	116	8	168	9.1–305
Marburg Subgroup: Gatton Sandstone	50	22	2	58	5	284	43	464	4–432.9
Woogaroo Subgroup	36	10	11	66	2	704	39	868	4.5–1202.7

Screen codes are: (I) bores with screen intervals inside the aquifer; (T) bores with a screen top inside the aquifer; (B) bores with a screen bottom within the aquifer; (E) bores with screen intervals penetrating the entire aquifer; (BOI) bores with their bottom inside the aquifer although without screen information in the database; (DS) aquifer assignment for a bore sourced directly from the state database where the bore is only open to a single aquifer; (DM) aquifer assignment for a bore sourced directly from the state database where the bore is screened to multiple aquifers.
Data: Bureau of Meteorology (Dataset 1), Queensland Department of Natural Resources and Mines (Dataset 3)

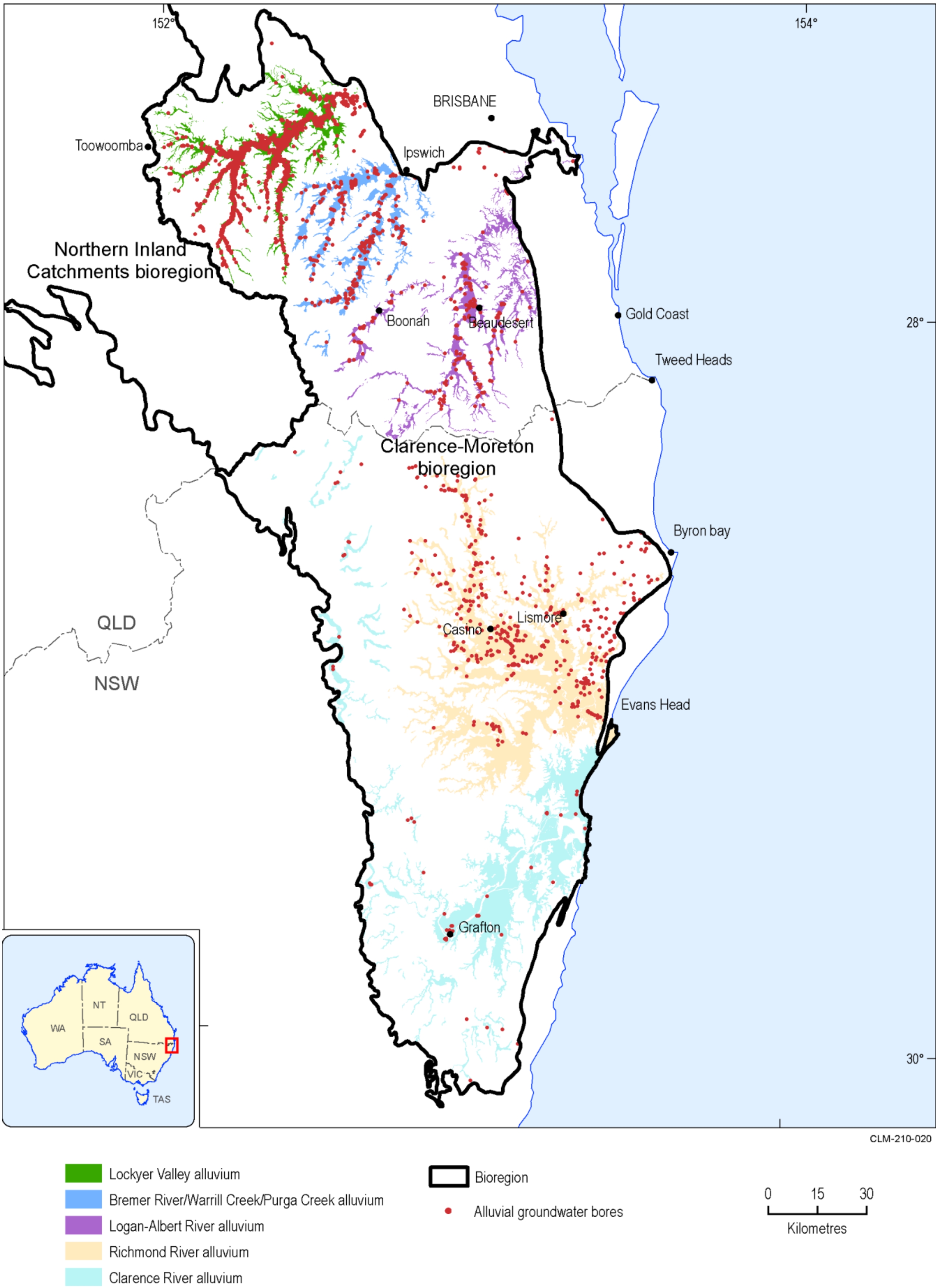

Figure 22 Spatial distribution of bores with construction information in the alluvial aquifers

Data: Bioregional Assessment Programme (Dataset 4)

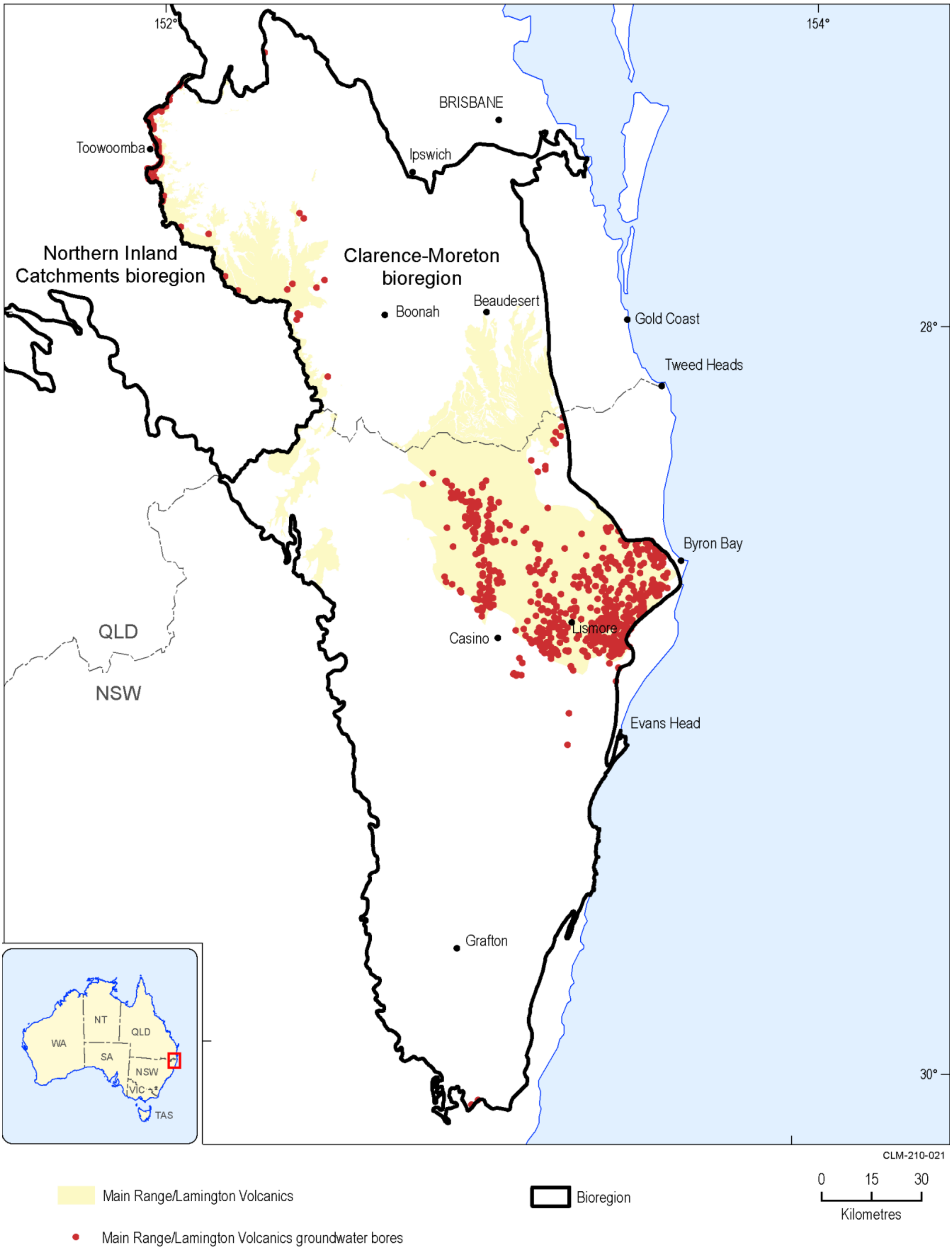

Figure 23 Spatial distribution of bores with construction information in the Main Range / Lamington Volcanics

Data: Bioregional Assessment Programme (Dataset 4)

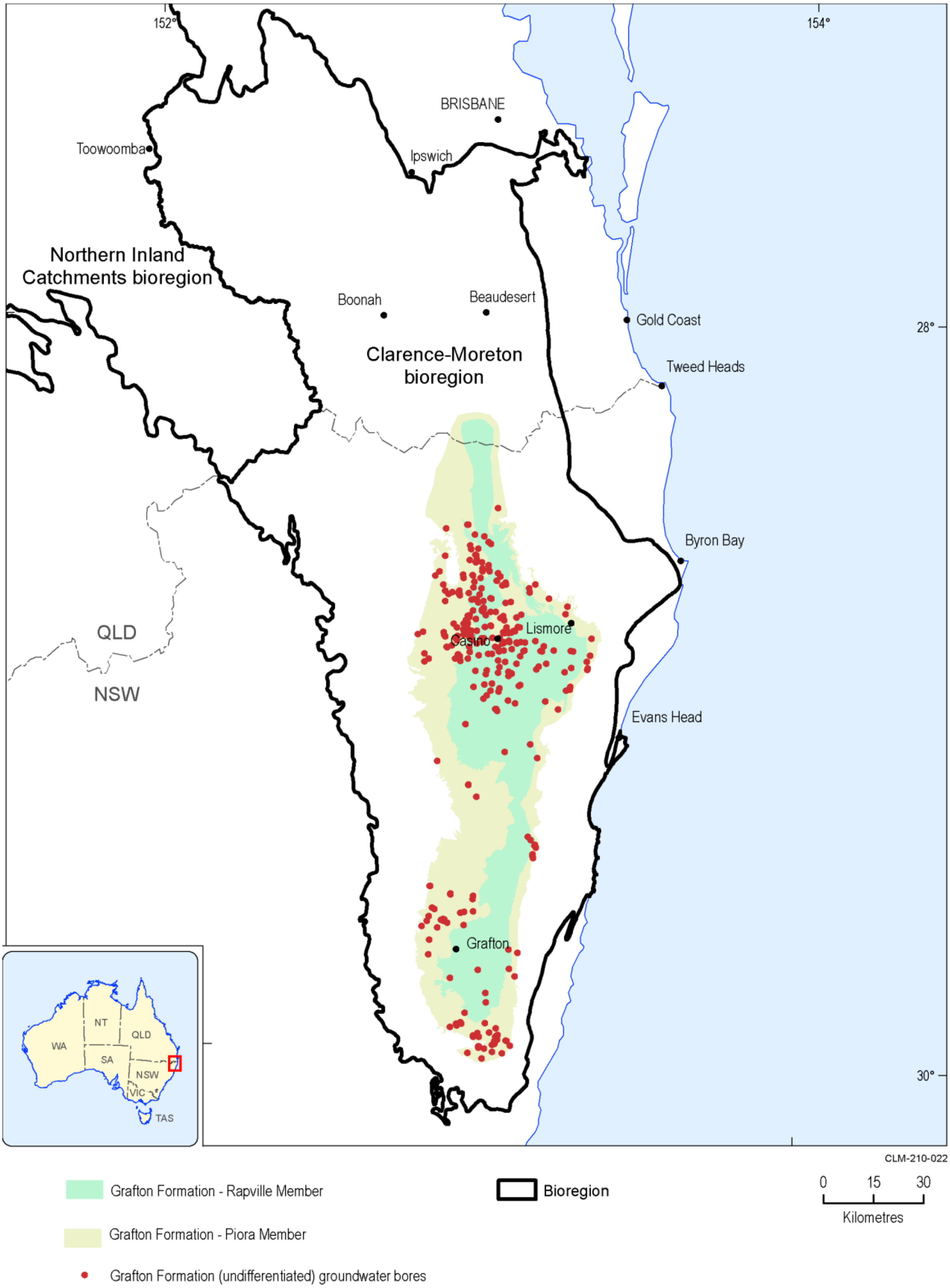

Figure 24 Spatial distribution of bores with construction information in the Grafton Formation

The presence of Rapville Member and Piora Member is mainly limited to NSW.
Data: Bioregional Assessment Programme (Dataset 4)

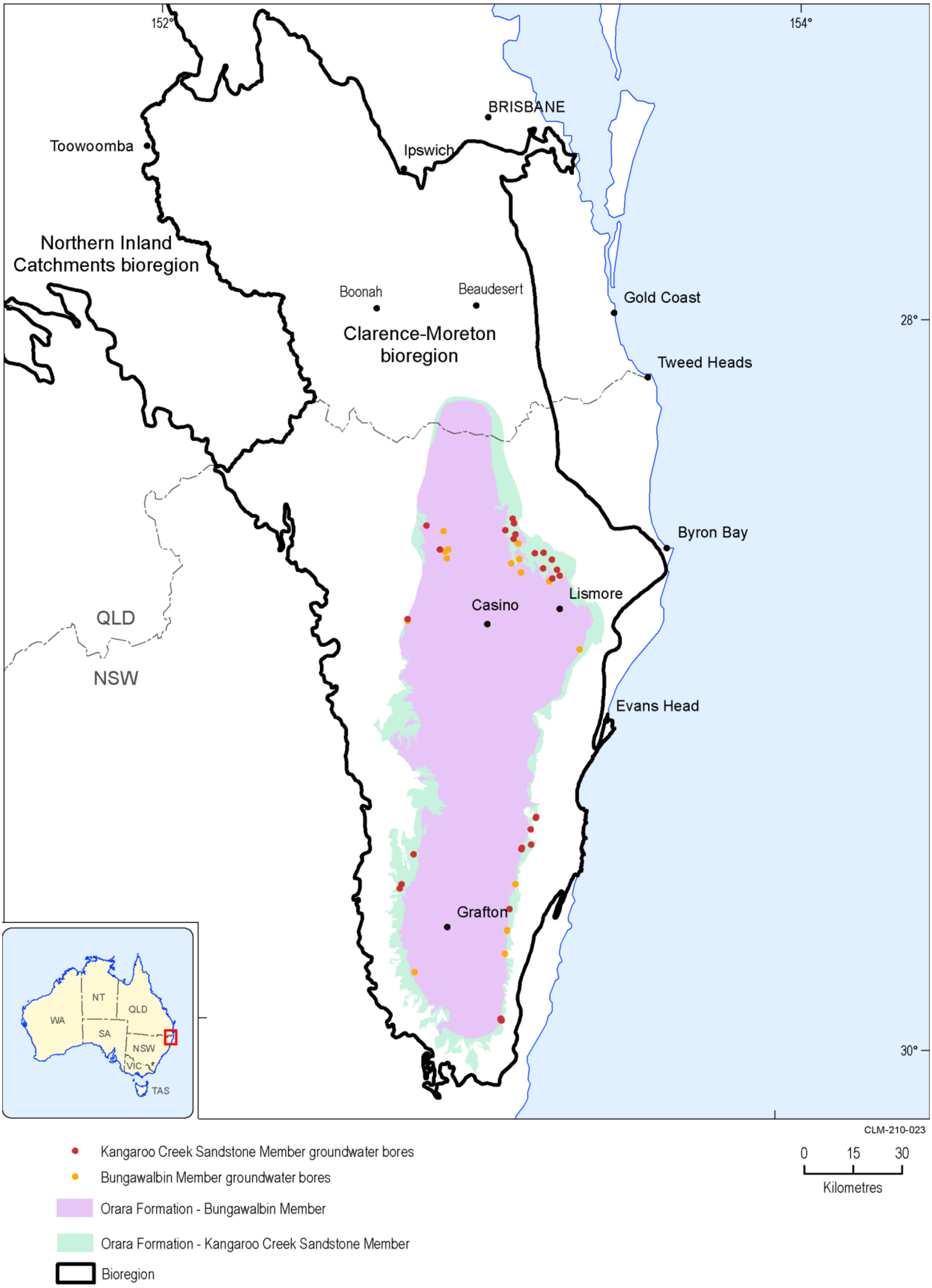

Figure 25 Spatial distribution of bores with construction information in the Orara Formation

This formation is mainly present in NSW.
Data: Bioregional Assessment Programme (Dataset 4)

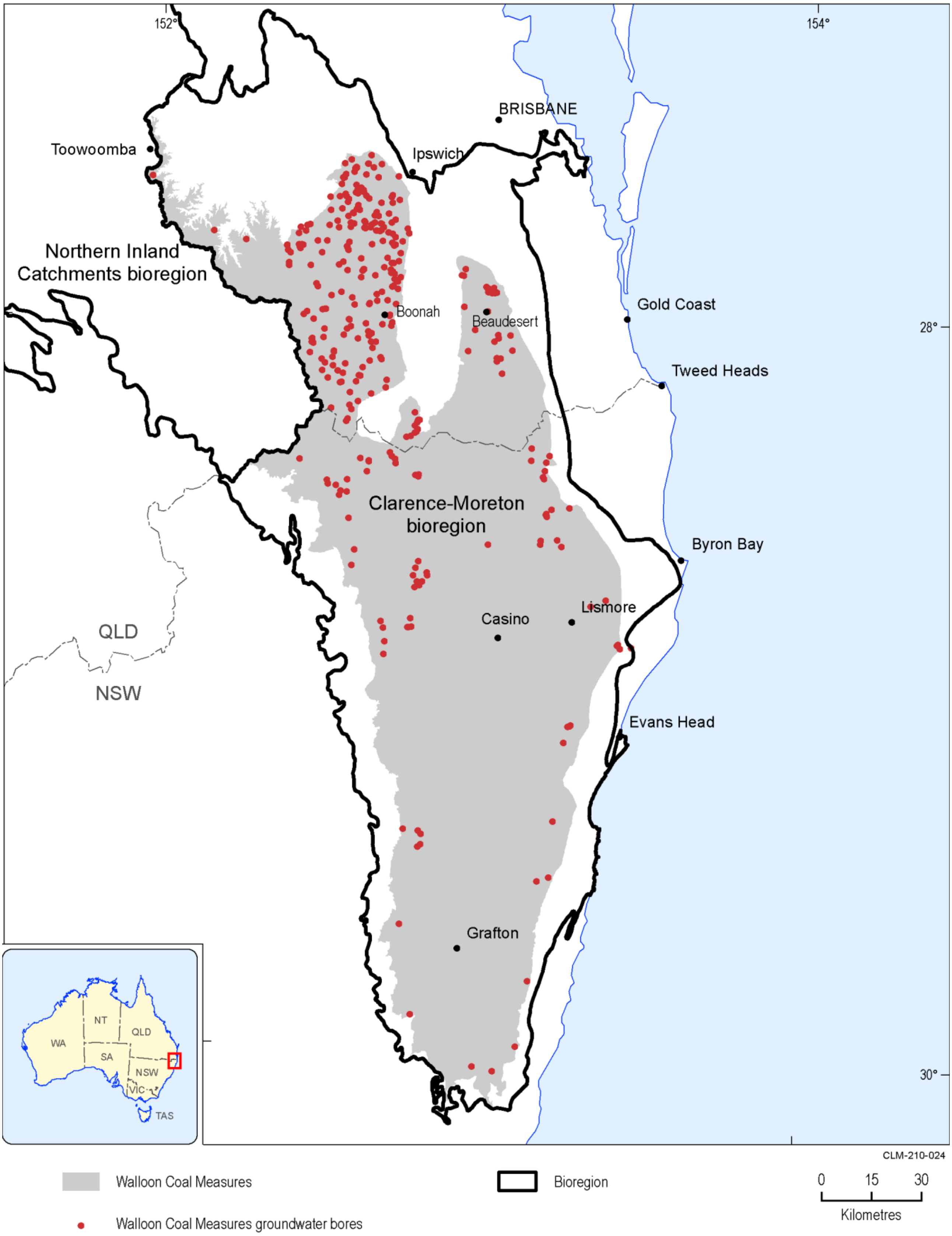

Figure 26 Spatial distribution of bores with construction information in the Walloon Coal Measures

Data: Bioregional Assessment Programme (Dataset 4)

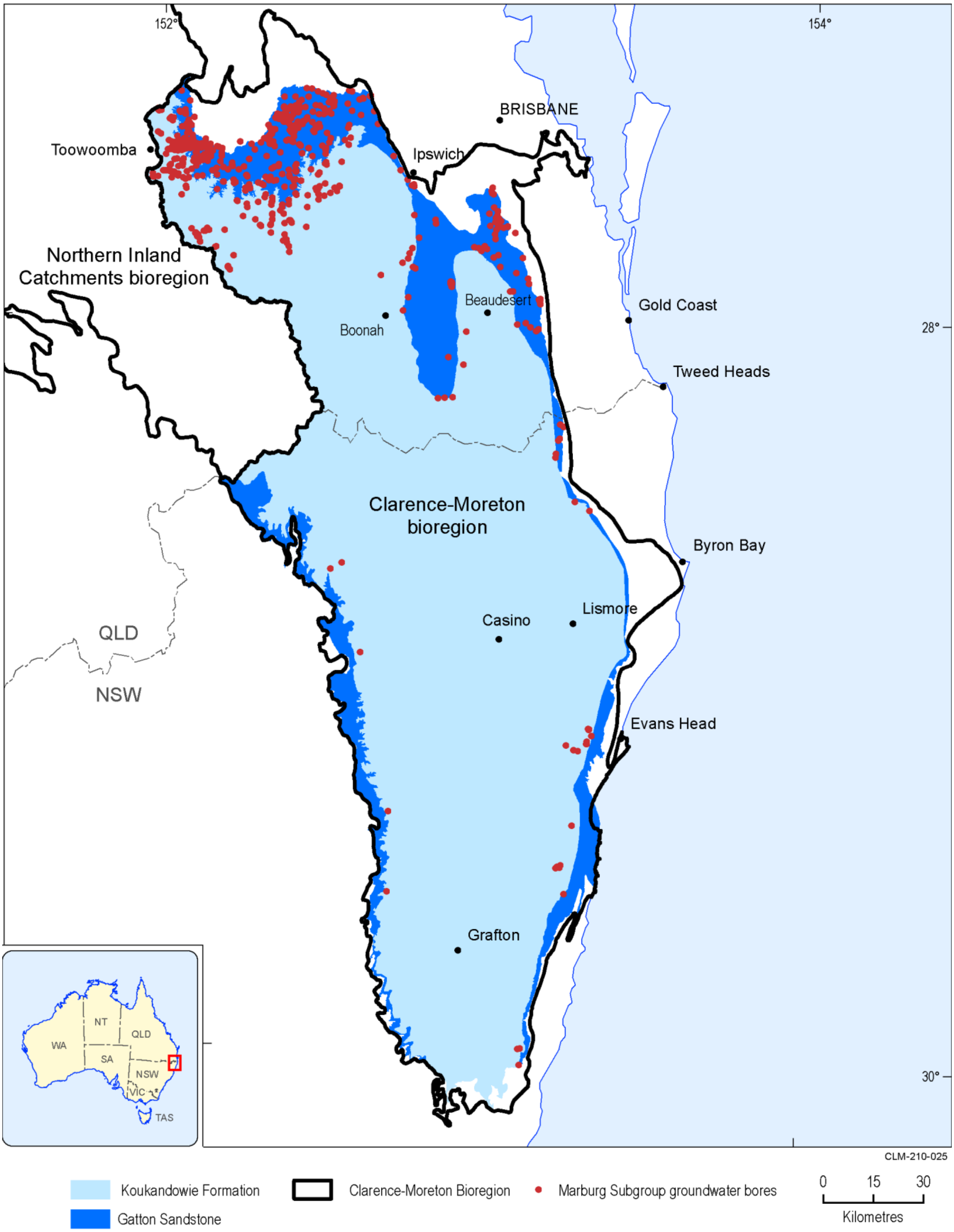

Figure 27 Spatial distribution of bores with construction information in the Marburg Subgroup

Data: Bioregional Assessment Programme (Dataset 4)

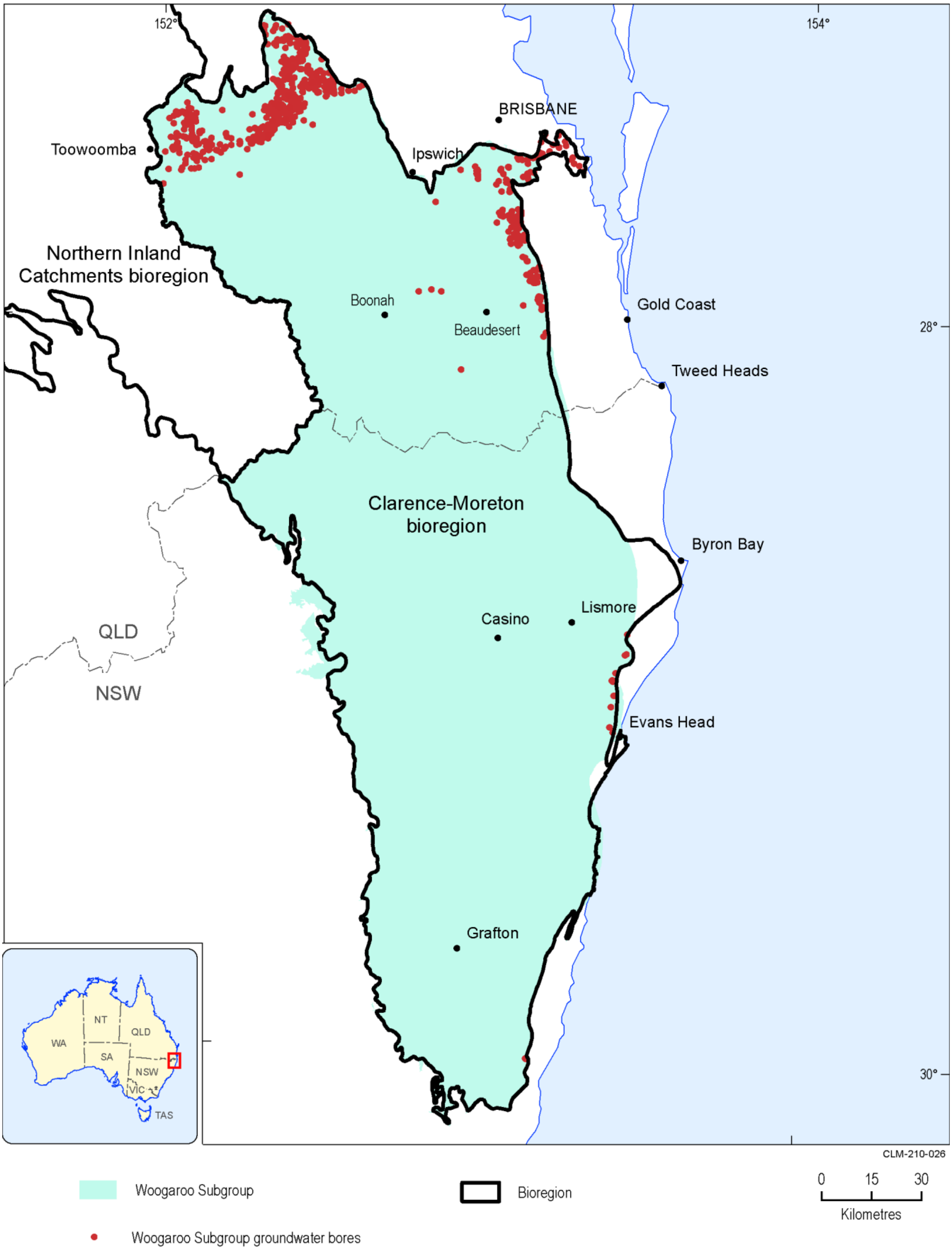

Figure 28 Spatial distribution of bores with construction information in the Woogaroo Subgroup

Data: Bioregional Assessment Programme (Dataset 4)

2.1.3.2.1 Groundwater levels

A summary of the measured groundwater level data used in this analysis is in Table 11. There are more observed data for Queensland than for NSW, and 94.5% of the records are from alluvial bores. Two histograms show the temporal distribution of the water level data (Figure 29 and Figure 30). In Queensland, most measurements were conducted between 1995 and 2012. However, there are two clusters of records for NSW: (i) between 1975 and 1985, and (ii) between 2000 and 2008. The groundwater level data (in metres with respect to AHD) were derived from groundwater depth measurements (in metres below ground surface) in the state databases together with the Australian 1-second DEM data.

Table 11 Summary of groundwater level records for bores in the Clarence-Moreton bioregion

Bores with different screen codes have been counted separately.

Major stratigraphic unit	Number of records: I	Number of records: T	Number of records: B	Number of records: E	Number of records: BOI	Number of records: DS	Number of records: DM	Total	Time period
Alluvium	8,123	3,778	42	658	8,930	138,600	911	161,042	1901–2013
Main Range / Lamington Volcanics	260	4	165	45	0	183	1	658	1962–2013
Grafton Formation: Rapville Member	112	0	48	21	0	0	0	181	1974–1987
Grafton Formation: Piora Member	0	0	0	0	0	0	0	0	NA
Orara Formation: Bungawalbin Member	0	0	0	0	0	0	0	0	NA
Orara Formation: Kangaroo Creek Sandstone Member	0	0	0	0	0	0	0	0	NA
Walloon Coal Measures	3	0	0	0	1	1,225	8	1,237	1988–2013
Marburg Subgroup (undifferentiated)	2	14	1	45	188	3,331	302	3,883	1960–2013
Marburg Subgroup: Koukandowie Formation	0	0	0	0	0	323	593	916	1992–2013
Marburg Subgroup: Gatton Sandstone	0	370	0	0	0	768	28	1,166	1977–2013
Woogaroo Subgroup	1	0	28	40	0	1,270	21	1,360	1900–2013

NA = data not available

Screen codes are: (I) bores with screen intervals inside the aquifer; (T) bores with a screen top inside the aquifer; (B) bores with a screen bottom within the aquifer; (E) bores with screen intervals penetrating the entire aquifer; (BOI) bores with their bottom inside the aquifer although without screen information in the database; (DS) aquifer assignment for a bore sourced directly from the state database where the bore is only open to a single aquifer; (DM) aquifer assignment for a bore sourced directly from the state database where the bore is screened to multiple aquifers.

Data: Bioregional Assessment Programme (Dataset 4)

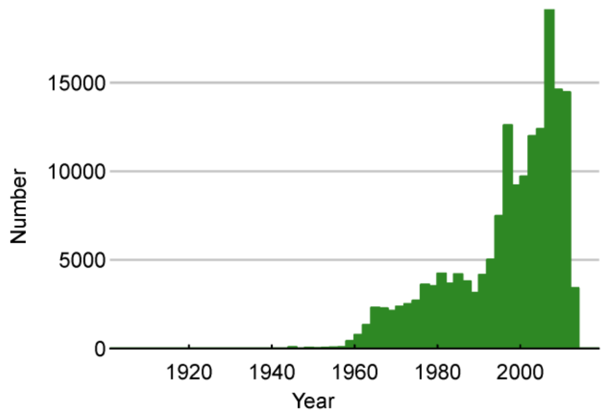

Figure 29 Histogram showing the temporal distribution of water level data in the in the Queensland part of the Clarence-Moreton bioregion

Data: Bioregional Assessment Programme (Dataset 5)

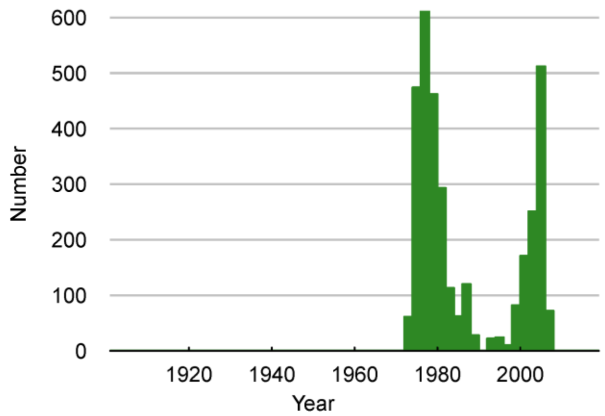

Figure 30 Histogram showing the temporal distribution of water level data in the NSW part of the Clarence-Moreton bioregion

Data: Bioregional Assessment Programme (Dataset 6)

2.1.3.2.2 Hydraulic conductivity

Most records in the pumping test database do not have an entry for hydraulic conductivity. The hydraulic conductivity was derived from the pumping test data by a two-step method to support the groundwater modelling: (i) transmissivity was estimated from the original test readings using the TGUESS approach and (ii) hydraulic conductivity was calculated based on the estimated transmissivity and the extracted screen information. The estimated hydraulic conductivity was mainly available for the alluvium and volcanics and varies across a range of six orders of magnitude (Table 12).

Table 12 Summary of hydraulic conductivity data for bores in the Clarence-Moreton bioregion

Bores with different screen codes have been counted separately.

Major stratigraphic unit	Number of bores: I	Number of bores: T	Number of bores: B	Number of bores: E	Number of bores: BOI	Number of bores: DS	Number of bores: DM	Total	Hydraulic conductivity range (m/day)
Alluvium	107	21	1	5	19	40	0	193	0.090–1499.680
Main Range / Lamington Volcanics	25	1	7	7	0	1	0	41	0.079–152.02
Grafton Formation: Rapville Member	4	0	1	1	0	0	0	6	3.841–75.765
Grafton Formation: Piora Member	5	0	0	0	0	0	0	5	0.213–25.900
Orara Formation: Bungawalbin Member	0	0	0	0	0	0	0	0	NA
Orara Formation: Kangaroo Creek Sandstone Member	0	0	0	0	0	0	0	0	NA
Walloon Coal Measures	5	1	0	1	0	0	0	7	0.486–17.220
Marburg Subgroup (undifferentiated)	2	1	0	3	0	2	0	8	0.027–5.752
Marburg Subgroup: Koukandowie Formation	0	0	0	0	0	NA	NA	0	NA
Marburg Subgroup: Gatton Sandstone	1	0	0	0	0	1	0	2	1.099–4.918
Woogaroo Subgroup	1	0	2	4	0	4	0	11	0.008–23.857

NA = data not available

Screen codes are: (I) bores with screen intervals inside the aquifer; (T) bores with a screen top inside the aquifer; (B) bores with a screen bottom within the aquifer; (E) bores with screen intervals penetrating the entire aquifer; (BOI) bores with their bottom inside the aquifer although without screen information in the database; (DS) aquifer assignment for a bore sourced directly from the state database where the bore is only open to a single aquifer; (DM) aquifer assignment for a bore sourced directly from the state database where the bore is screened to multiple aquifers.

Data: Bioregional Assessment Programme (Dataset 8, Dataset 9, Dataset 17)

2.1.3.2.3 Water quality

The observed water chemistry and quality data for the Clarence-Moreton bioregion are sourced primarily from the Queensland and NSW state groundwater databases.

In the Queensland database, 5854 water chemistry sampling records exist for the Clarence-Moreton bioregion, with the earliest sampling record dating back to 1919. Each record relates to an individual sampling event, conducted on 1 of 2509 bores. The breadth of bore data is variable. Multiple measurements (time series data) exist for some bores: 320 bores within the Clarence-

Moreton bioregion in Queensland have more than five water chemistry records, and one bore in the Lockyer Valley has been sampled 18 times for water chemistry. In contrast, only very few groundwater bores with multiple water chemistry records exist in the Clarence-Moreton bioregion in NSW.

The overall quality of the chemistry data is highly variable. For example, potassium was generally not measured in water chemistry analyses prior to 1975. Additionally, CBE, which are considered to be an indicator of the data quality of major ion analyses, are also highly variable. Due to quality concerns with older water chemistry records, only water chemistry records collected after 1980 were used.

After an extensive screening process, 3183 out of a total of 5854 individual sampling records (corresponding to 54%) were considered suitable for multivariate statistical analysis in the Clarence-Moreton bioregion in Queensland. Most (66%) are samples collected from the alluvial aquifers in the Lockyer Valley, the Warrill creek catchment and Bremer and Logan-Albert river basins (Table 13). The bedrock stratigraphic unit with the largest number of water chemistry sampling records is the Woogaroo Subgroup (approximately 5% of all sampling records), followed by the Gatton Sandstone (the lower member of the Marburg Subgroup).

Table 13 Number of water chemistry records for the Clarence-Moreton bioregion in the Queensland and New South Wales databases that meet the quality requirements for the multivariate statistical analysis

Major stratigraphic unit	Number of water chemistry records: Queensland	Number of water chemistry records: NSW
Alluvium	2113	276
Neogene Volcanics: Main Range Volcanics	34	0
Neogene Volcanics: Lamington Volcanics	0	121
Grafton Formation: Rapville Member	NP*	27
Grafton Formation: Piora Member	NP*	19
Orara Formation: Bungawalbin Member	NP*	2
Orara Formation Kangaroo Creek Sandstone Member	NP*	0
Walloon Coal Measures	83	10
Marburg Subgroup (undifferentiated)	23	0
Marburg Subgroup: Koukandowie Formation	12	0
Marburg Subgroup: Gatton Sandstone	161	4
Woogaroo Subgroup	190	0
Aquifer unknown	567	111
Total water chemistry records	5854	1201
Acceptable water chemistry records (number and percentage of total)	3183 (54%)	570 (47%)

NP* denotes stratigraphic units that are not present in Queensland.
Data: Bioregional Assessment Programme (Dataset 10, Dataset 19)

The NGIS groundwater database (Bureau of Meteorology, Dataset 1) contains 1201 water chemistry sampling records from 657 groundwater bores across the Clarence-Moreton bioregion in NSW. After quality checks (including calculation of CBE, and assessment of bore construction details), only 570 of these records (approximately 47%) were considered suitable for multivariate statistics (Table 13). The hydrostratigraphic units in which the bores in the Clarence-Moreton bioregion in NSW are screened are only known for nine bores, therefore the attribution to hydrostratigraphic units (Table 13) is based on our own assessment as outlined in Section 2.1.3.1.1. If major ions or other parameters were missing, but electrical conductivity measurements existed, then these measurements were used for the assessment of the spatial patterns of electrical conductivity.

2.1.3.2.4 Groundwater recharge

Figure 31 shows the log-linear relationship for estimating annual average recharge from annual average rainfall. This shows that for a given rainfall amount the Cenozoic volcanics have higher recharge than the Walloon Coal Measures; the other surface geology types have a considerable spread around the line of best fit. Figure 32 shows the upscaled annual average recharge with the highest recharge in the eastern part of the bioregion where rainfall is highest on the Cenozoic volcanics and alluvium; recharge is greatly reduced inland. The average areal recharge across the entire bioregion was estimated to be 116 mm/year.

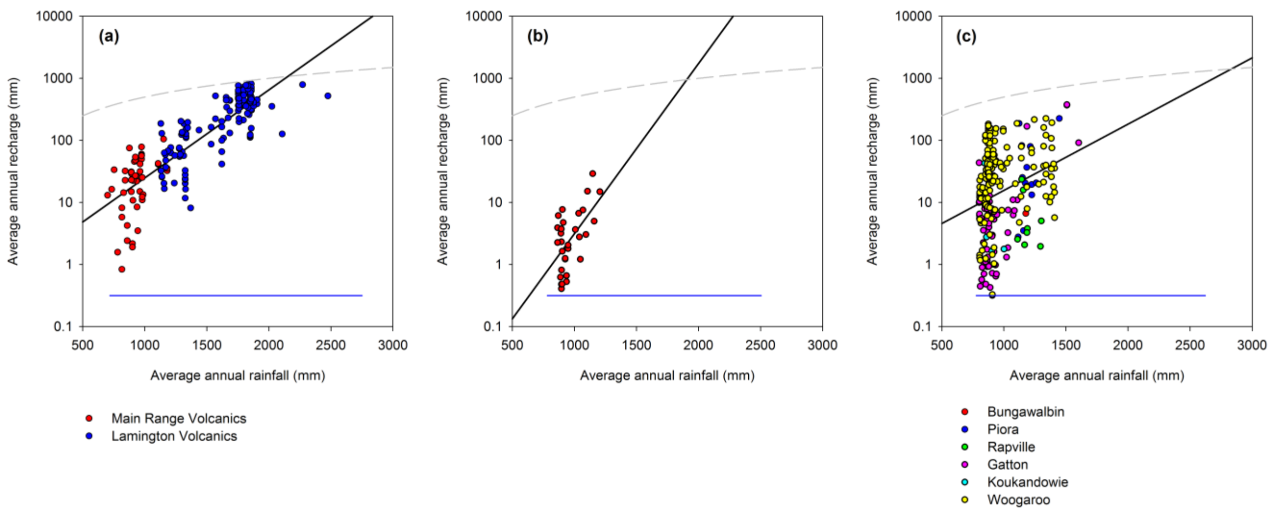

Figure 31 Relationship between annual average rainfall and annual average recharge for three groupings of surface geology

The black line is the line of best fit through the data points, the dashed grey line is recharge as half of rainfall and the blue line is the range of annual average rainfall within the bioregion for the surface geology class.
Data: Bioregional Assessment Programme (Dataset 2)

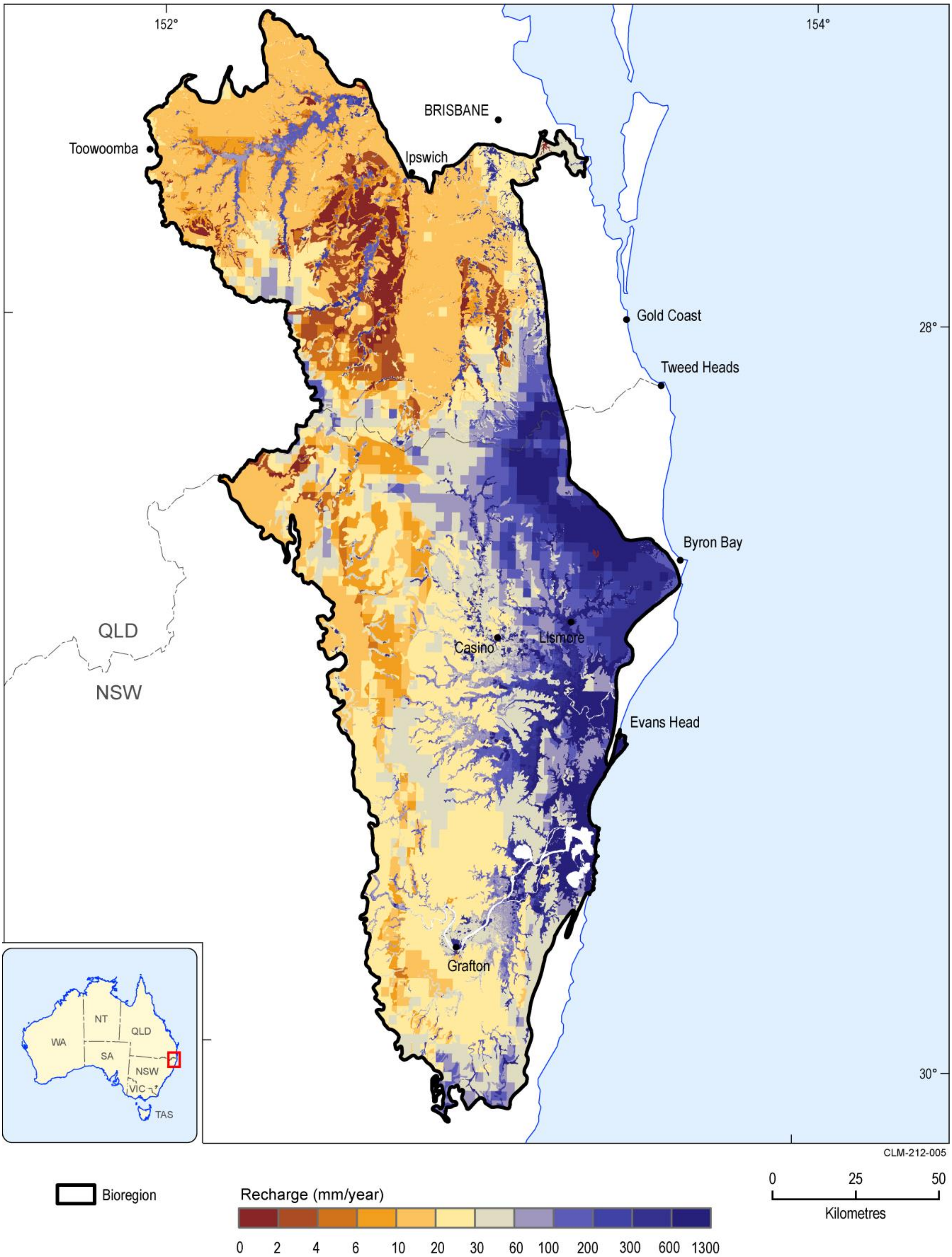

Figure 32 Upscaled estimates of annual average recharge over the bioregion

Data: Bioregional Assessment Programme (Dataset 2)

The deterministic estimate of recharge shown in Figure 32 was used as the base recharge in the numerical groundwater model. However, an estimate of the uncertainty around this deterministic estimate is necessary for carrying out the sensitivity and uncertainty analyses. The sources of uncertainty that can be quantified are the chloride deposition and the regression function. The chloride deposition shown in Figure 33 is the best estimate reported by Leaney et al. (2011), who also produced gridded estimates of the mean, standard deviation and skewness from 1000 equally well-calibrated replicates. These gridded datasets were used to stochastically generate ten alternate chloride deposition grids. Each of these ten deposition grids were used to generate the regression equations between annual average rainfall and annual average recharge using bootstrapping with replacement for ten replicates. This provided 100 replicate regression equations to use in up-scaling (Figure 33).

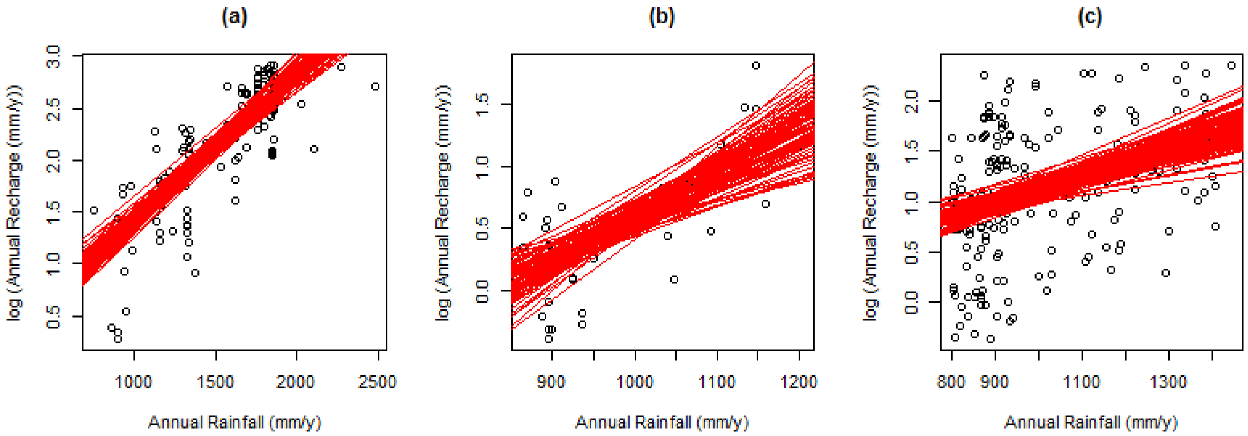

Figure 33 Relationship between annual average rainfall and annual average recharge considering the uncertainty in the chloride deposition and the regression equation for the a) Cenozoic Volcanics (Lamington Volcanics and Main Range Volcanics), b) Walloon Coal Measures and c) all other sedimentary bedrock formations undifferentiated

Each red line is 1 of 100 replicates of the regression equation between annual average rainfall and average annual recharge.
Data: Bioregional Assessment Programme (Dataset 2)

There is a higher uncertainty in the relationships developed for the Walloon Coal Measures compared to the other two classes (Figure 33) due to the lack of data and the spread in the point estimates of recharge. This is then transferred through to the upscaled estimates of recharge (Figure 34). The areally averaged recharge for the 50th percentile of the 100 replicates is 126 mm/year with the 5th and 95th percentiles being 107 and 154 mm/year, respectively.

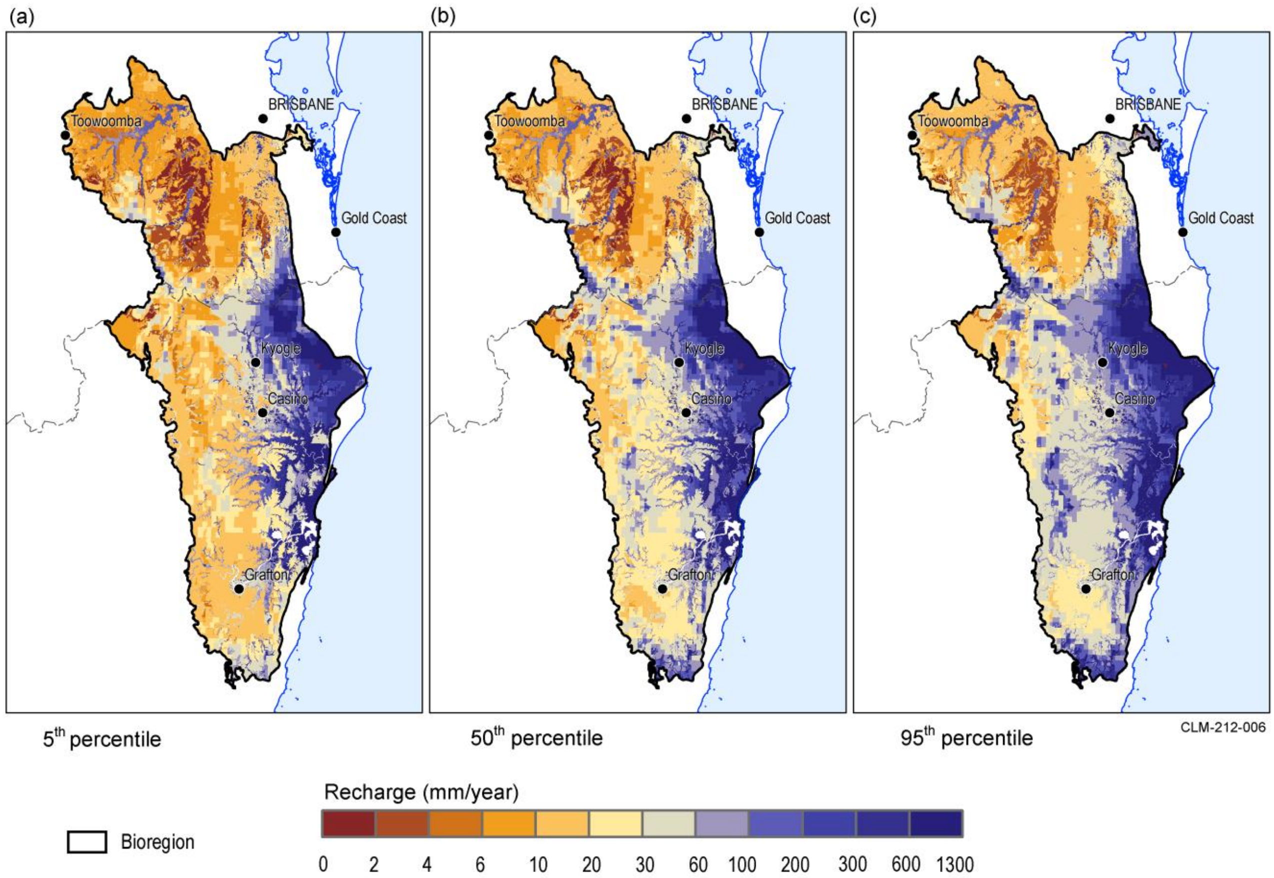

Figure 34 Uncertainty in the recharge estimation across the Clarence-Moreton bioregion displayed as the 5th, 50th and 95th percentiles from 100 replicates

Data: Bioregional Assessment Programme (Dataset 2)

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

2.1.3.2.5 Allocation

Groundwater allocation is discussed in the companion product 1.5 for the Clarence-Moreton bioregion (McJannet et al., 2015).

2.1.3.3 Statistical analysis and interpolation

2.1.3.3.1 Groundwater levels

The statistical analysis covers two periods: a period representing drought conditions (from 2000 to 2007) and a period during which the drought broke (from 2008 to 2012) (Figure 35). The temporal and spatial variability of water levels, the primary groundwater flow direction, and the response of aquifers to dry conditions and recovery from the drought were assessed and presented by hydrographs, contours and summary statistics.

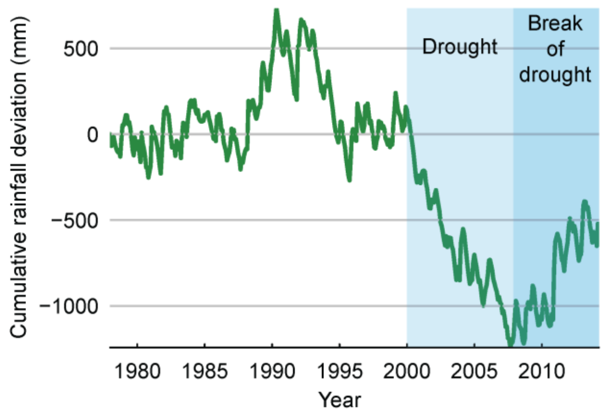

Figure 35 Cumulative deviation from mean monthly rainfall based on data from the Bureau of Meteorology (2014) at Harrisville Post Office (Bureau of Meteorology station 040094) about 25 km south of Ipswich, highlighting severe droughts that lasted until 2007 followed by the break of drought commencing in 2008

Data: Bioregional Assessment Programme (Dataset 11)

The comparison of the groundwater level response to rainfall events and long-term climate events such as droughts can provide useful information about the pattern of groundwater recharge of aquifers. Figure 36 shows a variable response of groundwater levels to rainfall events of five representative bores in different aquifers in the Clarence-Moreton bioregion. Bores in the same aquifer can show different responses depending on screen depth, local hydrogeological condition and water usage, although these bores may indicate general trends of response.

- The hydrograph of bore RN14320090 (screened in the alluvial aquifer of the Lockyer Valley less than 20 m away from Lockyer Creek) responds very rapidly to rainfall events with a clear seasonal pattern. It also shows a decline in water levels from approximately 13 m below ground level (mBGL) in 1999 to approximately 26 mBGL in 2007. This confirms the strong influence of the drought on groundwater levels in the alluvial aquifers. Following the break of the drought (end of 2007), the groundwater level recovered within one to two years to pre-drought levels. The rapid response to rainfall events suggests that the alluvial aquifer is probably recharged by the Lockyer Creek.
- Groundwater levels of bore RN14320257 (screened in the Marburg Subgroup) respond only to major rainfall events, whereas there is virtually no change following smaller events. Interestingly, a decline in water levels can be observed in 2008 at a time when the hydrographs of other bores showed rising water levels. This may be induced by groundwater abstraction but needs further investigation.
- The groundwater level hydrograph of bore RN14500103 (screened in the Walloon Coal Measures) shows no response to minor rainfall events. However, similar to bore RN14320257 (Marburg Subgroup), it also shows a weak response to major rainfall events. Likewise, decreasing groundwater levels can be observed from 2000 to 2007 as a consequence of the drought, although the drop in water levels occurs on a much smaller magnitude than within the alluvial aquifer.

- The groundwater level hydrograph of bore RN42231224 (screened in the Main Range Volcanics) shows some response to small rainfall events; however, overall its response is also more similar to the hydrographs of the other bedrock units than to those of the alluvial aquifer, with changes dominantly in response to long-term climate variability rather than short-term rainfall events.

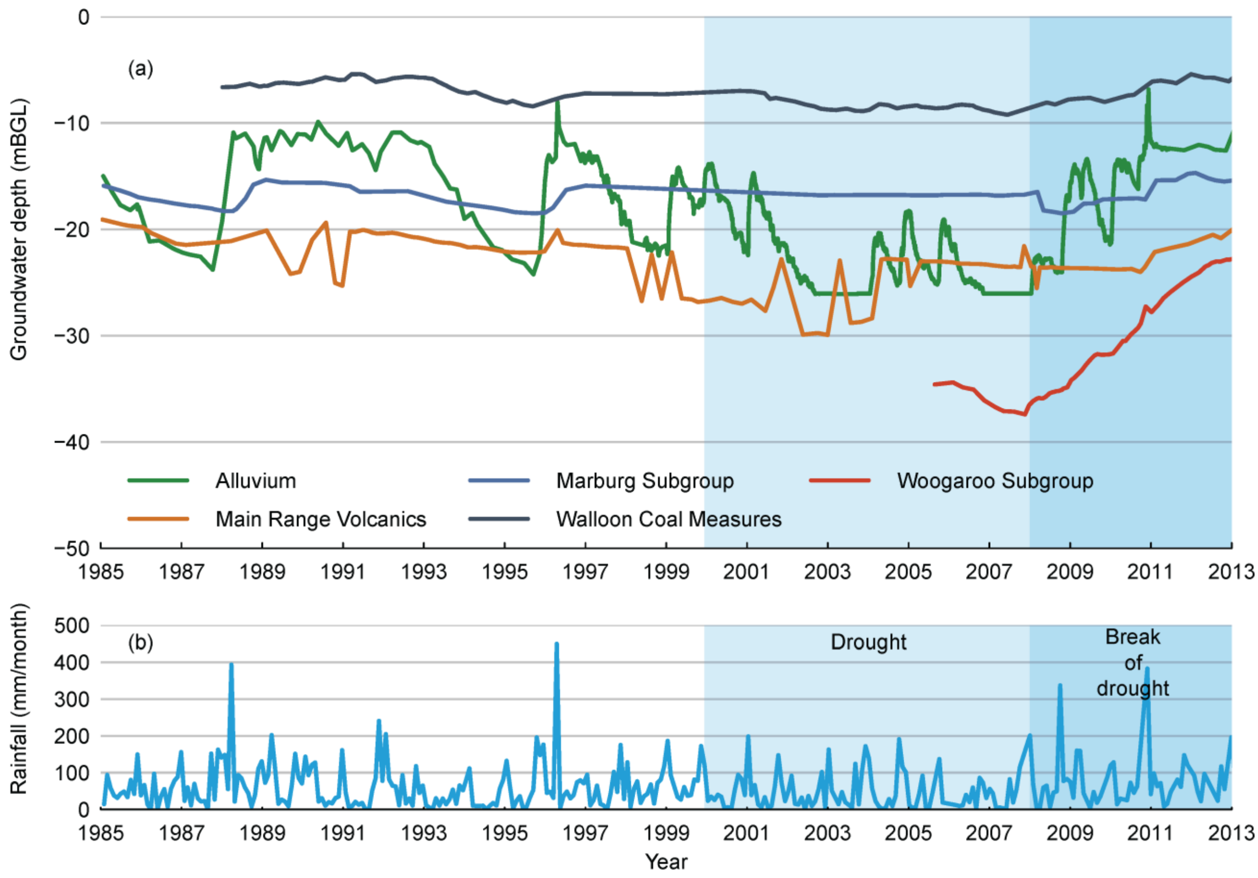

Figure 36 Groundwater depth in bores tapped into different aquifers in the Gatton area and monthly rainfall time series from the Gatton Allan Street station in the Clarence-Moreton bioregion

The selected bedrock bores are either in outcrops or close to outcrops and cannot represent the water level change in the deeper and confined part of bedrock aquifers.
Data: Bioregional Assessment Programme (Dataset 11)

Groundwater level elevation maps and groundwater flow direction

The contours of mean groundwater elevations for aquifers with sufficient groundwater data were generated using kriging interpolation (Figure 37 to Figure 43). Good spatial coverage of water level data enabled the analysis for the Walloon Coal Measures in the Bremer river basin (Figure 41). However, no analysis was conducted for the Walloon Coal Measures of the Richmond and Clarence river basins due to the paucity of data. Table 11 summarises the available water level records by aquifers, but does not indicate the spatial coverage of data. In addition, while Table 11 for example suggest that there are a large number of records for the Koukandowie Formation, 888 of the total 916 records for this formation are from only eight bores, which is not enough to generate contours.

Water levels generally follow the topographic gradient in alluvial aquifers. Groundwater flow direction is generally north-east following the topography in the Lockyer Valley, Bremer, and Logan-Albert river alluvia, and east in the Richmond River alluvium (Figure 22, Figure 37 to Figure 40). The spatial distribution of measurements is highly variable. Figure 22 indicates significantly higher data availability in the Lockyer Valley compared to the Richmond river basin. Hence, the uncertainty in the spatial interpolations is substantially higher in the Richmond river basin compared to the Lockyer Valley (Figure 37 and Figure 40).

Groundwater flow also follows the topography in a north-easterly direction in bedrock aquifers such as the Walloon Coal Measures and the Gatton Sandstone (Figure 41 and Figure 42). In contrast, the groundwater flow direction in the Woogaroo Subgroup at the northern margin of the Clarence-Moreton Basin (in the Lockyer Valley) is in the opposite south-easterly direction towards the deep depositional centre located underneath the Bremer river basin (Figure 43). As this is where the Gatton Sandstone pinches out against the underlying Woogaroo Subgroup, it is very likely that discharge of groundwater from the Gatton Sandstone to the surface occurs here. This is supported by shallow watertables in the Gatton Sandstone and along the northern margin of the Lockyer Creek alluvial aquifer, as well as the presence of wetlands (see Section 2.1.5).

At the eastern margin of the Laidley sub-basin within the Bremer river basin (west of Ipswich), the general groundwater flow direction in the Walloon Coal Measures is towards the point where the Bremer River, Warrill Creek and Purga Creek exit the Clarence-Moreton Basin (Figure 41). In this area, which is bounded by the West Ipswich Fault the Clarence-Moreton Basin stratigraphic units pinch out against the low-permeability basement rocks at the margin of the sub-basin. As a result, groundwater from the Walloon Coal Measures and underlying formations is likely to be pushed upwards and discharged into the surrounding wetlands and alluvia (see Section 2.1.5). Similarly, in the Richmond and Clarence river basins, groundwater flow in the sedimentary bedrock is controlled by basement highs, which occur both in the north-east of the Richmond river basin and south-east of the Clarence river basin. The likely primary area of sedimentary bedrock groundwater discharge is located in the south-east of the Richmond river basin and north-east of the Clarence river basin in between these basement highs.

Uncertainty in groundwater level predictions is captured through a summary of prediction standard deviations. Generally, predictive uncertainty is relatively low close to bores (where data were collected) and increases with distance. In addition, in some locations, the predictive uncertainty increases as the topographic elevation increases. This arises because the topography is used as a predictor in the kriging, but wells tend to be located at lower elevations. Hence, there is greater uncertainty in predictions at higher elevations.

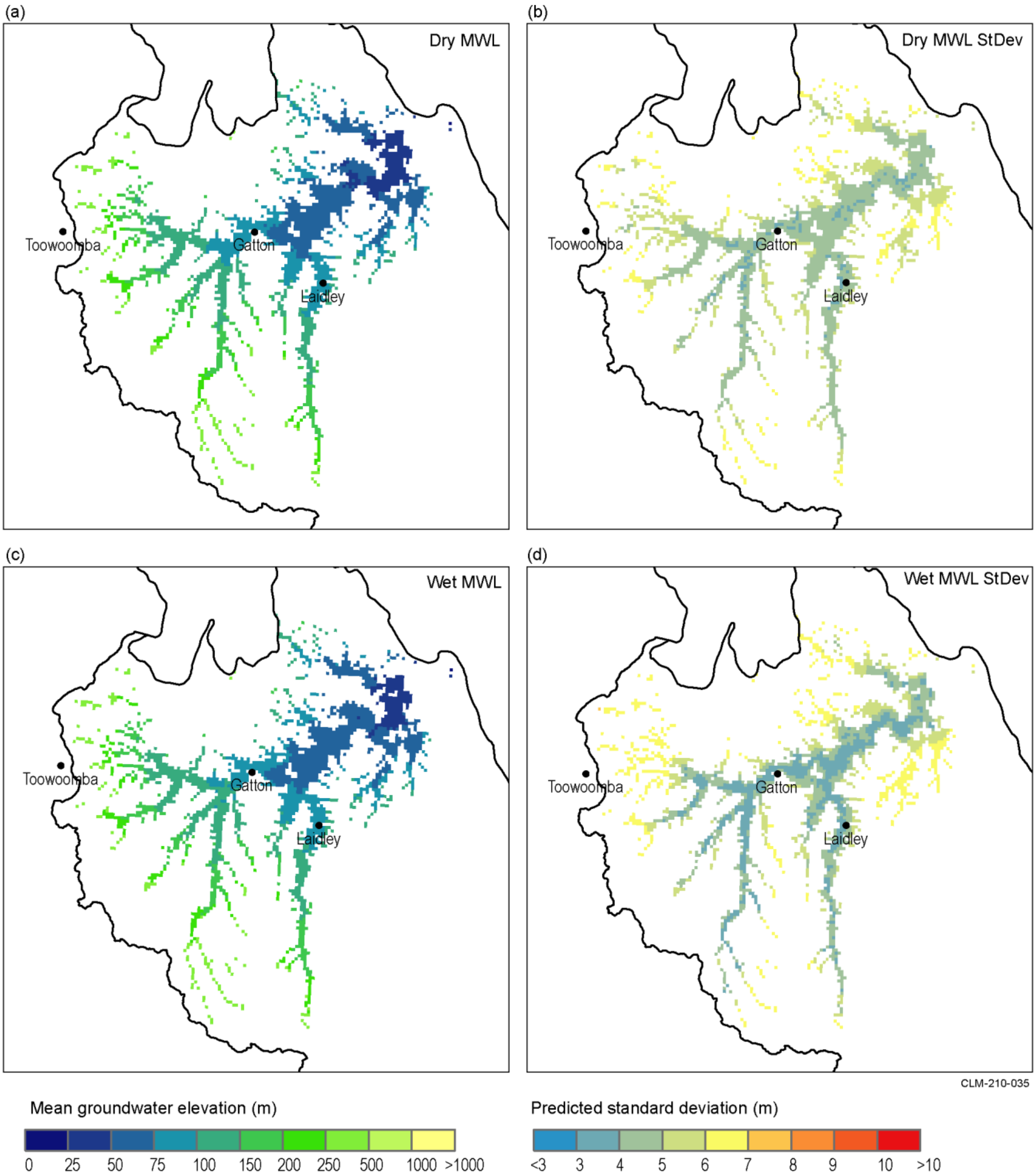

Figure 37 Mean groundwater level elevation and standard deviation for the Lockyer Valley alluvium during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

Data: Bioregional Assessment Programme (Dataset 12)

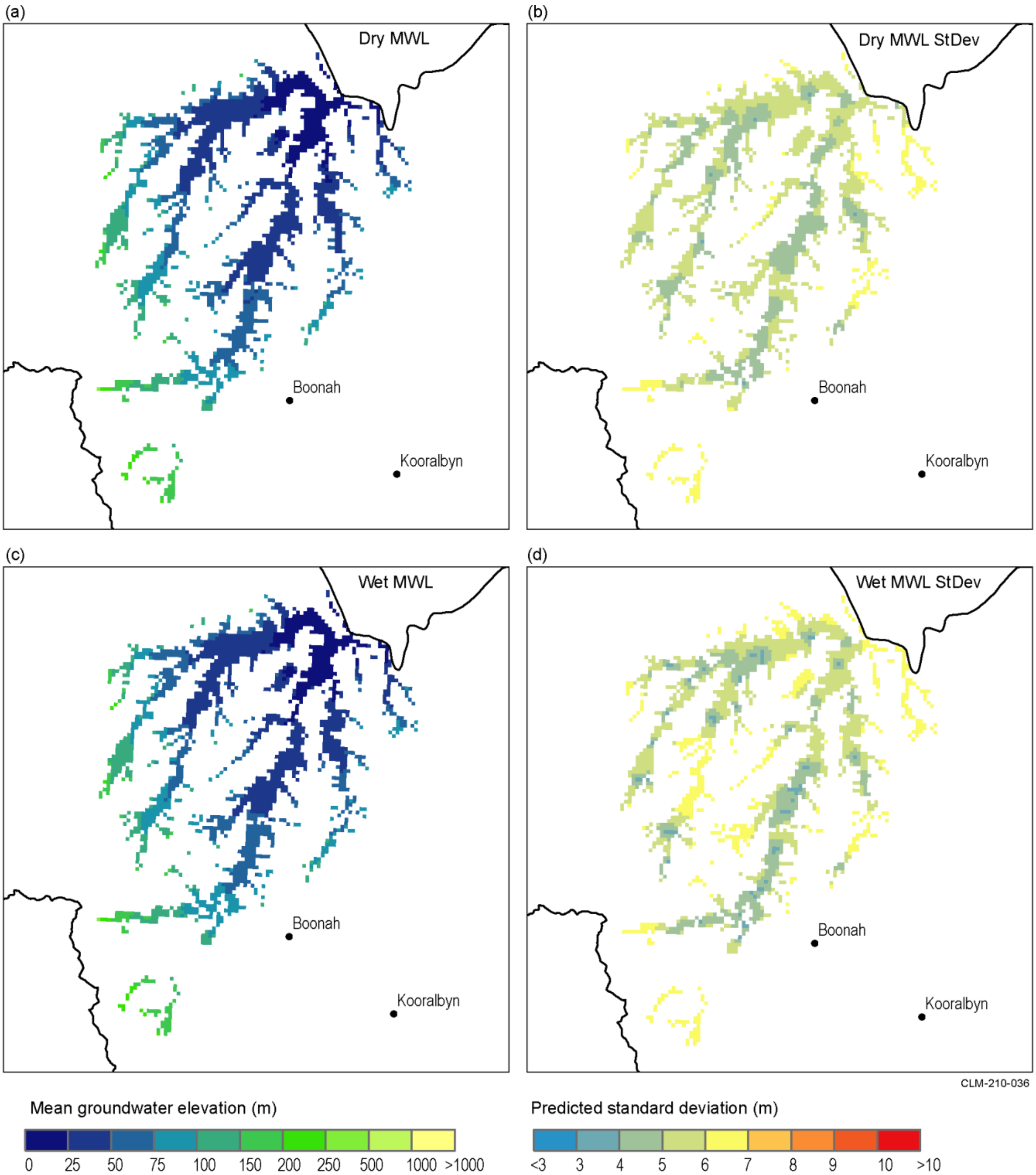

Figure 38 Mean groundwater level elevation and standard deviation for the Bremer River alluvium during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

Data: Bioregional Assessment Programme (Dataset 12)

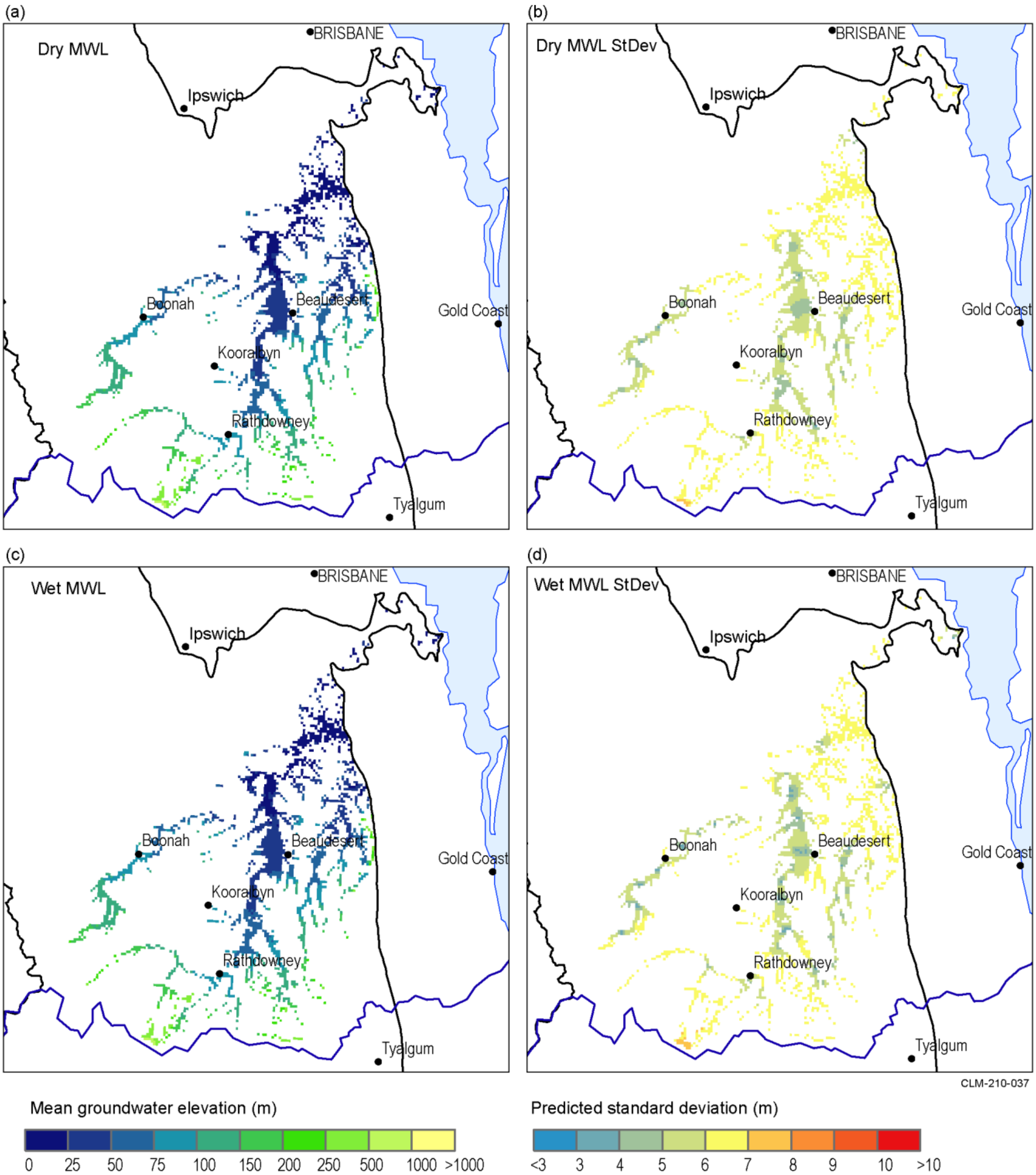

Figure 39 Mean groundwater level elevation and standard deviation for the Logan-Albert River alluvium during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

Data: Bioregional Assessment Programme (Dataset 12)

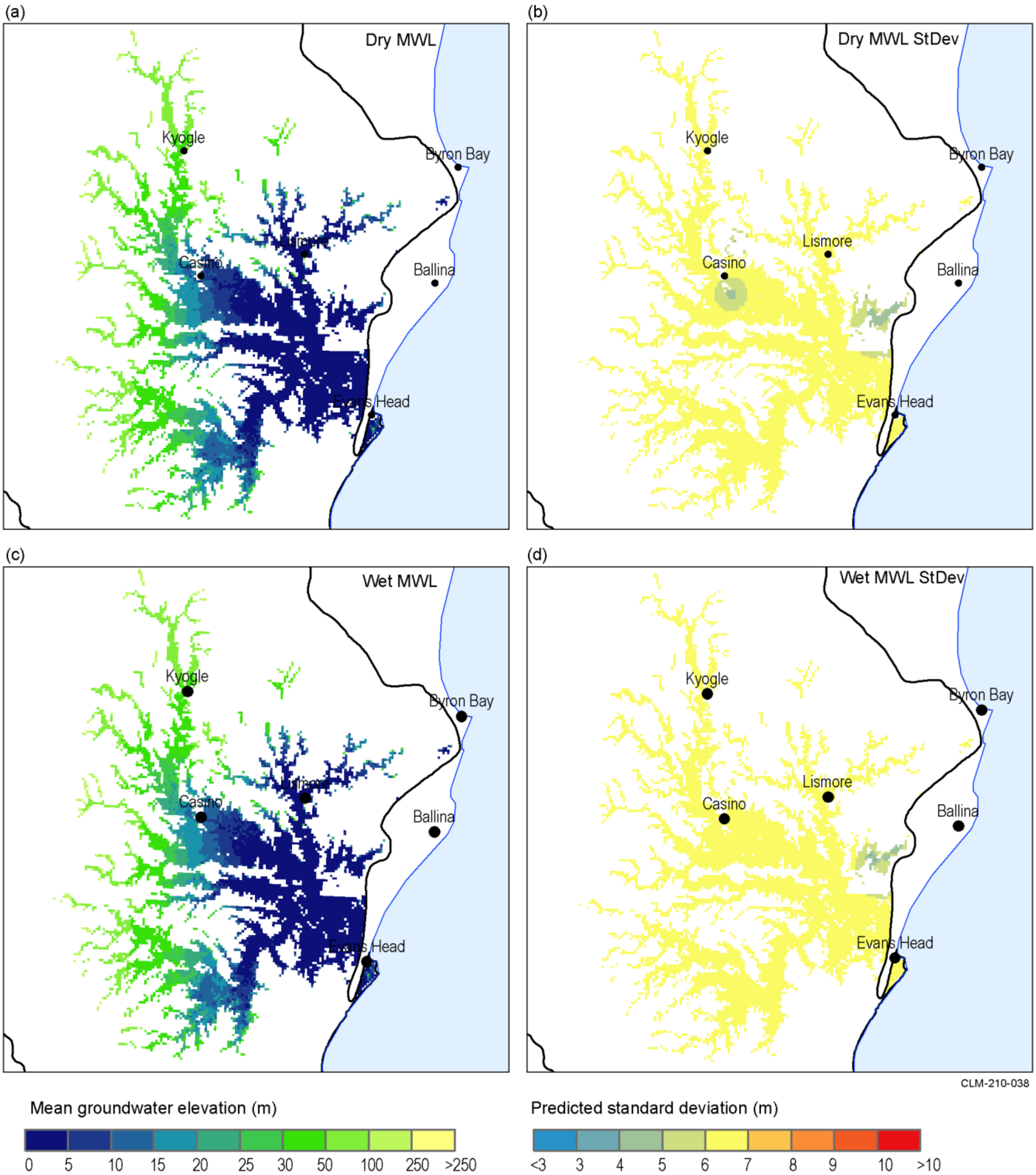

Figure 40 Mean groundwater level elevation and standard deviation for the Richmond River alluvium during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

Data: Bioregional Assessment Programme (Dataset 12)

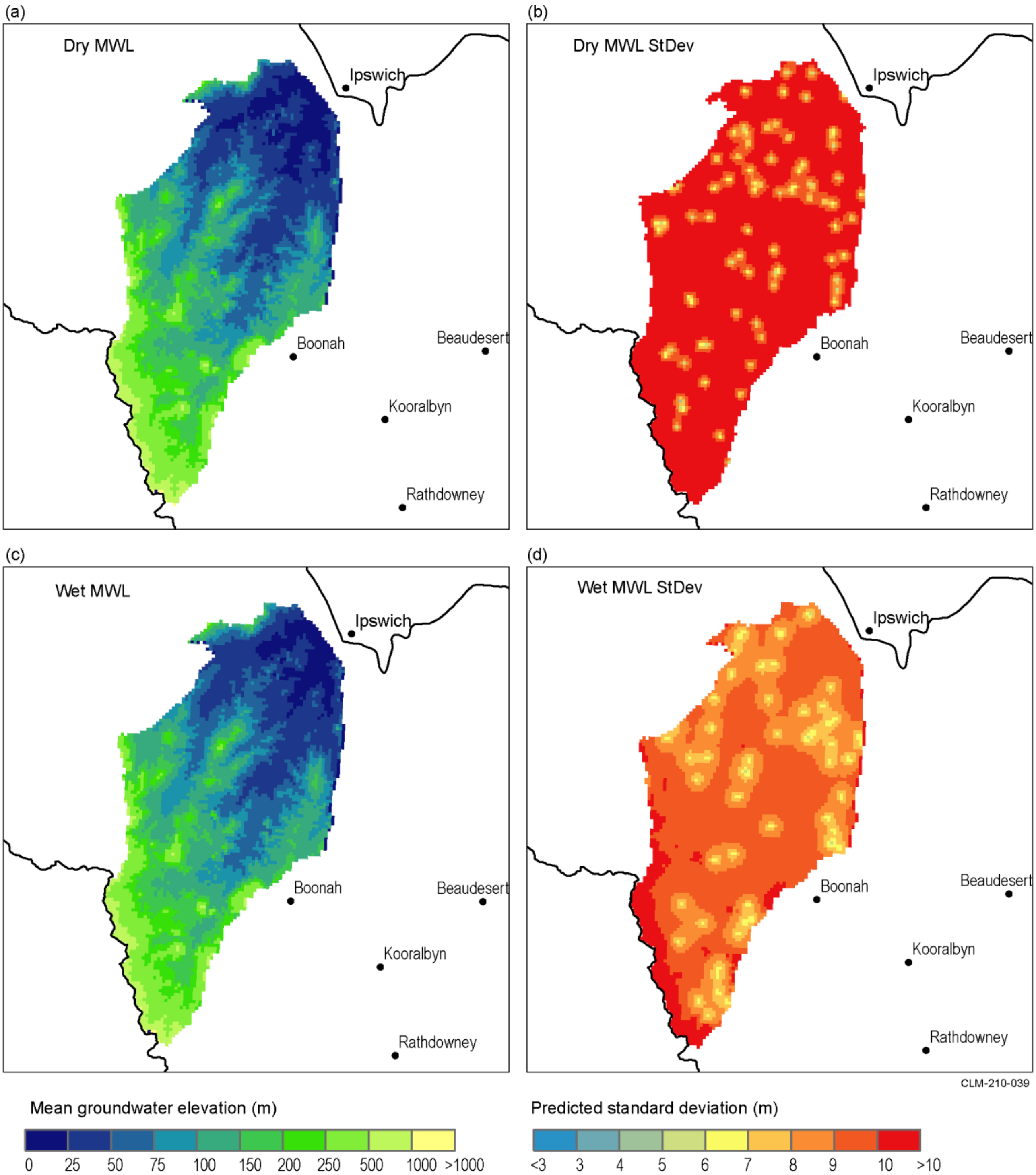

Figure 41 Mean groundwater level elevation and standard deviation for the Walloon Coal Measures during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

The analysis is limited to Walloon Coal Measures in the Bremer river basin where there are enough data.
Data: Bioregional Assessment Programme (Dataset 13)

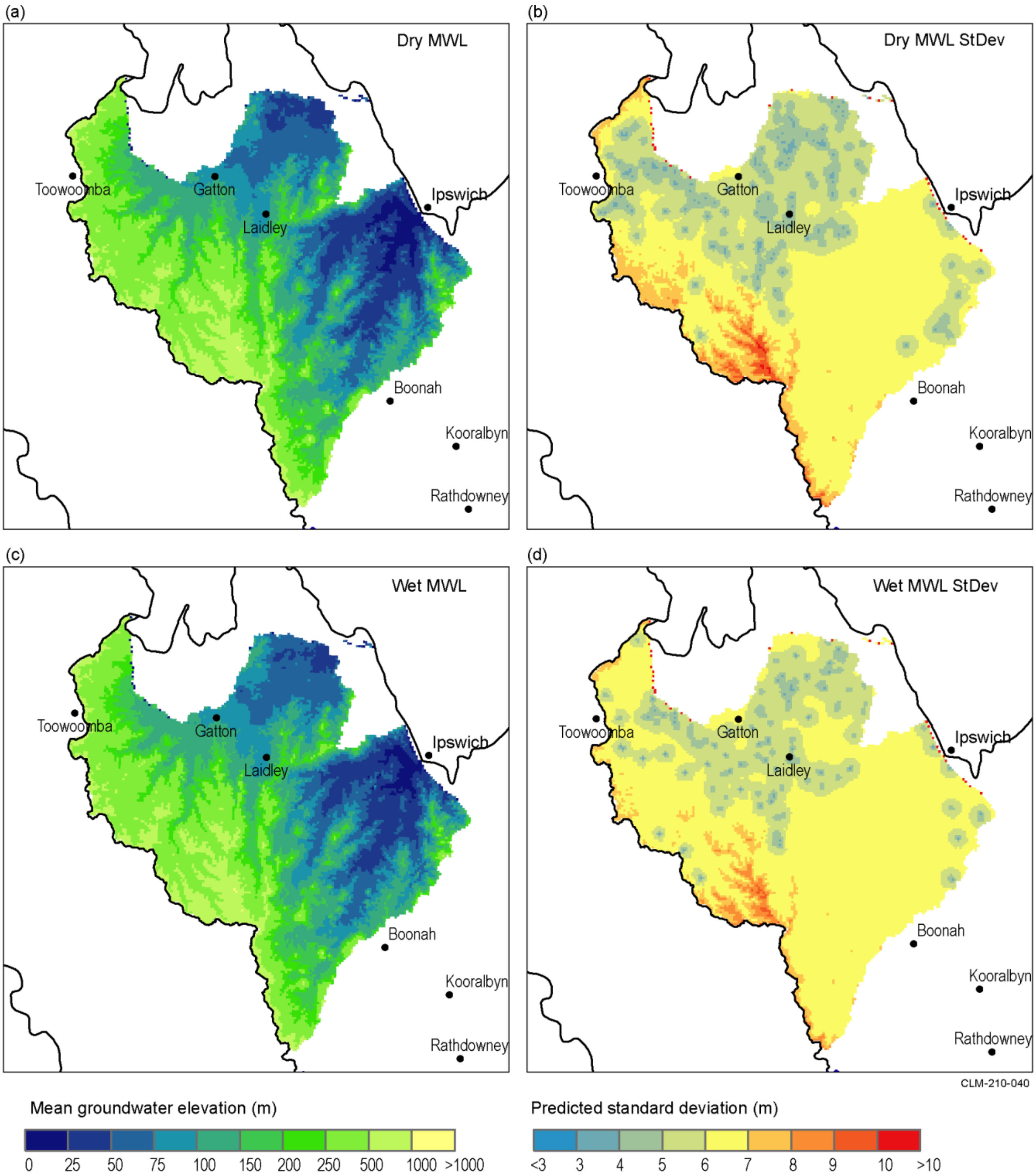

Figure 42 Mean groundwater level elevation and standard deviation for the Gatton Sandstone during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

The analysis is limited to Gatton Sandstone in the Lockyer Valley and Bremer river basin where there are enough data.
Data: Bioregional Assessment Programme (Dataset 14)

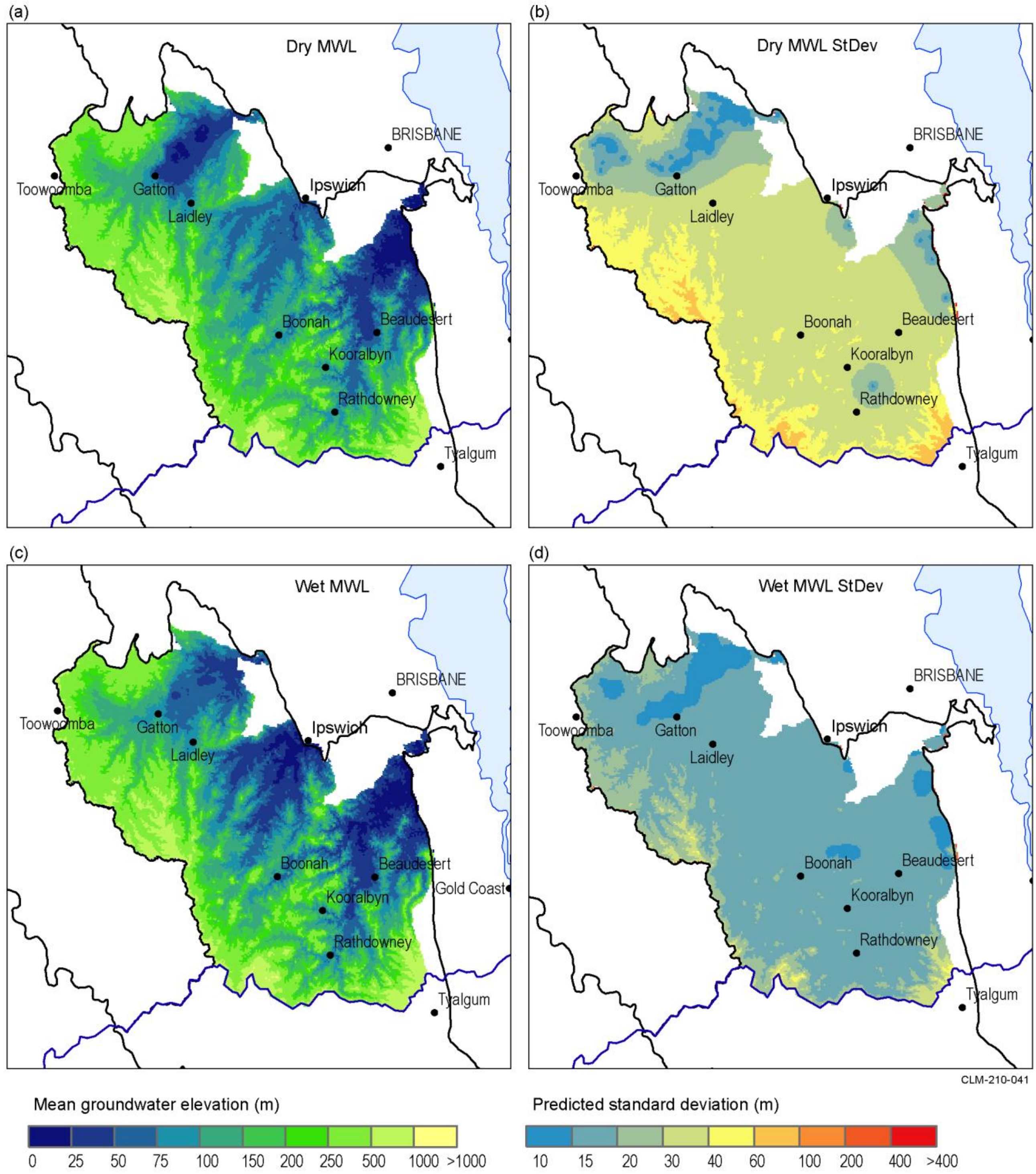

Figure 43 Mean groundwater level elevation and standard deviation for the Woogaroo Subgroup during a dry period (2000 to2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

The analysis is limited to Woogaroo Subgroup in the Lockyer Valley, and the Bremer and Logan-Albert river basins where there are enough data.
Data: Bioregional Assessment Programme (Dataset 15)

Mean depth to groundwater

The mean depths to groundwater (watertable depth) for the alluvial aquifers are shown in Figure 44 to Figure 47. The alluvial aquifers have a mean watertable depth in the range of 1.83 m to 17.54 m. A comparison of the watertable depths for the drought and periods following the break of drought shows that there is considerable difference in the watertable surfaces in some areas. This indicates a direct relationship to the recharge from rainfall and groundwater pumping.

The depth summary statistics (Table 14) indicate that the Lockyer Valley alluvium ('Lockyer Valley alluvium (dry)') has a mean depth to groundwater of 17.54 m during the dry period. This is the deepest of the alluvial systems within the Clarence-Moreton bioregion. Extensive groundwater extraction adds significant pressure on water levels – especially during drought periods. The decline of groundwater levels during the drought also induces upwards discharge from the underlying Gatton Sandstone into the alluvium. This is confirmed by a substantial increase in the electrical conductivity of groundwater in this area (see Section 2.1.3.4). Following the break of the drought, groundwater levels recovered to pre-drought levels, accompanied by a freshening of groundwater within the alluvial aquifers.

Groundwater depth is generally deeper in the central part of the alluvium, where the thickness of the alluvial sediments is greatest. At the edge of the alluvial aquifers, groundwater levels are typically shallower. This is associated with the generally smaller thickness of the alluvial aquifers at the basin margins, but also likely to be the result of groundwater discharge from the underlying bedrock into the alluvial aquifers at the margin of the alluvium. This is independently confirmed in the Lockyer Valley and Bremer Valley by water levels, water chemistry and electrical conductivities (Section 2.1.3.3.3) as well as isotopic data (Raiber, unpublished data).

Groundwater in the Woogaroo Subgroup is deeper than in other bedrock aquifers with a mean and a maximum depth of 38.43 and 92.46 m, respectively, based on the data that are mainly for the unconfined part of bedrock aquifers (Table 14). This might be related to the high quality of groundwater in the Woogaroo Subgroup in comparison to most other sedimentary bedrock units (the Woogaroo Subgroup contains very fresh groundwater with electrical conductivities which are often less than 300 µS/cm (see Section 2.1.3.3.3)). As a result, this aquifer is very heavily exploited for agriculture (primarily orchards in the Lockyer Valley), which may induce a substantial drawdown. In addition, the deep groundwater levels within the Woogaroo Subgroup might reflect that this formation dips very steeply towards the south-east at the northern basin margin.

Table 14 Statistical summary of the mean groundwater depth in main aquifers

Artesian bores are not included in this table.

Aquifers	Minimum (m)	Mean (m)	Median (m)	Maximum (m)	Total number of measurements
Lockyer Valley alluvium (dry)	0.25	17.54	18.52	32.60	693
Lockyer Valley alluvium (wet)	0.02	13.73	13.80	33.43	683
Bremer River alluvium (dry)	1.03	10.26	10.30	23.85	164
Bremer River alluvium (wet)	1.60	8.54	8.40	15.07	107
Logan-Albert River alluvium (dry)	1.34	10.21	10.29	21.73	87
Logan-Albert River alluvium (wet)	1.03	9.01	8.50	20.72	83
Richmond River alluvium (dry)	1.40	5.33	2.61	11.77	20
Richmond River alluvium (wet)	0.85	1.83	2.01	2.73	5
Walloon Coal Measures (dry)	0.41	15.47	12.91	56.13	80
Walloon Coal Measures (wet)	0.02	12.22	10.08	36.43	52
Gatton Sandstone (dry)	0.25	16.37	13.34	69.368	165
Gatton Sandstone (wet)	0.81	12.44	9.28	73.34	118
Woogaroo Subgroup (dry)	2.11	38.43	33.19	92.46	98
Woogaroo Subgroup (wet)	1.65	27.16	18.93	79.13	61

Data: Bioregional Assessment Programme (Dataset 11, Dataset 16)

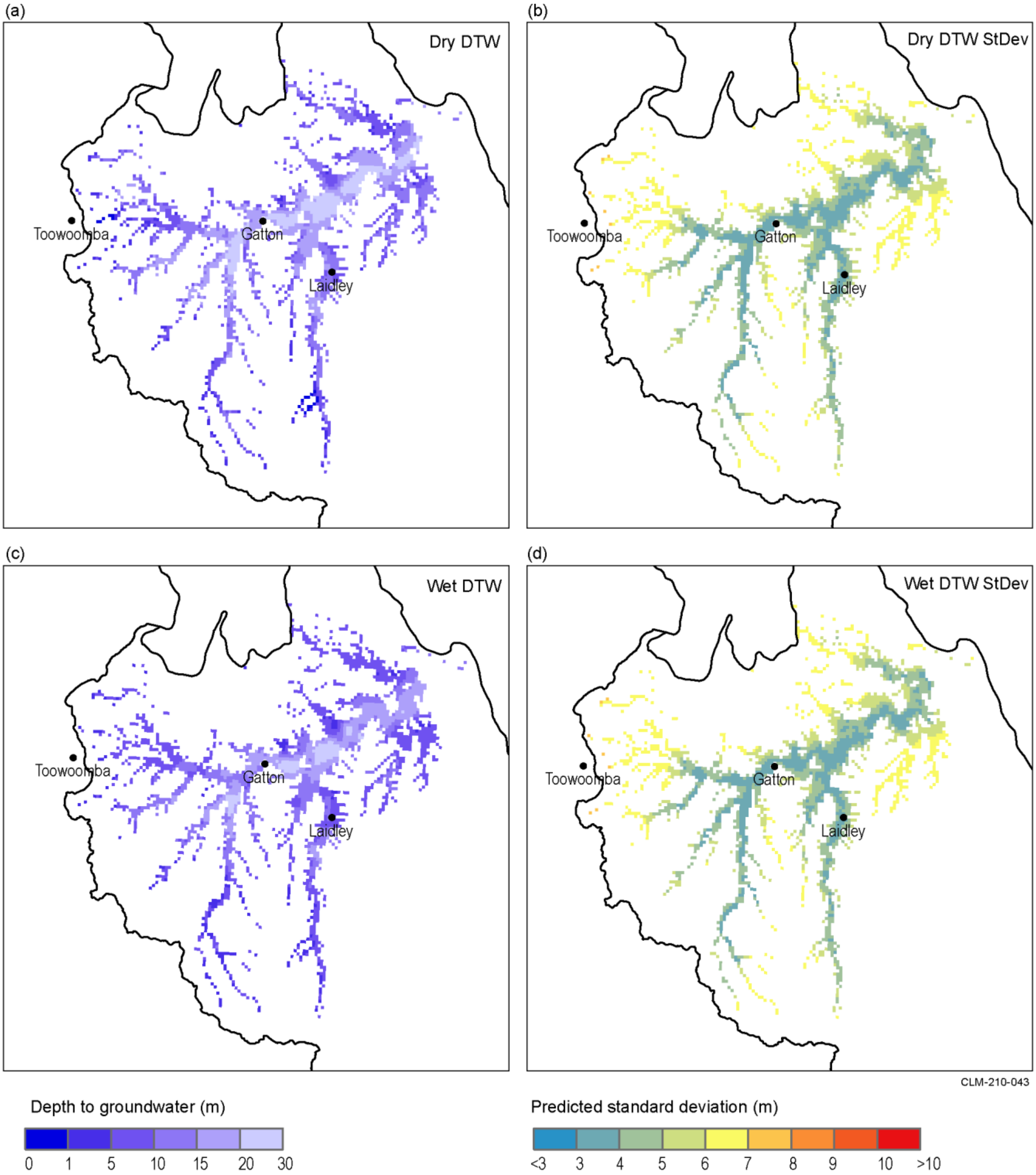

Figure 44 Mean groundwater depth and standard deviation for the Lockyer Valley alluvium during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

Data: Bioregional Assessment Programme (Dataset 12)

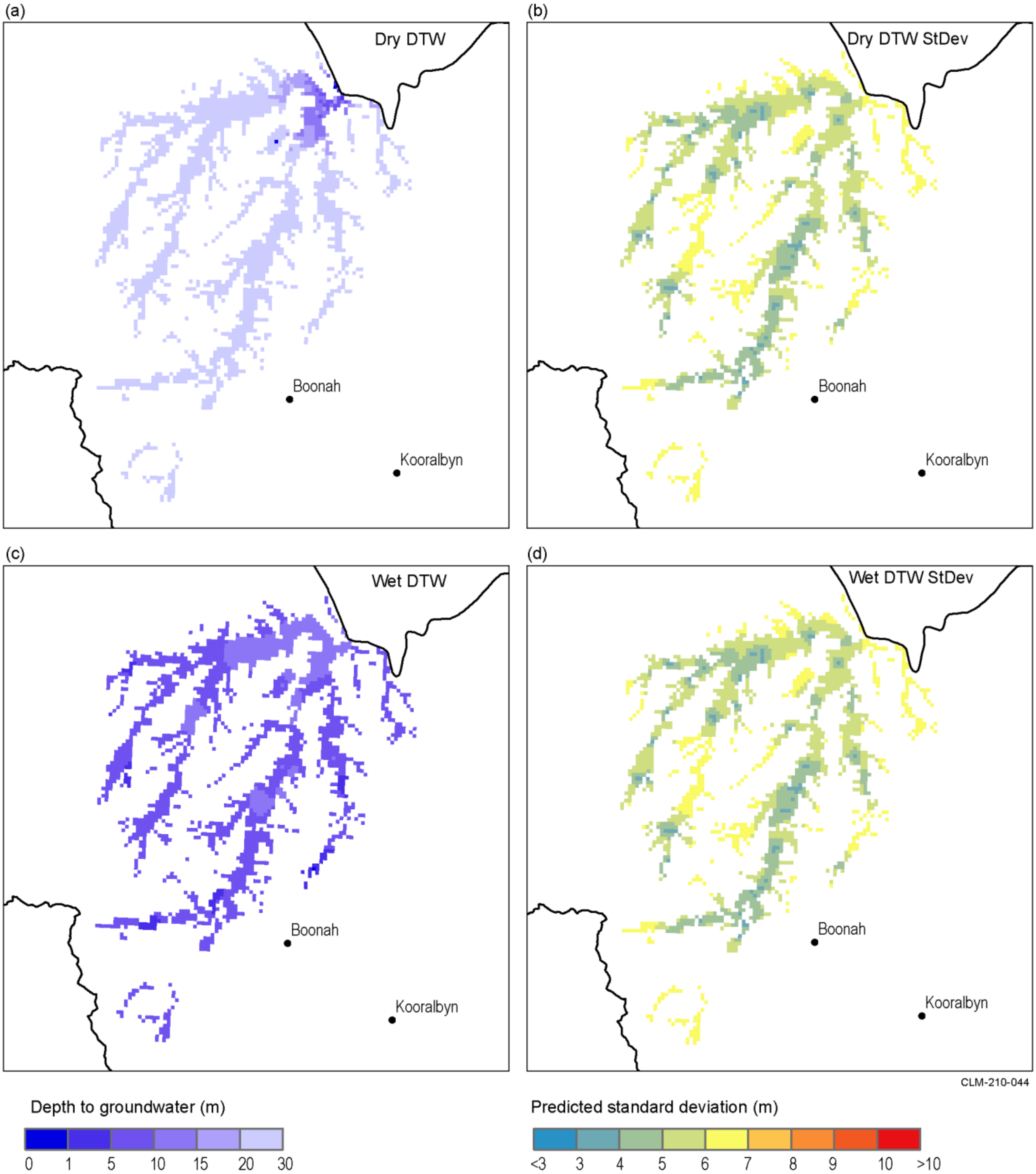

Figure 45 Mean groundwater depth and standard deviation for the Bremer River alluvium during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

Data: Bioregional Assessment Programme (Dataset 12)

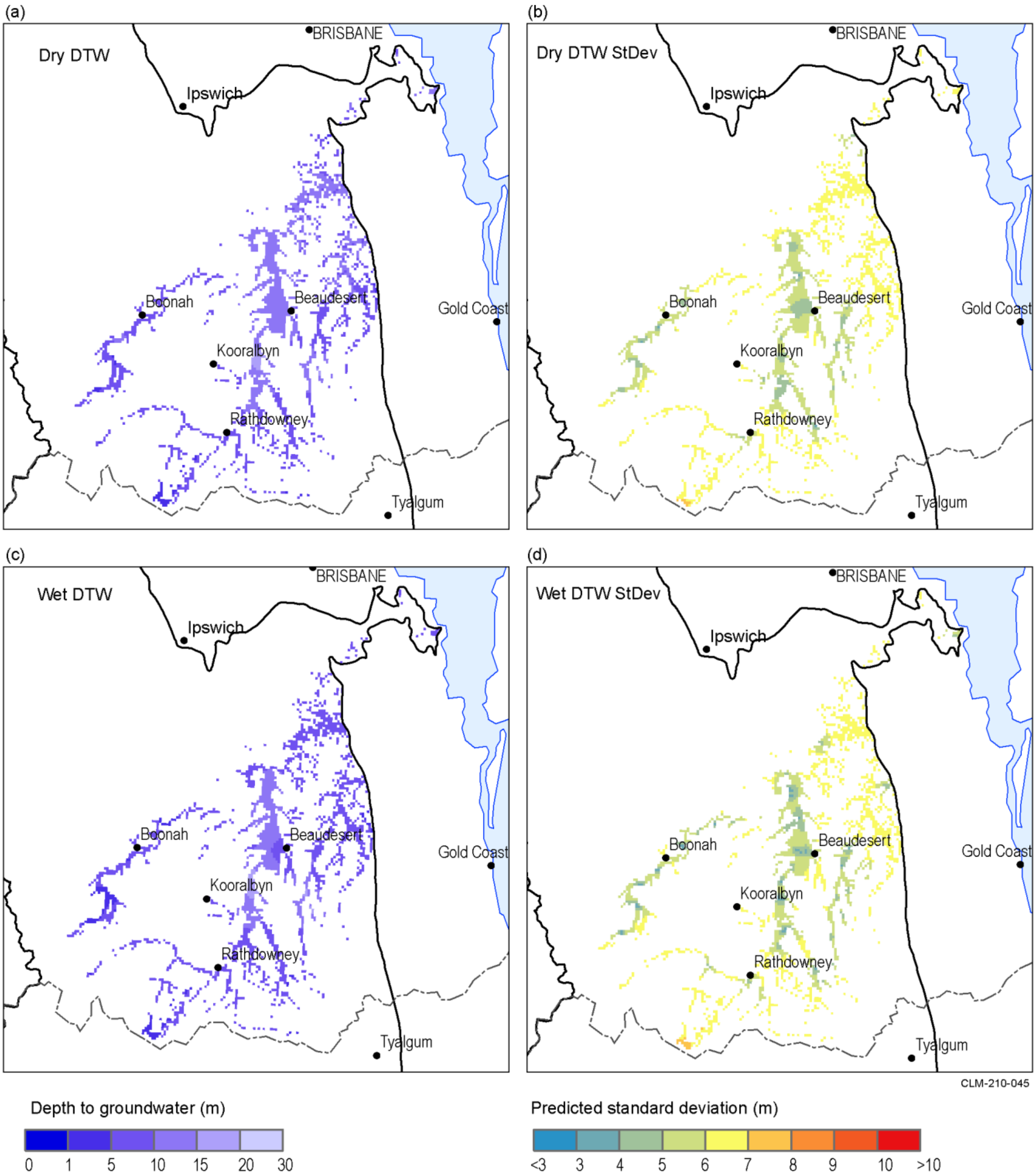

Figure 46 Mean groundwater depth and standard deviation for the Logan-Albert River alluvium during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

Data: Bioregional Assessment Programme (Dataset 12)

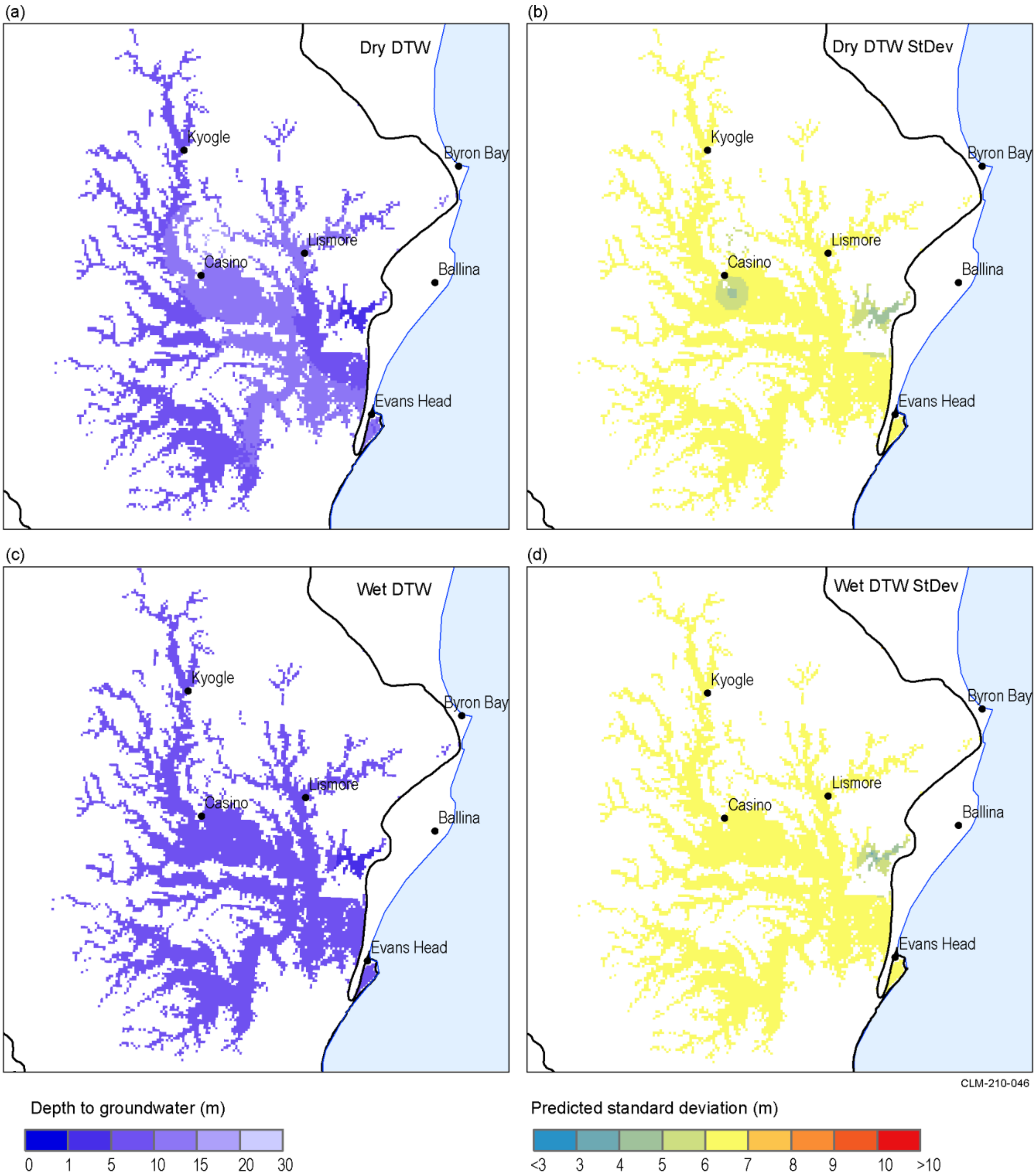

Figure 47 Mean groundwater depth and standard deviation for the Richmond River alluvium during a dry period (2000 to 2007) (a) and (b), and a wet period (2008 to 2012) (c) and (d)

Data: Bioregional Assessment Programme (Dataset 12)

Temporal variability of groundwater levels

The statistical techniques provide a quantitative assessment of the temporal variability of groundwater levels as they respond to various stresses that are mainly driven by climate and/or extraction. The Mann-Kendall tau statistic (Mann, 1945) provides an indicator of the strength of the monotonic trend of a groundwater level time series. Values of –1 and 1 indicate a monotonic decline or rise in all groundwater heads in the series, respectively. Values between –1 and 1 correspond to less monotonic trends, with a zero value indicating an equal number of rises and declines among all data pairs in the time series. The Mann-Kendall tau statistic provided a means of identifying statistically significant trends in groundwater levels for a number of bores in the Lockyer, Bremer and Logan-Albert river alluvia as well as bedrock aquifers. Trends are deemed statistically significant when the p-value for the Mann-Kendall tau statistic is less than 0.05. The Theil-Sen estimator (also referred to as Sen's slope estimate) (Theil, 1950; Sen, 1968) is a robust estimator of the rate of change of a monotonic groundwater trend (m/year). It provides insight into how rapidly the water level responds in different aquifers. For aquifers showing a statistically significant trend, box plots of the Sen's slope estimate during the wet and dry periods were calculated (Figure 48 and Figure 49). The bores available for the analysis of the bedrock aquifers are mainly within/close to the area where bedrock aquifers outcrop. There are not enough data for the deep part of the bedrock aquifers to generate Sen's slope values.

Substantial declines in water levels occurred during the drought in all alluvial aquifer systems within the Clarence-Moreton bioregion, followed by an increase in groundwater levels after the drought broke in 2007 to 2008. The magnitude of change is highly variable throughout different parts of the alluvial aquifer systems. For example, water levels in the Lockyer Valley aquifers had declined by more than 10 m in some areas (Figure 36), although part of this is possibly due to increased pumping. In many locations, following the break of the drought, the groundwater levels in alluvial aquifers have recovered to pre-drought levels, with maximum increases of groundwater levels greater than 20 m. However, in some areas, the magnitude of groundwater level change has been much smaller. In general, groundwater levels in the alluvium responded rapidly to variations in rainfall. The steepest declines were observed in the Bremer and Lockyer Valley alluvia at rates ranging from 1.36 to 3.75 m/year (Figure 48). More moderate declines were observed in the Logan-Albert and Richmond alluvia with the steepest being 1.32 and 0.13 m/year (Figure 48), respectively. Similarly, during the wetter period, the greatest rates of change were observed at bores of the Bremer and Lockyer Valley alluvia, with rates of 3.27 and 6.85 m/year (Figure 48), respectively. During these wetter years, the maximum observed rate of change for the Logan-Albert alluvium was 1.49 m/year. There were not enough data to obtain a statistically significant number for the Richmond alluvium (Figure 48). As expected, water levels were consistently declining during the drought period (2000 to 2007) with substantial recoveries in all systems after the drought period. This implies a good connection between the alluvium and the surface water.

Potentiometric surfaces in the bedrock aquifers also showed declining trends during the drought and a recovery following the break of the drought. The rate and the magnitude of the response during and after the drought, however, was less pronounced compared to the alluvial aquifers (Figure 49). Groundwater levels in bedrock aquifers generally follow long-term or decadal patterns and are less affected by short-term climate patterns. This is probably related to different recharge mechanisms (i.e. alluvial aquifers are closely linked to streams and receive recharge from streams, whereas bedrock aquifers are predominantly recharged by rainfall recharge within the Clarence-Moreton bioregion as indicated by the high electrical conductivities (EC)). In addition, this difference probably also reflects that the alluvial aquifers within the Clarence-Moreton bioregion are used more for extraction than the bedrock aquifers due to the often poor groundwater quality within bedrock aquifers. Pumping of alluvial groundwater during the drought due to diminishing surface water resources was a major driver of the declining groundwater levels within the alluvial systems. During the high-rainfall period, the steepest ascent in groundwater levels observed at a bore in the Gatton Sandstone was 4.01 m/year (Figure 49). Some bores in the Woogaroo Subgroup showed strong responses to climate variability, with the steepest decrease during the dry years occurring at a bore at a rate of –1.51 m/year and the steepest increase at one bore being 5.91 m/year. Changes in the Walloon Coal Measures were less pronounced, with the steepest decline during the dry period being –0.57 m/year and the steepest ascent during the wet period being 1.09 m/year (Figure 49).

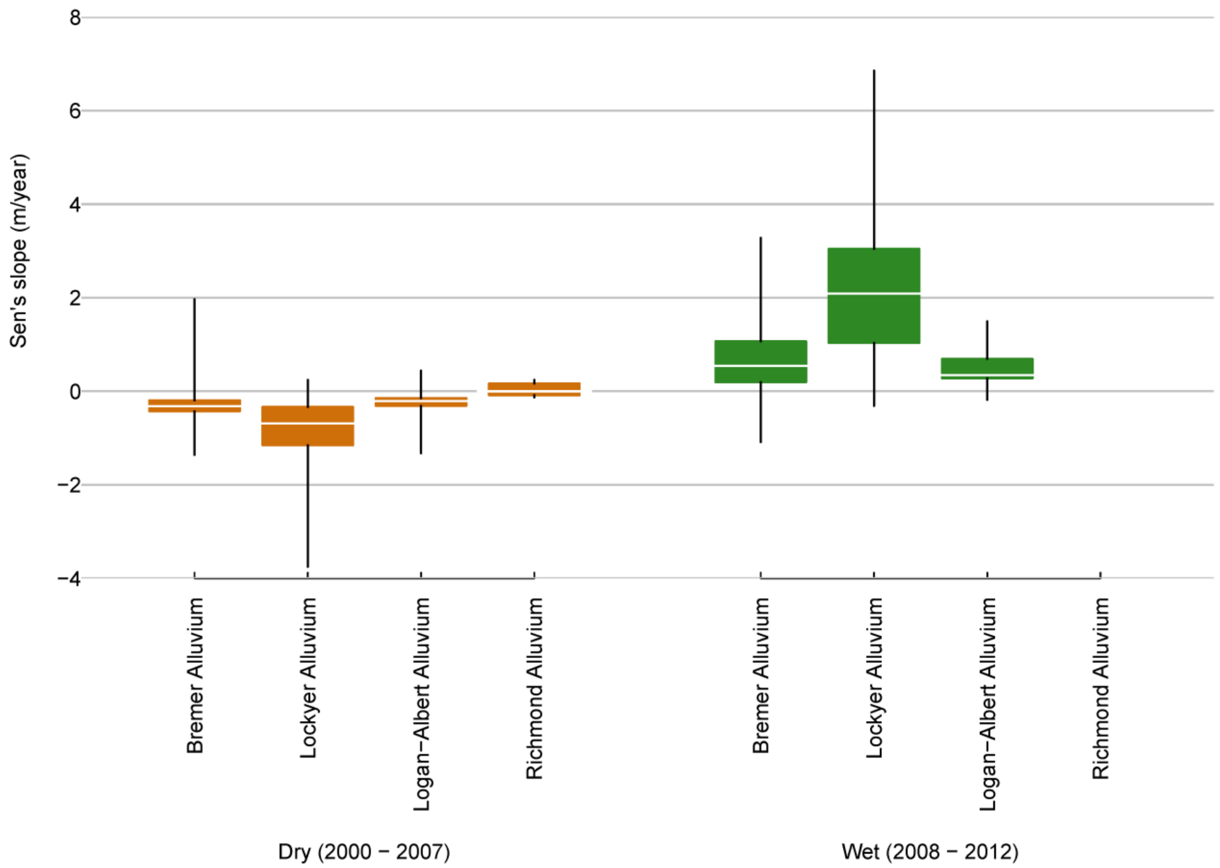

Figure 48 Sen's slope estimate to show the average declining and recovering rates of groundwater levels in the alluvia during a dry (2000 to 2007) and a wet (2008 to 2012) period, respectively

Black lines extend to the minimum and maximum values.
Data: Bioregional Assessment Programme (Dataset 11, Dataset 16)

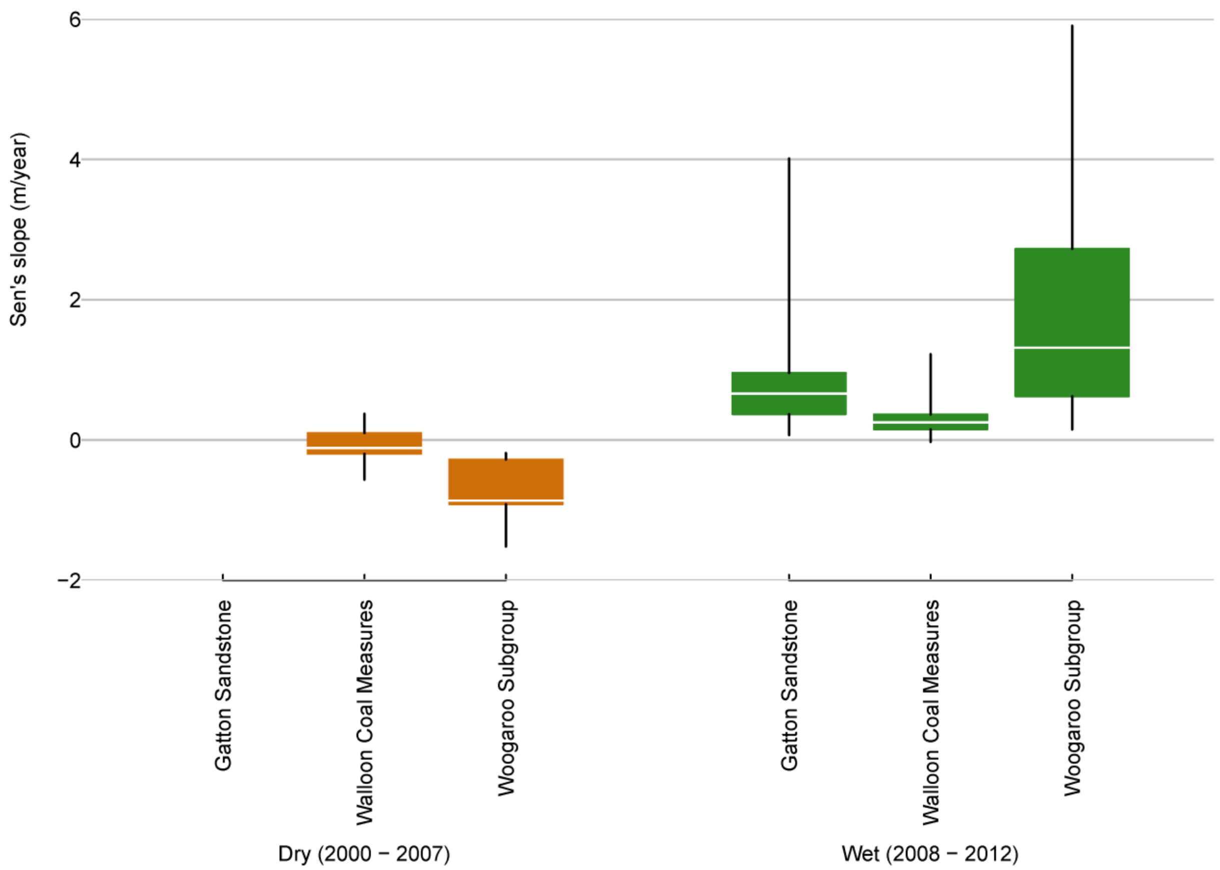

Figure 49 Sen's slope estimate to show the average declining and recovering rates of groundwater levels in the bedrock aquifers during a dry (2000 to 2007) and a wet (2008 to 2012) period, respectively

Black lines extend to the minimum and maximum values.
Data: Bioregional Assessment Programme (Dataset 11, Dataset 16)

2.1.3.3.2 Hydraulic parameters

Transmissivity and hydraulic conductivity determine the capability and efficiency of an aquifer to transmit groundwater. In the context of coal mining and CSG extraction, these parameters serve as controlling factors to the impact of coal resource developments on their surrounding aquifers. They also have a dominant role in spreading potential contaminants. This analysis aims to gain a comprehensive understanding of the hydraulic properties of main aquifers in the Clarence-Moreton bioregion, provide initial hydraulic parameters for the subsequent numerical groundwater model, and locate gaps in the state groundwater databases.

Analyses of the hydraulic parameters were conducted for the alluvium and several bedrock aquifers where enough data were available. The log-transformed hydraulic conductivities generally follow a normal distribution (Figure 50) and there is no clear relationship between hydraulic conductivity and screen depth in the alluvium (Figure 51). The box plots in Figure 52 and Figure 53 demonstrate the variability of transmissivity and hydraulic conductivity across aquifers. Transmissivity and hydraulic conductivity in the Lockyer Valley, Bremer and Logan-Albert river alluvia are similar in terms of median values, although they can change over a range of six orders of magnitude. The Richmond River alluvium shows a lower hydraulic conductivity than any other alluvium. Transmissivity is more uniform than hydraulic conductivity in the alluvium. The bedrock aquifers are less permeable than the alluvium with variations between one to two orders of magnitude. Most of the current data for the bedrock aquifers relate to the area where outcrops appear. The confined part of the bedrock aquifer should show lower hydraulic properties. The limited data suggest that the Woogaroo Subgroup is the most permeable aquifer among the bedrock aquifers. Most pumping tests for the Lamington Volcanics were conducted in the area surrounding Kyogle and Lismore. The fractured basalt has a median hydraulic conductivity of 3.82 m/day, which is similar to the unconfined bedrock aquifers.

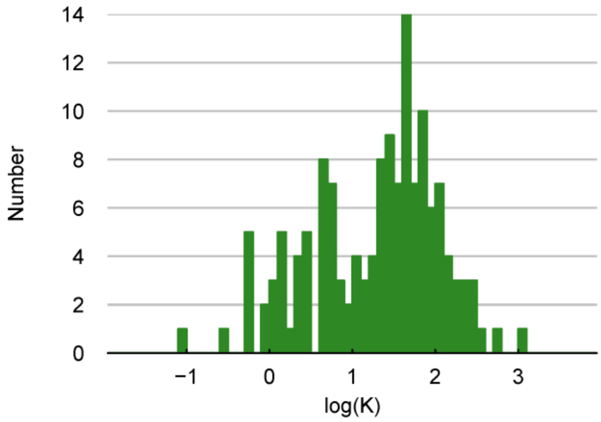

Figure 50 Histogram showing the distribution of log(K) in the alluvium across the Clarence-Moreton bioregion, where K is hydraulic conductivity (m/day)

Data: Bioregional Assessment Programme (Dataset 7, Dataset 8)

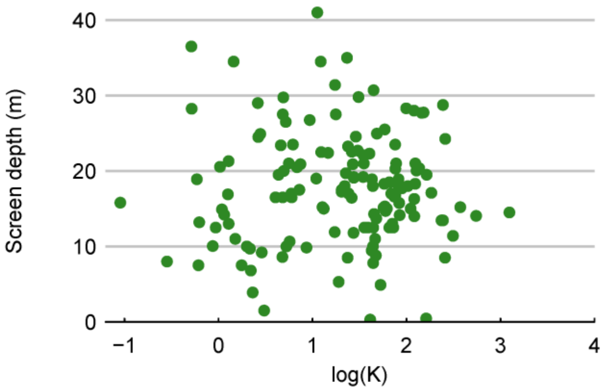

Figure 51 Scatter plot showing the relationship between the screen depth and log(K) in alluvium, where K is hydraulic conductivity (m/day)

The screen depth was considered to be the midpoint of the screen interval.
Data: Bioregional Assessment Programme (Dataset 7, Dataset 8)

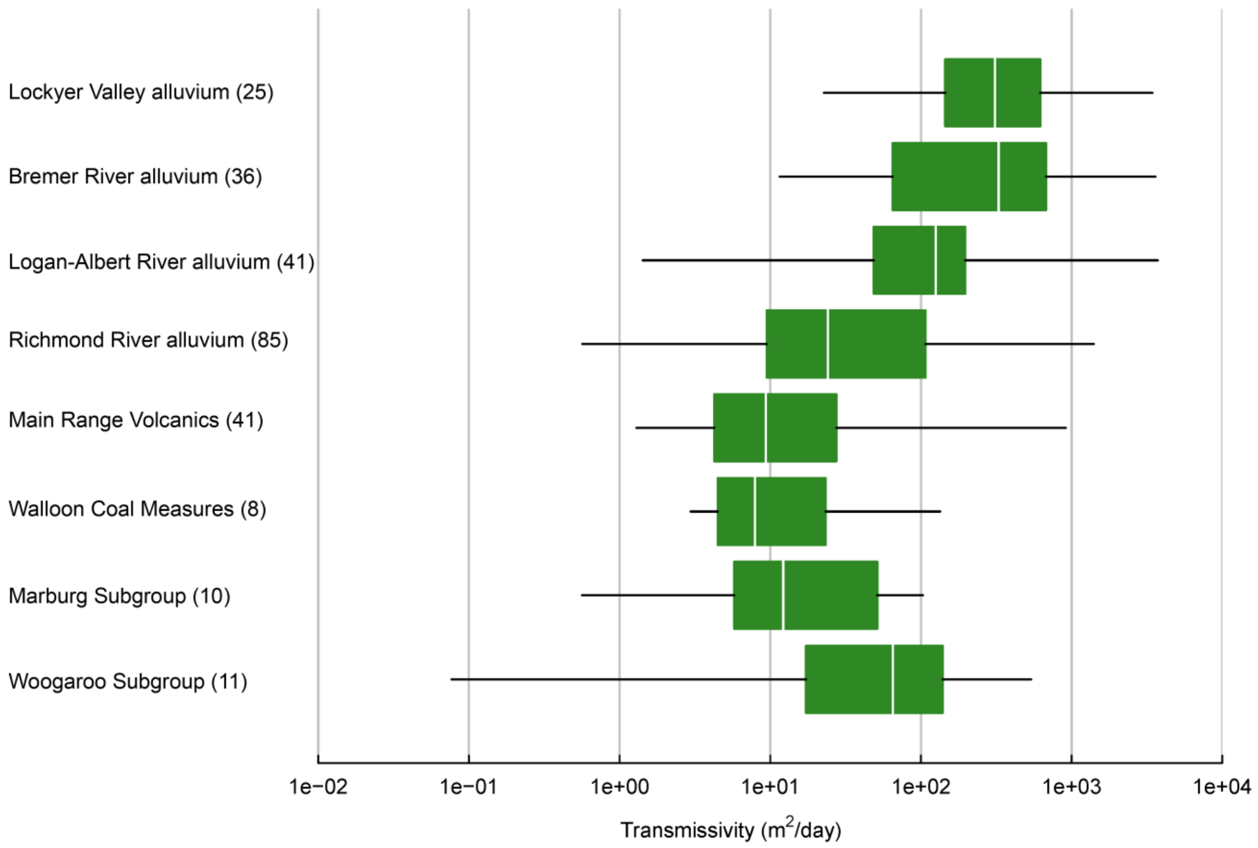

Figure 52 Box plot to show the transmissivity range of aquifers with enough data

The black lines in the plot extend to the minimum and maximum for each aquifer. The extent of the green boxes represents the 25th (left) and 75th (right) percentile, respectively. The white line represents the median. The number of records for each unit downward is shown in brackets after the formation name.
Data: Bioregional Assessment Programme (Dataset 7, Dataset 8)

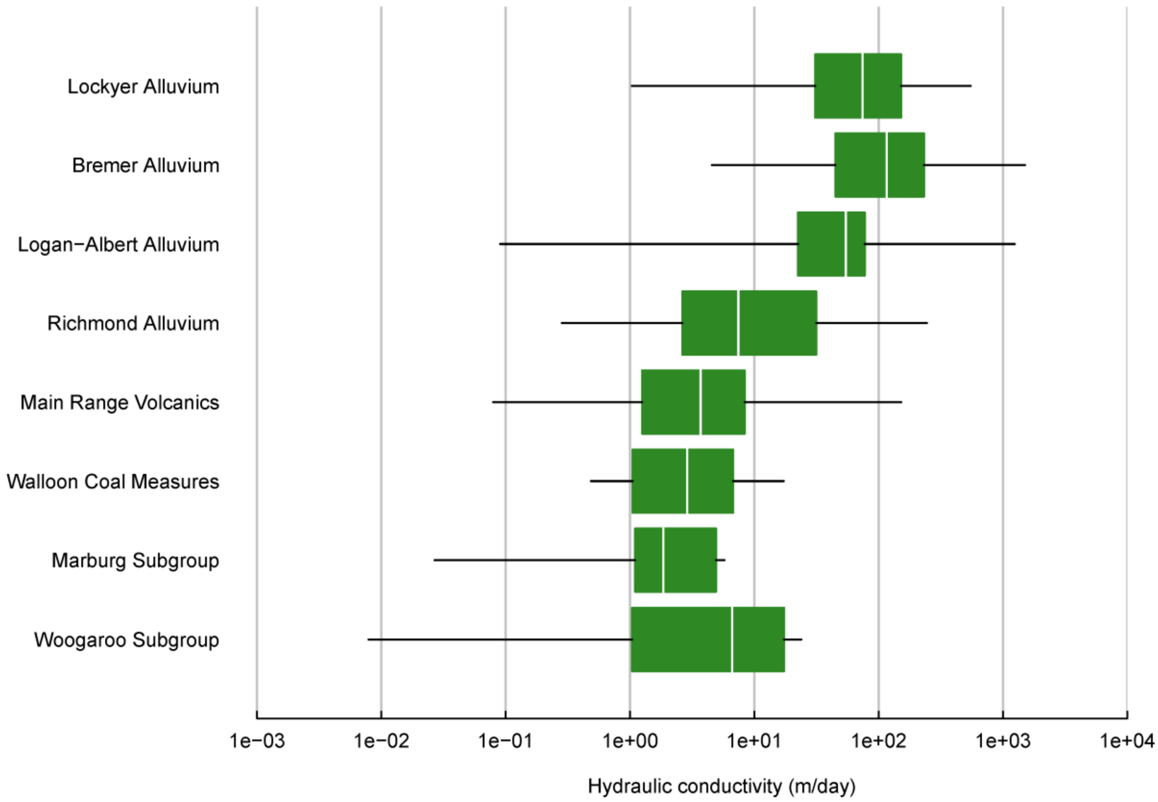

Figure 53 Box plot to show the hydraulic conductivity range of aquifers with enough data

The black lines in the plot extend to the minimum and maximum for each aquifer. The number of records for each unit downward is 30, 25, 40, 75, 39, 8, 9, and 11, respectively.

Data: Bioregional Assessment Programme (Dataset 7, Dataset 8)

2.1.3.3.3 Water chemistry and quality

Spatial variability of groundwater chemistry

Groundwater chemistry can provide useful insights into a range of important groundwater processes, including:

- groundwater recharge
- hydrochemical evolution within aquifers (e.g. influence of ion exchange or methanogenesis)
- connectivity between different aquifers
- surface water – groundwater interactions.

This section describes the results of analyses of groundwater chemistry from the records in the Queensland and NSW groundwater databases. Multivariate statistical analyses of groundwater chemistry records (hierarchical cluster analysis; HCA) were conducted to make inferences about the likely processes that control spatial and temporal variability of water chemistry. These analyses are useful in identifying areas where deep aquifers (bedrock) might interact with shallow aquifers (alluvia) and where aquifers interact with streams. It will support the development of a conceptual model of causal pathways and a numerical groundwater model in the context of coal mining and potential CSG development.

For different river basins within the Clarence-Moreton bioregion, a hydrochemical assessment of different subsets of the groundwater chemistry dataset was conducted to account for region-specific characteristics. The analysis focused on areas with similar geology to avoid 'dilution' of the hydrochemical signal. For example, in the Bremer river basin, Walloon Coal Measures and Main Range Volcanics form the bedrock underneath much of the alluvium, whereas in the Lockyer Valley, the Walloon Coal Measures are almost absent. The different subsets of hydrochemistry for which a multivariate statistical analysis was conducted are as follows:

- bedrock (all bedrock samples from the entire Clarence-Moreton bioregion combined)
- Lockyer Valley (alluvium and bedrock)
- Bremer river basin, Warrill creek catchment, Logan-Albert river basin (alluvium and bedrock)
- Richmond and Clarence river basins (alluvium and bedrock).

The results of multivariate statistical analyses should not be considered in isolation, as it is possible to misinterpret them if the results are not placed within the geological and hydrogeological context. Therefore, it is important that these results are interpreted in combination with additional lines of evidence such as:

- a three-dimensional geological model or other geological information
- other types of hydrochemical information (e.g. isotopes or maps showing the distribution of EC)
- physical hydraulic measurements (e.g. potentiometric surface map, depth to groundwater maps)
- other region-specific datasets, such as wetlands, that may be an indication of surface water – groundwater interaction
- cross-sections that allow the inference of spatial relationships between aquifers and streams in selected areas.

Only major findings are presented for the results of the multivariate statistical analysis. The median concentrations of the identified hydrochemical clusters are also shown on Piper plots to compare the major differences between clusters. More detail will be provided as part of companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016), where the hydrochemical patterns will be assessed for specific areas within the Clarence-Moreton bioregion to determine the degree of hydraulic connectivity between bedrock and shallow aquifers and between groundwater and surface water. Where sufficient data exist, this more detailed assessment will also include the differentiation of hydrochemical patterns during dry and wet periods.

Bedrock hydrochemical assessment

HCA of the bedrock water chemistry records in the Clarence-Moreton bioregion demonstrates that there is considerable hydrochemical variability, which is likely to be linked to the geological characteristics of the different bedrock formations. Following the identification and removal of outliers, seven distinct clusters were identified. The median values for the different parameters were calculated to identify the major characteristic of each cluster (Table 16). Cluster membership and source aquifer of the water chemistry sample (Figure 55) were compared to show how many water chemistry records from each stratigraphic unit were assigned to the different clusters. The spatial variability of the clusters is shown in Figure 54.

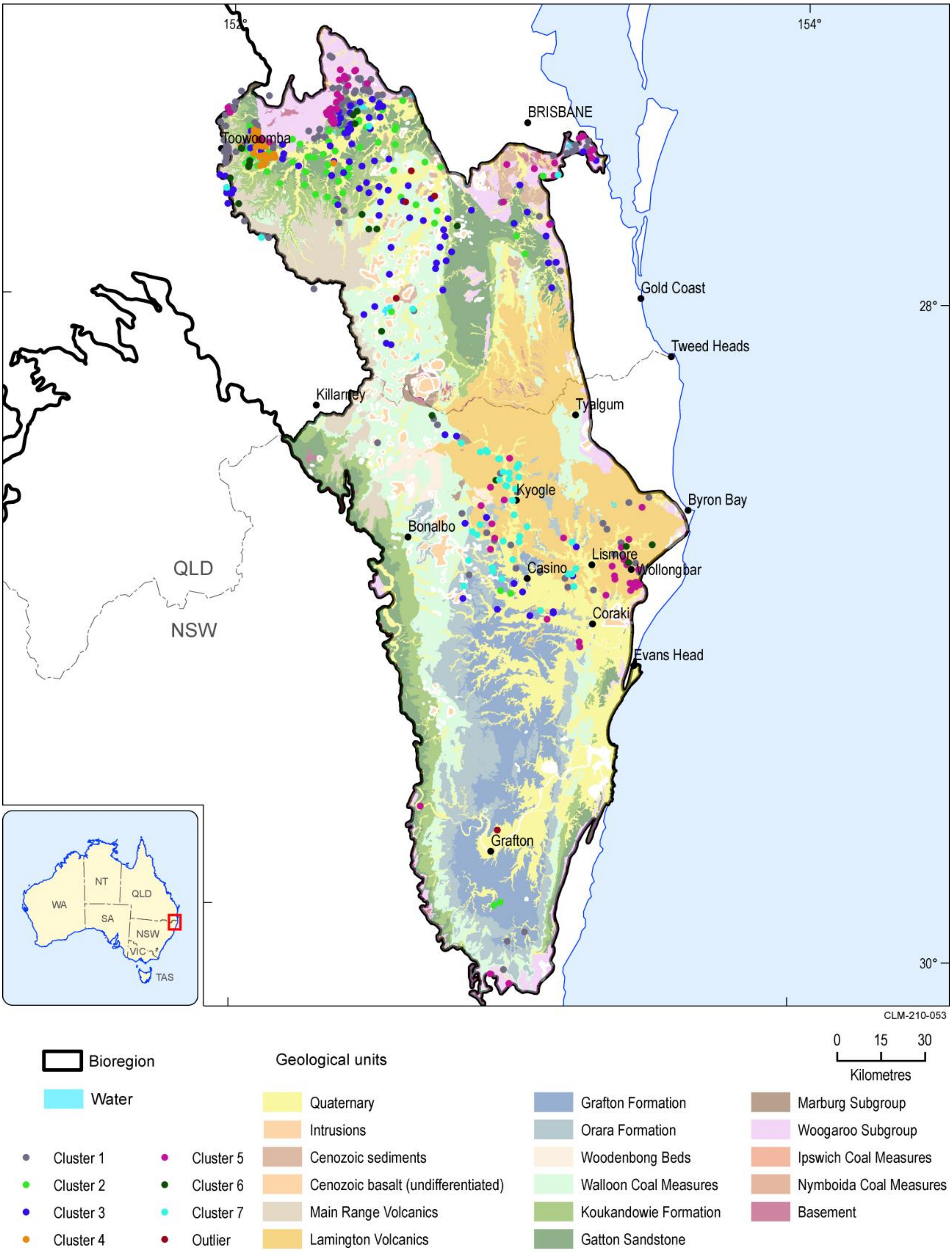

Figure 54 Spatial variability of hierarchical cluster analysis membership of bedrock groundwater in the Clarence-Moreton bioregion

Data: Bioregional Assessment Programme (Dataset 17)

Hydrochemical characteristics of major bedrock stratigraphic units

Woogaroo Subgroup. The Woogaroo Subgroup is the oldest bedrock stratigraphic unit in the Clarence-Moreton Basin. Most groundwater samples collected from the Woogaroo Subgroup were assigned during the HCA to clusters 1, 4 and 5 (Figure 55, Table 15, Table 16).

Clusters 1 and 5 generally contain fresh groundwater with median EC of 820 µS/cm and 210 µS/cm, respectively, and a dominance of HCO_3 over Cl (Figure 55). Cluster 4 contains samples that are brackish with a median EC of 3600 µS/cm. Overall, the Woogaroo Subgroup is the bedrock formation that contains the freshest groundwater in the Clarence-Moreton bioregion. This is likely attributed to the dominance of coarse-grained and clean quartz-rich sandstone as well as quartz-rich granule conglomerate over minor mudstones or siltstones (Rassam et al., 2014), and the lithological nature of this aquifer, which facilitates rapid groundwater recharge.

Some samples from the Woogaroo Subgroup, however, are assigned to cluster 2, which contains substantially more saline groundwater (median EC 12,000 µS/cm). The reasons are not clear, but could be explained in a few ways: (i) local differences in the composition of the Woogaroo Subgroup that impede groundwater recharge and movement, (ii) interactions with over- or underlying aquifer or (iii) the documented screened intervals of the bores were incorrectly assigned to the Woogaroo Subgroup.

Table 15 Median values for hydrochemical parameters of identified clusters in bedrock groundwater in the Clarence-Moreton bioregion

	Cluster 1	Cluster 2	Cluster 2a	Cluster 2b	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Number of records	209	115	86	29	166	73	105	39	55
Percentage of all records (%)	27.4%	15.1%	11.3%	3.8%	21.8%	9.6%	13.8%	5.1%	7.2%
Depth (mBGL)	62	28	25	30	32	70	35	120	16.1
EC (µS/cm)	820	12,000	9,580	19,500	4,250	3,600	210	1,700	970
pH (mg/L)	7.7	7.8	7.8	7.8	8.1	7.7	6.4	8.4	7.45
SiO_2 (mg/L)	29	25	25	20	25	13	20	14	51
Na (mg/L)	89	2,000	1,895	3,550	765	800	24	380	77
K (mg/L)	5	16	14	27	5	30	2	3	1
Ca (mg/L)	29	161	130	340	57	30	5	4	74
Mg (mg/L)	19	239	200	505	76	15	4	2	43
HCO_3 (mg/L)	250	692	722	660	707	1,700	32	460	485
Cl (mg/L)	100	3,918	3,000	7,030	997	295	28	222	87
NO_3 (mg/L)	0.5	5.0	4.0	12.5	2.5	2.0	0.5	0.5	0.7
SO_4 (mg/L)	7	199	186	334	31	10	3	6	14

Data: Bureau of Meteorology (Dataset 1), Bioregional Assessment Programme (Dataset 17)

Gatton Sandstone. The Gatton Sandstone is the second oldest bedrock stratigraphic unit of the Clarence-Moreton bioregion in this multivariate statistical analysis. Most hydrochemical records of the Gatton Sandstone are assigned to clusters 2, 3 and 4 (Figure 55, Table 16).

Groundwater assigned to cluster 2 is generally saline (median EC 12,000 µS/cm) with very low HCO_3:Cl ratios (Figure 55), whereas groundwater grouped into clusters 3 and 4 is brackish and has higher HCO_3:Cl ratios. Nearly 60% of all groundwater hydrochemical records in cluster 2 originate from the Gatton Sandstone, highlighting that the Gatton Sandstone appears to contain the most saline groundwater in the Clarence-Moreton bioregion. This distinct difference, when compared to the underlying Woogaroo Subgroup, also suggests that the hydraulic properties of the Gatton

Sandstone are very different. While the Gatton Sandstone is also dominated by sandstones, these are likely to contain substantially more clay and cement (i.e. a matrix such as calcite, dolomite or silicate minerals that bind together the grains of the rocks) than the clean sandstones of the Woogaroo Subgroup (Rassam et al., 2014). As a result of this and also the commonly thick weathering profiles, groundwater recharge to the Gatton Sandstone is likely to be very slow and the potential for evapotranspiration to occur during or prior to groundwater recharge is high. All groundwater samples assigned to cluster 4 are sourced from the Gatton Sandstone and the Woogaroo Subgroup in the western part of the Lockyer Valley near Helidon. These groundwater sources have very high HCO_3:Cl ratios (Figure 55) and elevated pH.

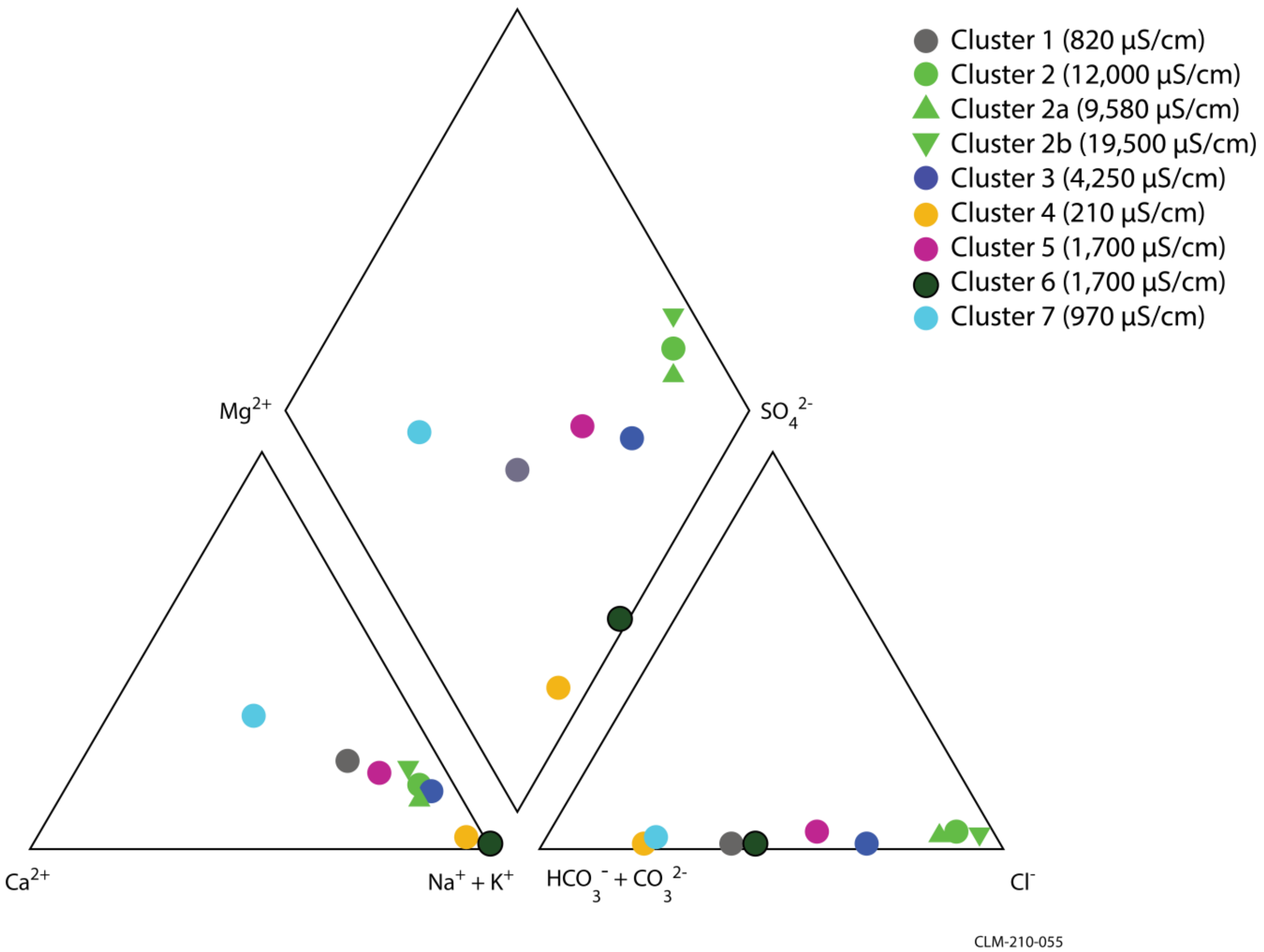

Figure 55 Piper diagram showing the major ion relationships of different bedrock hydrochemical clusters in the Clarence-Moreton bioregion (based on the median concentrations shown in Table 15)

Table 16 Cluster membership of bedrock groundwater chemistry sampling records in the Clarence-Moreton bioregion

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Total
Lamington Volcanics: count	37	0	4	0	32	11	37	121
Lamington Volcanics: percentage (%)	4.9%	0.0%	0.5%	0.0%	4.2%	1.4%	4.9%	15.9%
Main Range Volcanics: count	30	1	7	0	1	2	2	43
Main Range Volcanics: percentage (%)	3.9%	0.1%	0.9%	0.0%	0.1%	0.3%	0.3%	5.6%
Rapville (Grafton Formation): count	7	2	9	0	4	0	4	26
Rapville (Grafton Formation): percentage (%)	0.9%	0.3%	1.2%	0.0%	0.5%	0.0%	0.5%	3.4%
Piora (Grafton Formation): count	6	2	0	0	7	0	4	19
Piora (Grafton Formation): percentage (%)	0.8%	0.3%	0.0%	0.0%	0.9%	0.0%	0.5%	2.5%
Bungawalbin Member (Orara Formation): count	0	0	1	0	1	0	2	4
Bungawalbin Member (Orara Formation): percentage (%)	0.0%	0.0%	0.1%	0.0%	0.1%	0.0%	0.3%	0.5%
Walloon Coal Measures: count	15	18	39	0	0	9	3	84
Walloon Coal Measures: percentage (%)	2.0%	2.4%	5.1%	0.0%	0.0%	1.2%	0.4%	11.1%
Marburg Subgroup undifferentiated: count	3	7	7	0	0	9	0	26
Marburg Subgroup undifferentiated: percentage (%)	0.4%	0.9%	0.7%	0.0%	0.0%	1.2%	0.0%	3.2%
Koukandowie Formation: count	3	5	13	0	0	0	0	21
Koukandowie Formation: percentage (%)	0.4%	0.7%	1.7%	0.0%	0.0%	0.0%	0.0%	2.8%

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Total
Gatton Sandstone: count	15	67	74	43	5	3	2	209
Gatton Sandstone: percentage (%)	2.0%	8.8%	9.7%	5.6%	0.7%	0.4%	0.3%	27.5%
Woogaroo Subgroup: count	93	13	12	30	55	5	1	209
Woogaroo Subgroup: percentage (%)	12.2%	1.7%	1.6%	3.9%	7.2%	0.7%	0.0%	27.5%
Cluster total: count	209	115	166	73	105	39	55	762
Cluster total: percentage (%)	27.4%	15.1%	21.8%	9.6%	13.8%	5.1%	7.2%	100.0%

Data: Bureau of Meteorology (Dataset 1), Bioregional Assessment Programme (Dataset 17)

Koukandowie Formation. The hydrochemistry of groundwater collected from the Koukandowie Formation in the Clarence-Moreton bioregion shows similarities to the Gatton Sandstone, as indicated by the assignment of all samples to clusters 1, 2 and 3 and the dominance of brackish to saline groundwater. This indicates that the composition of the Koukandowie Formation is similar to the Gatton Sandstone, and hydraulic properties are likely similar.

Walloon Coal Measures. Most Walloon Coal Measures groundwater chemistry records contained within the Queensland and NSW groundwater databases for the Clarence-Moreton bioregion were collected from the Bremer river basin and the Logan-Albert river basin. Most of the outliers removed from the entire groundwater chemistry dataset prior to HCA are from the Walloon Coal Measures in the Bremer river basin (Figure 54). The characteristic properties that differentiate the outliers from other samples are their very high pH and very low HCO_3 concentrations (pH is outside the range where HCO_3 is the dominant carbonate species).

During the HCA, the hydrochemical records of the Walloon Coal Measures were mostly assigned to clusters 1, 2 and 3. A further subdivision of cluster 2 into clusters 2a and 2b (Table 15 and Figure 55) shows that there are two distinct groups with a median of 9,580 µS/cm and 19,500 µS/cm, respectively. Most of the Walloon Coal Measures groundwater samples were assigned to the more saline cluster 2b. This is attributed to very low recharge rates and long retention times in the unsaturated zone prior to groundwater recharge, causing a high degree of evapotranspiration.

Walloon Coal Measures groundwater that has interacted with coal is assigned to cluster 6. These groundwater samples show the typical characteristics of CSG groundwater (Van Voast, 2003), such as elevated pH and very high Na and HCO_3 concentrations, and simultaneously low Ca, Mg and SO_4 concentrations as shown in the Piper diagram (Figure 55). This was independently confirmed by the analysis of dissolved methane (Raiber, unpublished data) which showed high concentrations for these groundwater samples. However, rather than being controlled exclusively by methanogenesis, some of these characteristics are also due to the influence of ion exchange: Ca and Mg are exchanged for Na. This is indicated by the large number of samples from the Main Range Volcanics and Lamington Volcanics contained in the same cluster (Table 16 and Figure 54). A further subdivision of this cluster would likely result in a separation of groundwater from the Walloon Coal Measure and the volcanic aquifers.

Bungawalbin Member (Orara Formation). Only four groundwater chemistry records assigned to the Bungawalbin Member were included in the HCA. These were assigned to clusters 3, 5 and 7 (Figure 55, Table 16), but due to the small number of samples, it is not possible to make any inferences about groundwater chemistry patterns within the Bungawalbin Member.

Piora Member (Grafton Formation). Groundwater chemistry samples from the Piora Member, which is only present in the NSW part of the Clarence-Moreton Basin, were assigned to clusters 1, 2, 5 and 7 (Figure 55, Table 16). Most of the samples assigned to these clusters contain comparatively fresh groundwater, and this freshness suggests that the Piora Member is likely to be a good aquifer (i.e. relatively high yields and relatively fresh groundwater) with comparatively high recharge rates. The similarity of groundwater of the Piora Member and groundwater sourced from the Lamington Volcanics suggests that the Piora Member is recharged through the overlying basalts.

Rapville Member (Grafton Formation). Similarly to the Piora Member, the Rapville Member is characterised by variable groundwater chemistry, as documented by the assignment of samples to clusters 1, 2, 3, 5 and 7 (Figure 55, Table 16). This might reflect a variable composition of this formation, but possibly also variable recharge processes. For example, the fresh groundwater of the Rapville Member assigned to cluster 5 might be related to recharge through the Lamington Volcanics, which overlie the formation in the north-eastern part of NSW, whereas the brackish groundwater might be related to recharge through outcrops of the formation. In contrast to the Piora Member, groundwater samples of the Rapville Member are also assigned to cluster 3, which contains more saline groundwater.

Main Range Volcanics and Lamington Volcanics. Most groundwater samples from the Main Range Volcanics are assigned to cluster 1, which contains samples that are characterised by their freshness (median 820 µS/cm) and high HCO_3:Cl ratios (Figure 55). Interestingly, the Lamington Volcanics show more hydrochemical variability, as documented by assignment of most samples to clusters 1, 5 and 7. Cluster 7 samples are fresher than cluster 1 groundwater samples and have higher HCO_3:Cl ratios (Figure 55). Furthermore, they were collected from bores that are shallower (median depth of 35 m below ground level) than the bores from which the cluster 1 samples originate (median depth of 62 m). This suggests that within the Lamington Volcanics, there appears to be a depth-related resolution that results in an increase of EC with depth. This indicates that there are shallow flow paths where groundwater is recharged rapidly and probably has only short residence times within the aquifers before it discharges at springs (discussed in more detail in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016)).

Lockyer Valley hydrochemical assessment

Seven clusters were identified during the HCA of groundwater chemistry in the Lockyer Valley. The main focus of this catchment-scale hydrochemical assessment was to identify areas where the alluvial aquifers interact with the bedrock or with surface water systems. While a very comprehensive evaluation of the spatial and temporal patterns is beyond the scope of the Assessment (but will be studied in more detail in subsequent parts of this Assessment), some key characteristics are:

- Most alluvial groundwater chemistry records are assigned to clusters 2, 3, 5 and 6 (Figure 56). The median ECs of these clusters are highly variable, ranging from fresh (median of approximately 850 µS/cm in cluster 6 (Table 18)) to saline (median of approximately 9300 µS/cm in cluster 2 (Table 18)). This variability highlights the complex nature of groundwater recharge in this catchment.
- Many of the alluvial groundwater samples assigned to the most saline cluster (cluster 2) were collected from the alluvial systems of smaller tributary systems of the central Lockyer Creek drainage line. In their headwaters, most of these smaller tributaries are generally not deeply incised into the Main Range Volcanics of the Great Dividing Range. As a result, there is little or no influence of the basalts on the water chemistry, and instead it is influenced by discharge from the bedrock (Gatton Sandstone and Koukandowie Formation, which contain saline groundwater throughout most of the catchment) to the alluvium. In addition, saline alluvial groundwater samples of cluster 2 are also present at the edge of the alluvium throughout different parts of the catchment, confirming that the Gatton Sandstone and the Koukandowie Formation discharge into the alluvial aquifer at the edge of the alluvium.
- Alluvial groundwater samples assigned to cluster 6 (median EC of ~850 µS/cm (Table 18)) dominate the headwaters of the larger tributaries of the Lockyer Creek such as Laidley Creek (Figure 57), but are also present further downstream. Apart from their low salinities, groundwater samples within this cluster are characterised by relatively high Ca:Na and Mg:Na and HCO_3:Cl ratios (Figure 56). These are typical hydrochemical characteristics of groundwater recharge by streams (Raiber et al., 2012), although basalt groundwater from the Main Range Volcanics can also share these attributes (Figure 56, Table 17). These tributary systems are deeply incised into the Main Range Volcanics in their headwaters, and the hydrochemical results confirm that there is a strong hydraulic connection of the alluvial aquifers with the basalts of the Main Range Volcanics. In addition, the presence of cluster 6 groundwater samples further down-gradient highlights a high degree of surface water – groundwater connectivity.

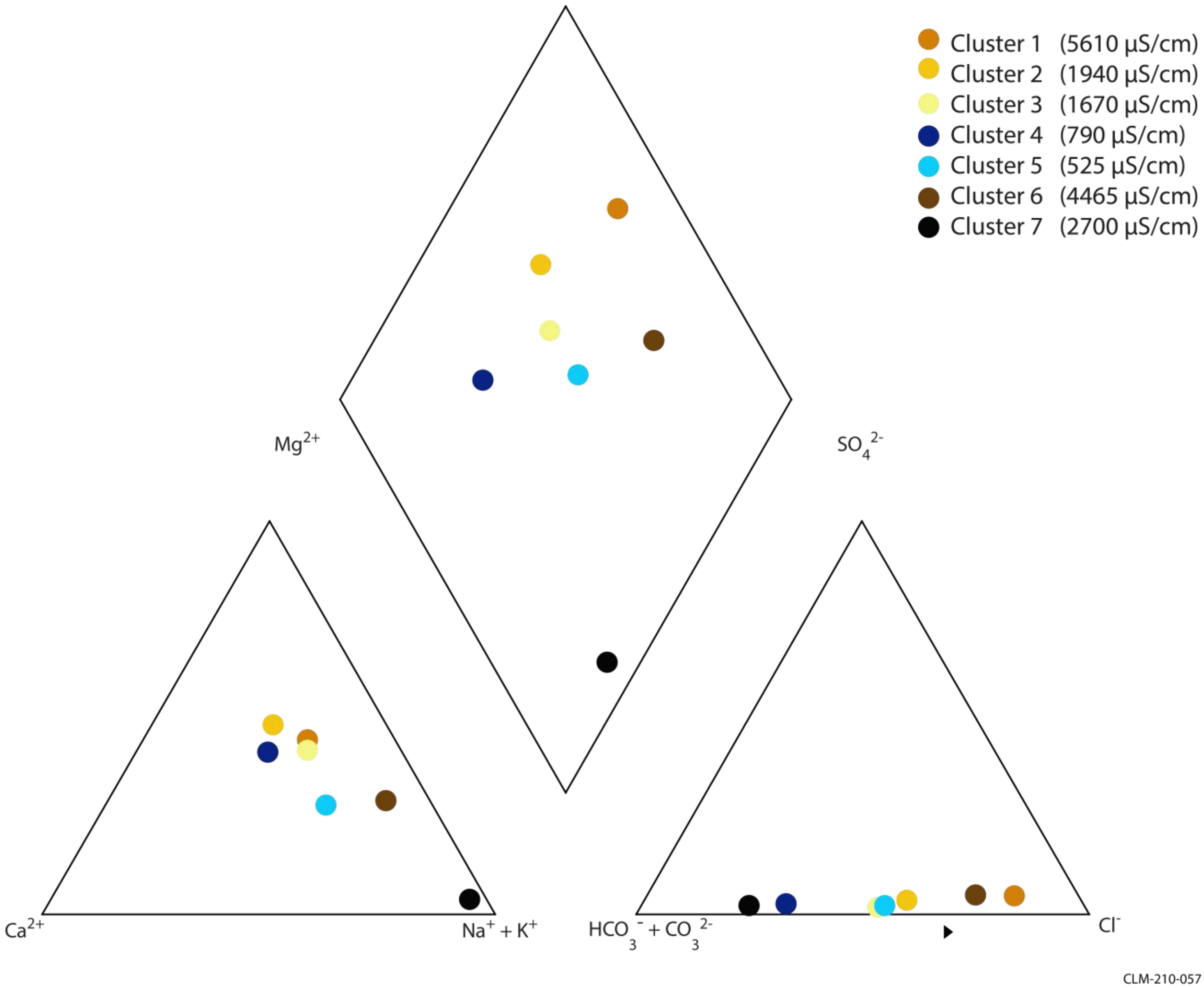

Figure 56 Piper diagram showing the major ion relationships of hydrochemical clusters in the Lockyer Valley (based on the median concentrations shown in Table 17)

Table 17 Comparison of cluster membership and stratigraphic formation for hydrochemical assessment in the Lockyer Valley

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7	Total
Alluvium: count	1	159	360	21	400	415	66	1422
Alluvium: percentage (%)	0.1%	7.3%	16.5%	1%	18.4%	19.1%	3%	65%
Main Range Volcanics: count	0	1	1	3	4	20	0	29
Main Range Volcanics: percentage (%)	0%	0.1%	0.1%	0.1%	0.2%	0.9%	0%	1.4%
Koukandowie Formation: count	0	0	0	0	2	0	0	2
Koukandowie Formation: percentage (%)	0%	0%	0%	0%	0.1%	0%	0%	0.1%
Gatton Sandstone: count	34	34	41	2	13	6	11	141
Gatton Sandstone: percentage (%)	1.6%	1.6%	1.9%	0.1%	0.6%	0.3%	0.5%	7%
Marburg Subgroup (undifferentiated): count	0	6	0	0	0	0	15	21
Marburg Subgroup (undifferentiated): percentage (%)	0%	0.3%	0%	0%	0%	0%	0.7%	1%
Woogaroo Subgroup: count	27	6	1	68	3	17	24	146
Woogaroo Subgroup: percentage (%)	1.2%	0.3%	0.1%	3.1%	0.1%	0.8%	1.1%	6.7%
Unknown: count	74	52	41	59	59	92	41	418
Unknown: percentage (%)	3.4%	2.4%	1.9%	2.7%	2.7%	4.2%	1.9%	19.2%
Total: count	136	258	444	153	481	550	157	2179
Total: percentage (%)	6.2%	11.8%	20.4%	7%	22.1%	25.2%	7.2%	99.9%

Table 18 Median values for hydrochemical parameters of identified clusters in the Lockyer Valley

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
Number of records	136	258	444	153	481	550	157
Percentage (%)	6%	12%	20%	7%	22%	25%	7%
Electrical conductivity (µS/cm)	3600	9286	3510	381	1974	857	1495
pH	7.8	7.6	7.9	6.9	8.0	8.0	8.1
SiO_2 (mg/L)	13	29	35	24	35	41	18
Na (mg/L)	853	1096	288	47	162	65	208
K (mg/L)	28	7	3	5	2	1	4
Ca (mg/L)	28	266	121	10	82	47	29
Mg (mg/L)	14	364	168	7	98	39	27
HCO_3 (mg/L)	1876	548	535	74	499	317	438
Cl (mg/L)	306	2891	855	61	373	103	255
NO_3 (mg/L)	2	16	14	1	3	2	1
SO_4 (mg/L)	13	217	50	1	21	8	11

Data: Bioregional Assessment Programme (Dataset 18)

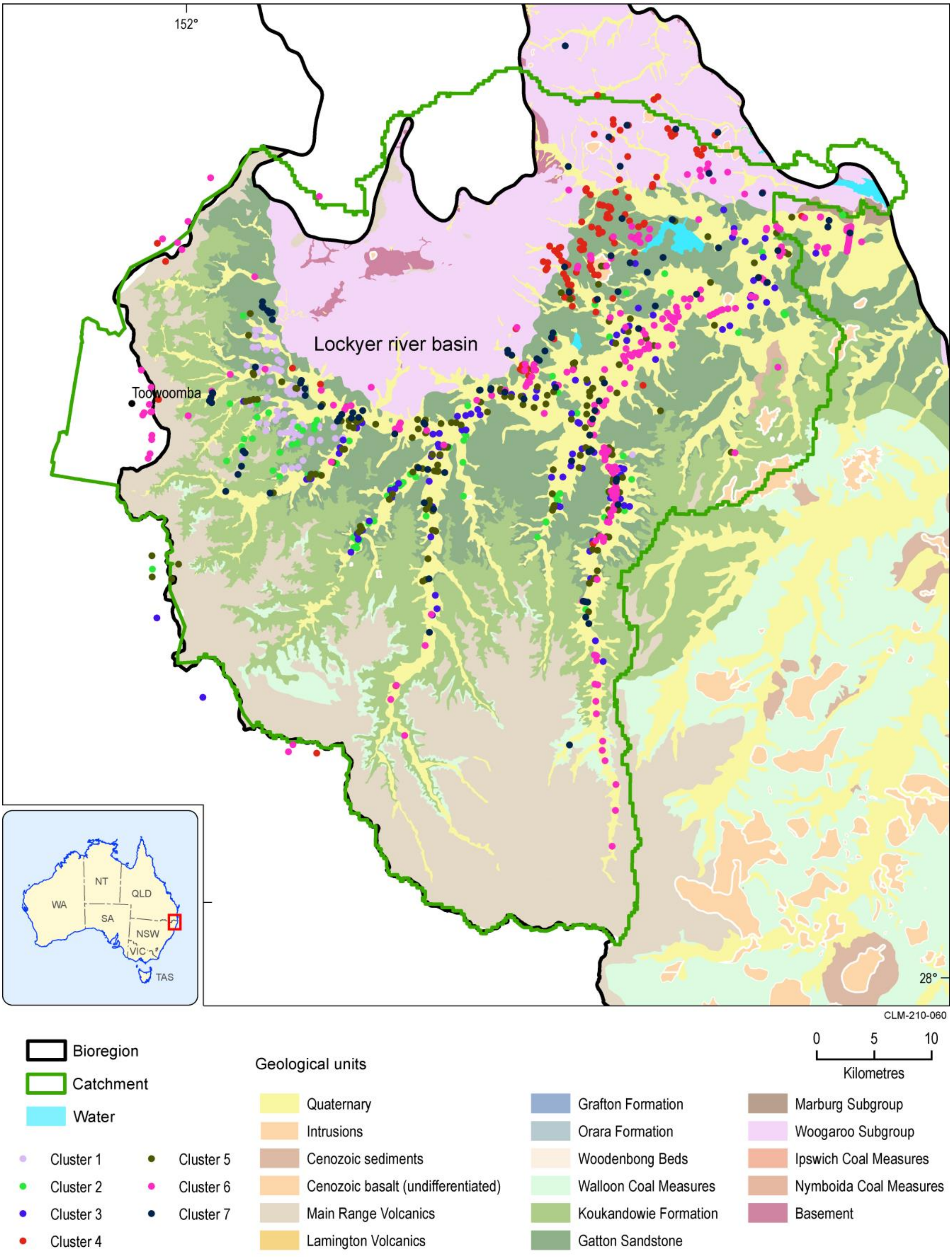

Figure 57 Spatial variability of hierarchical cluster analysis membership of alluvial and bedrock groundwater in the Lockyer Valley

Data: Bioregional Assessment Programme (Dataset 18)

Bremer river basin, Warrill Creek catchment and Logan-Albert river basin hydrochemical assessment

The Bremer river basin and Warrill creek catchment, as well as the Logan-Albert river basin, are dominated by the extensive outcrops of the Walloon Coal Measures and the presence of the basalts of the Great Dividing Range (Main Range Volcanics) and the Lamington Plateau (Lamington Volcanics) in the headwaters of the major rivers and creeks. Due to their geological similarities, the water chemistries of these river basins were assessed together.

Five distinct hydrochemical clusters were identified during the HCA. The major chemical characteristics of the alluvial groundwater in these river basins are:

Median groundwater EC of the clusters that were identified during the HCA in these catchments range from 860 µS/cm to approximately 6925 µS/cm (cluster 1, Table 19). Most alluvial groundwater samples were assigned to clusters 2 and 3 (Table 20).

- Groundwater assigned to cluster 3 (median EC of approximately 950 µS/cm) occurs primarily in the headwaters or close to the central drainage line of the major rivers and creeks (e.g. Bremer River, Warrill Creek and Logan-Albert River (Figure 59)). Cluster 3 is characterised by high HCO_3:Cl ratios and high Ca:Na and Mg:Na ratios (Figure 58), all of which are characteristics of groundwater recharged by streams and through the basaltic aquifers. This groundwater is therefore likely to be related to direct or indirect (via surface water runoff) recharge from the basalts of the Main Range Volcanics and Lamington Volcanics, which are prominent in the headwaters of these river basins. Further downstream, the presence of cluster 3 near the central drainage lines in the Bremer river basin and Warrill creek catchment also indicates that surface water recharge to the alluvial aquifer occurs here.
- The more saline alluvial groundwater (cluster 1; Table 19) has very high Cl:HCO_3 and very low Ca:Na and Mg:Na ratios (Figure 58), and was collected from bores further down-gradient. These bores are mostly located at the edge of the alluvium, and the water chemistry in these bores is more similar to the groundwater chemistry of the Walloon Coal Measures, which form the outcrop over much of the Bremer river basin and Warrill creek catchment and which typically contain relatively saline groundwater. The hydrochemical similarity within the alluvial aquifer and the underlying bedrock aquifer suggests that these aquifers are hydraulically connected.
- Where observation bore transects exist across floodplains, a typical pattern that can be observed is that of salinity increasing away from the creeks towards the edge of the alluvial aquifer. This transition is accompanied by a change from mostly cluster 3 near the central drainage lines towards the more saline clusters 1, 2 or 5.

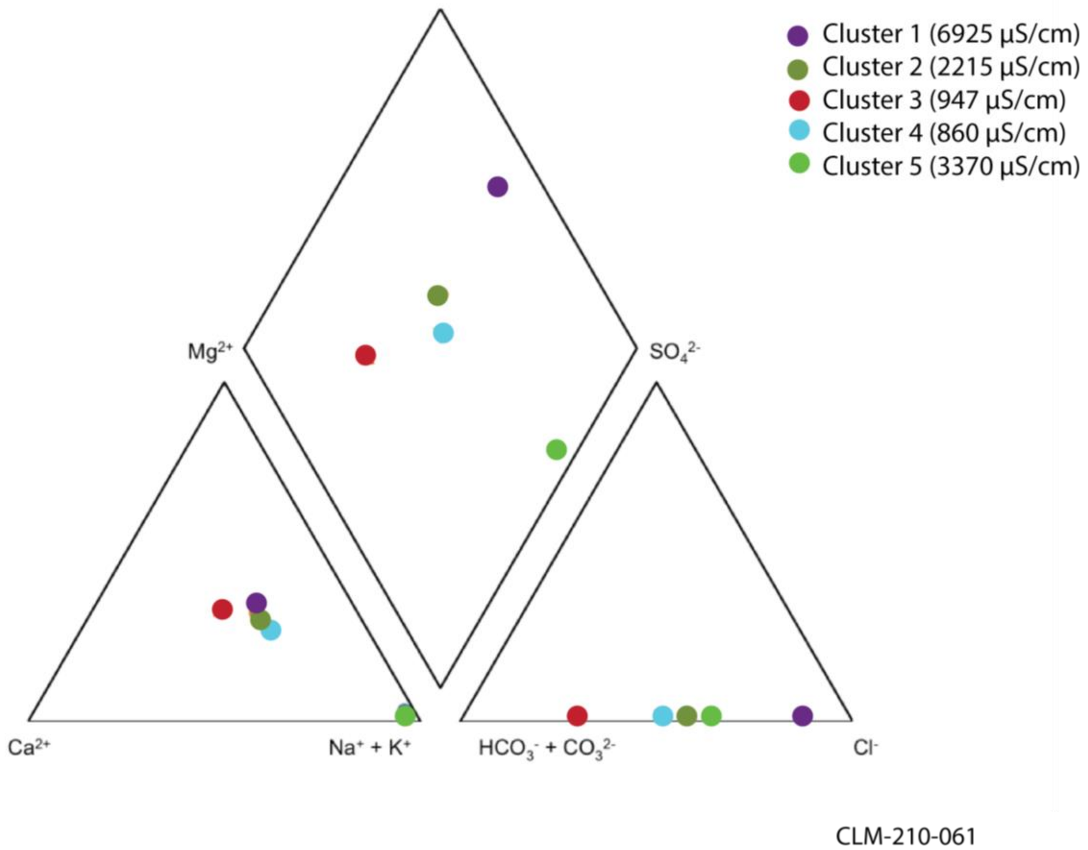

Figure 58 Piper diagram showing the major ion relationships of hydrochemical clusters in the Warrill creek catchment, Bremer and Logan-Albert river basins (based on median concentrations shown in Table 19)

Table 19 Median values for hydrochemical parameters for different clusters in the Warrill creek catchment and Bremer and Logan-Albert river basins

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
Number of records	104	230	203	125	43
Percentage (%)	15%	33%	28.7%	17.8%	6.1%
Electrical conductivity (µS/cm)	6925	2215	947	860	3370
pH	7.5	7.8	8	7.4	8.2
SiO_2 (mg/L)	36	39	43	23	18
Na (mg/L)	599	205	71	80	680
K (mg/L)	5	2	1	3	3
Ca (mg/L)	313	110	66	37	16
Mg (mg/L)	276	83	39	24	12
HCO_3 (mg/L)	552	552	416	205	740
Cl (mg/L)	2270	434	100	125	762
NO_3 (mg/L)	5	2	1	1	3
SO_4 (mg/L)	55	13	5	4	20

Data: Bioregional Assessment Programme (Dataset 18)

Table 20 Comparison of groundwater cluster membership and stratigraphic formation for the Warrill creek catchment and Bremer and Logan-Albert river basins

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Total
Alluvium: count	76	189	177	78	5	525
Alluvium: percentage (%)	10.78%	26.8%	25.1%	11.1%	0.7%	74.5%
Main Range Volcanics: count	2	1	1	1	0	5
Main Range Volcanics: percentage (%)	0.28%	0.1%	0.1%	0.1%	0.0%	0.6%
Walloon Coal Measures: count	9	5	7	2	17	40
Walloon Coal Measures: percentage (%)	1.28%	0.7%	1.0%	0.3%	2.4%	5.7%
Koukandowie Formation: count	1	0	0	0	4	5
Koukandowie Formation: percentage (%)	0.14%	0.0%	0.0%	0.0%	0.6%	0.7%
Gatton Sandstone: count	2	3	0	1	5	11
Gatton Sandstone: percentage (%)	0.28%	0.4%	0.0%	0.1%	0.7%	1.5%
Marburg Subgroup undifferentiated: count	0	0	0	0	1	1
Marburg Subgroup undifferentiated: percentage (%)	0%	0.0%	0.0%	0.0%	0.1%	0.1%
Woogaroo Subgroup: count	1	3	2	15	0	21
Woogaroo Subgroup: percentage (%)	0.14%	0.4%	0.3%	2.1%	0.0%	2.9%
Unknown: count	13	29	16	28	11	97
Unknown: percentage (%)	1.84%	4.1%	2.3%	4.0%	1.6%	13.8%
Cluster total: count	104	230	203	125	43	705
Cluster total: percentage (%)	14.75%	32.6%	28.8%	17.7%	6.1%	99.9%

Data: Bioregional Assessment Programme (Dataset 18)

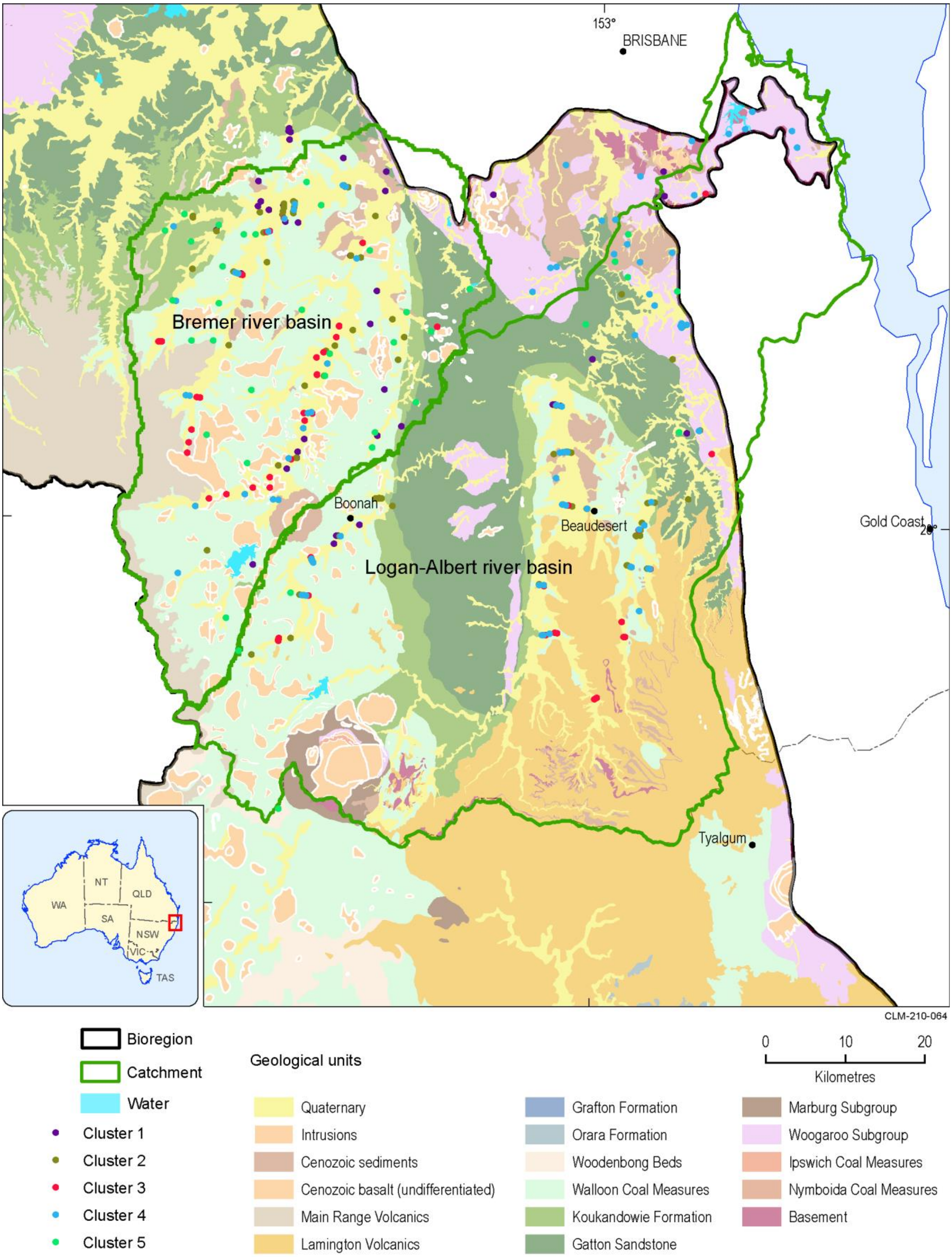

Figure 59 Spatial variability of hierarchical cluster analysis membership of alluvial and bedrock groundwater in the Warrill creek catchment and Bremer and Logan-Albert river basins

Data: Bioregional Assessment Programme (Dataset 18)

Hydrochemical assessment of the Richmond and Clarence river basins

Six hydrochemical clusters were identified during the HCA of groundwater chemistry in the Richmond and Clarence river basins (most samples are sourced from the Richmond River; Table 21, Figure 60).

Major characteristics of the hydrochemistry in the Richmond and Clarence river basins are:

- Cluster 4 alluvial groundwater samples dominate the headwaters of the Richmond River alluvium in the western part of the Lamington Plateau near Kyogle (Figure 60). As noted before in the hydrochemical assessment of the bedrock stratigraphic units (Table 15, Figure 55, Table 16), two distinct groups with very fresh and fresh groundwater, respectively, have been identified within the Lamington Volcanics. Alluvial groundwater samples assigned to cluster 4 in the assessment of hydrochemical variability within the Richmond river basin have high HCO_3:Cl ratios and high Ca:Na and Mg:Na ratios (Figure 61). These groundwater samples are likely to have evolved by discharge from the bedrock into the alluvium or surface water recharge.
- Clusters 2 and 3 contain the more saline groundwater in the Richmond and Clarence river basins. These sampling sites are primarily located on the floodplains of Richmond River, and indicate a lack of influence of the Lamington Volcanics, less influence of surface water recharge and more influence of rainfall recharge. The absence of hydrochemical signatures that indicate surface water recharge on the central part of the floodplain in the Richmond river basin contrasts with the hydrochemical observation from other river basins within the Clarence-Moreton bioregion. This may be linked to the different geomorphological and geological characteristics of the Richmond river basin, where the alluvial aquifer system is much wider and has a lower width-to-depth ratio than other alluvia within the Clarence-Moreton bioregion.
- Clusters 5 and 6 contain the freshest groundwater in the Richmond river basin. These groundwater samples were mostly collected from the eastern part of the Richmond river basin. This groundwater was likely recharged via discharge from the basalts or surface water recharge in the steep headwater catchments in this area. Unlike other fresh groundwater in the Clarence-Moreton bioregion, this groundwater has lower HCO_3:Cl and lower Ca:Na and Mg:Na ratios (Figure 61).

Generally, it appears as if the groundwater in the Richmond river basin is fresher than in the river basins north of the state border between NSW and Queensland. There appears to be less interaction of the sedimentary bedrock units, which contain the most saline groundwater with shallow alluvial aquifers, namely the Gatton Sandstone, Koukandowie Formation and the Walloon Coal Measures south of the border, as the areas where these bedrock units underlie alluvial systems are much smaller than in south-east Queensland. Furthermore, the extent of the volcanic bedrock which is generally associated with high recharge rates and fresh groundwater in the Richmond river basin is larger than in the Lockyer Valley or Bremer river basin. This means that the influence of this volcanic bedrock aquifer on adjacent alluvial aquifers is larger in the Richmond river basin than elsewhere within the Clarence-Moreton bioregion (further discussed in companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016)).

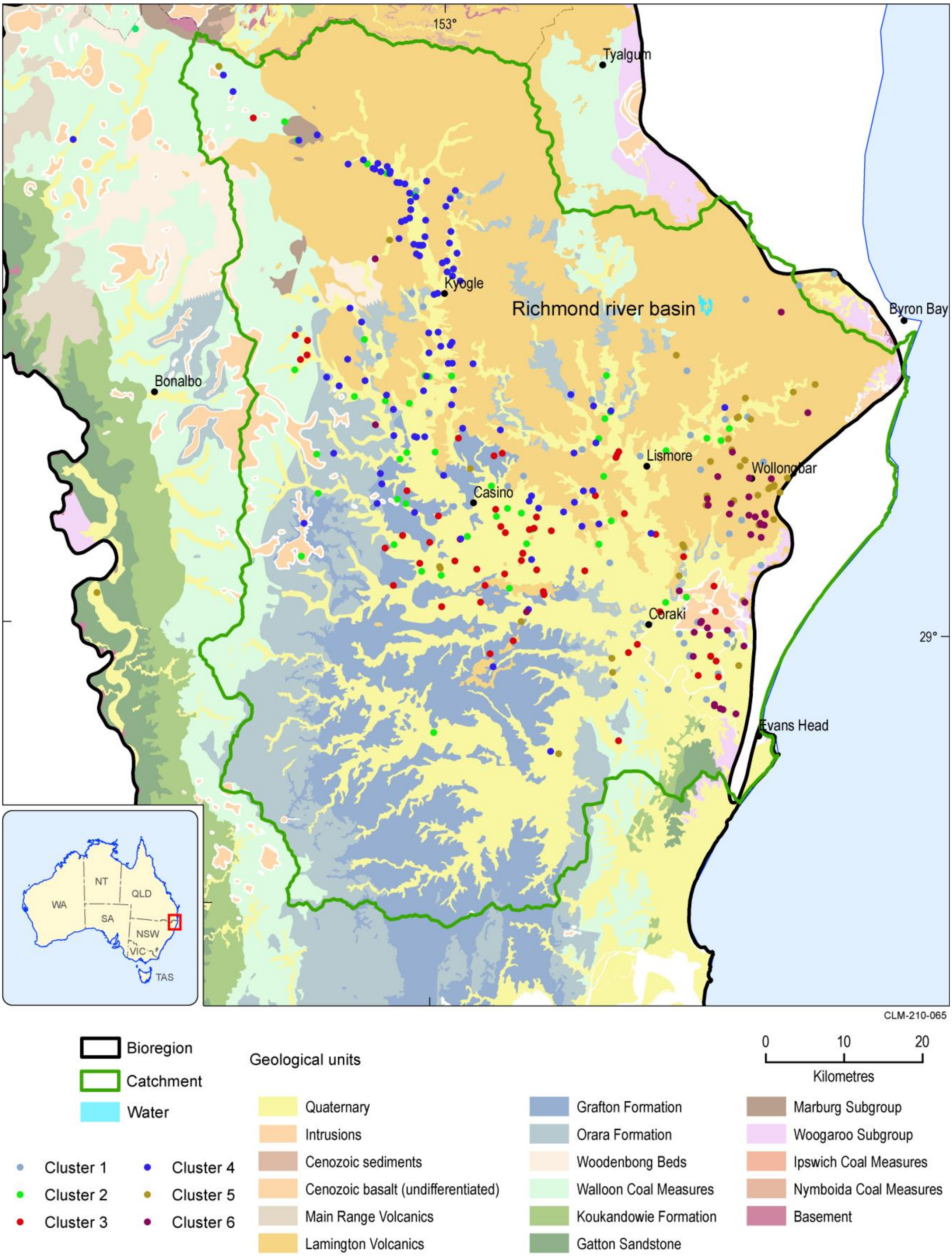

Figure 60 Spatial variability of hierarchical cluster analysis membership of alluvial and bedrock groundwater in the Richmond river and Clarence river basins

Data: Bioregional Assessment Programme (Dataset 19)

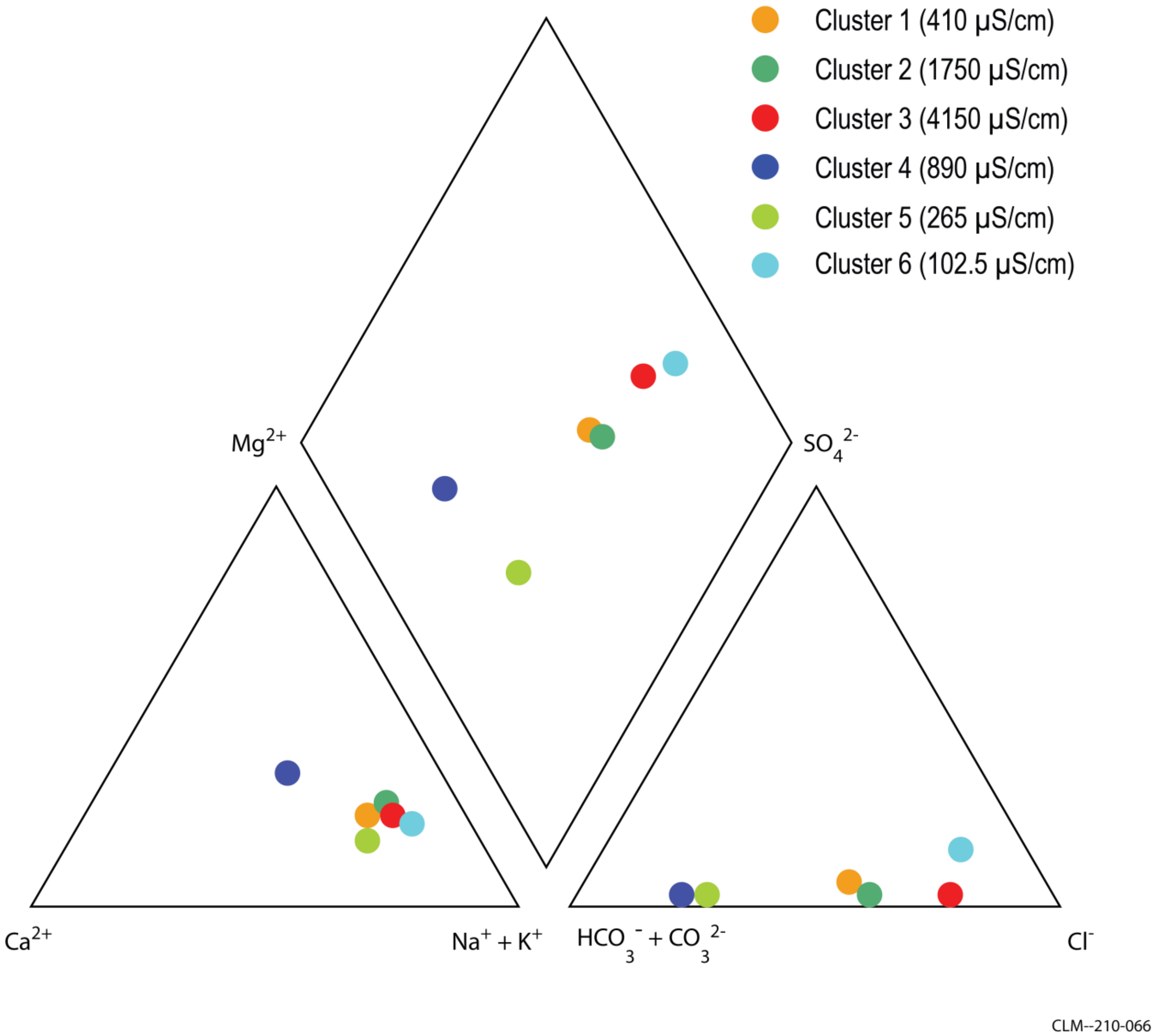

Figure 61 Piper plot showing the major ion relationships of different hydrochemical clusters in the Richmond and Clarence river basins (based on median concentrations shown in Table 21)

Table 21 Median values for hydrochemical parameters for different clusters in the Richmond and Clarence river basins

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Count	81	86	74	180	84	54
Percentage (%)	14.49%	15.38%	13.24%	32.2%	15.03%	9.66%
Depth (mBGL)	23.6	25.9	22.5	25.3	39.8	17.1
Electrical conductivity (µS/cm)	410	1750	4150	890	265.5	102.5
pH	6.64	7.45	7.25	7.45	7.75	5.7
Na (mg/L)	43	269	563	72	26	12
K (mg/L)	3	3	4	2	2	1
Ca (mg/L)	14	62	124	57	9	2
Mg (mg/L)	9	56	109	34	4	2
HCO_3 (mg/L)	83	394	567	432	110	7
Cl (mg/L)	63	347	1103	72	23	19
SO_4 (mg/L)	10	24	61	7	4	5

Data: Bioregional Assessment Programme (Dataset 19)

Table 22 Comparison of groundwater cluster membership and stratigraphic formation for the Richmond and Clarence river basins

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Total
Alluvium: count	52	41	42	80	33	22	270
Alluvium: percentage (%)	9.3%	7.3%	7.5%	14.3%	5.9%	3.9%	48.2%
Lamington Volcanics: count	9	19	1	37	38	15	119
Lamington Volcanics: percentage (%)	1.6%	3.4%	0.2%	6.6%	6.8%	2.7%	21.3%
Rapville Member: count	1	4	8	10	0	3	26
Rapville Member: percentage (%)	0.2%	0.7%	1.4%	1.8%	0.0%	0.5%	4.6%
Piora Member: count	3	4	2	7	1	2	19
Piora Member: percentage (%)	0.5%	0.7%	0.4%	1.3%	0.2%	0.4%	3.5%
Bungawalbin Member: count	1	1	0	0	0	0	2
Bungawalbin Member: percentage (%)	0.2%	0.2%	0.0%	0.0%	0.0%	0.0%	0.4%
Walloone Coal Meaures: count	1	1	2	5	1	0	10
Walloon Coal Measures: percentage (%)	0.2%	0.2%	0.4%	0.9%	0.2%	0.0%	1.9%
Gatton Sandstone: count	1	1	0	1	0	2	5
Gatton Sandstone: percentage (%)	0.2%	0.2%	0.0%	0.2%	0.0%	0.4%	1.0%
Unknown: count	13	15	19	2	11	10	70
Unknown: percentage (%)	2.3%	2.7%	3.4%	6.8%	2.0%	1.8%	19.0%
Cluster total: count	81	86	74	180	84	54	559
Cluster total: percentage (%)	14.5%	15.4%	13.2%	32.2%	15.0%	9.7%	100.0%

Data: Bioregional Assessment Programme (Dataset 19)

Temporal variability of groundwater chemistry

While a comprehensive assessment of the temporal change of groundwater chemistry is outside the scope of this report, an assessment was conducted from sites where at least eight groundwater chemistry sampling events were conducted to assess whether cluster membership changes over time. As shown in Table 23, Table 24 and Table 25, there appears to be considerable variability, and for many of the sites, the cluster membership switches between at least two clusters. Many of these sites are located relatively close to creeks or rivers, suggesting that there may be a change of recharge mechanism, e.g. more surface-water dominated during periods of above average rainfall, and a stronger influence of rainfall recharge or discharge from the underlying bedrock at other times. The variability of surface water – groundwater connectivity is discussed in more detail in Section 2.1.5.

Table 23 Temporal variability of hierarchical cluster analysis membership in the Lockyer Valley for bores where time-series data are available (the numbers correspond to the number of hydrochemical records assigned to a cluster)

Bore registration number	Aquifer	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6	Cluster 7
14320033	Alluvium	NA	NA	NA	NA	2	NA	7
14320101	Alluvium	NA	NA	NA	NA	5	5	NA
14320130	Alluvium	NA	NA	NA	NA	3	8	NA
14320268	Alluvium	NA	NA	2	NA	5	NA	2
14320317	Alluvium	NA	9	NA	NA	NA	NA	NA
14320339	Alluvium	NA	1	7	NA	1	NA	NA
14320432	Alluvium	NA	NA	NA	NA	11	NA	NA
14320435	Alluvium	NA	NA	5	NA	5	NA	NA
14320462	Alluvium	NA	NA	8	NA	5	NA	NA
14320477	Alluvium	NA	NA	7	NA	6	NA	NA
14320493	Alluvium	NA	10	2	NA	NA	NA	NA
14320528	Alluvium	NA	NA	NA	NA	9	NA	NA
14320711	Gatton Sandstone	NA	NA	8	NA	NA	NA	NA

NA = data not available
Data: Bioregional Assessment Programme (Dataset 18)

Table 24 Temporal variability of hierarchical cluster analysis membership in the Richmond river basin for bores where time-series data are available (the numbers correspond to the number of hydrochemical records assigned to a cluster)

Bore registration number	Aquifer	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
GW39152	Alluvium	4	NA	NA	5	1	5
GW39107	Alluvium	NA	NA	3	4	4	NA
GW39132	Alluvium	1	NA	NA	8	NA	NA
GW39149	Alluvium	NA	6	2	NA	NA	NA

NA = data not available
Data: Bioregional Assessment Programme (Dataset 19)

Table 25 Temporal variability of hierarchical cluster analysis membership in the Warrill creek catchment and Bremer and Logan-Albert river basins for bores where time series data are available (the numbers correspond to the number of hydrochemical records assigned to a cluster)

Bore registration number	Aquifer	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
14310086	Alluvium	NA	12	NA	NA	NA	NA
14500086	Alluvium	NA	9	1	NA	NA	NA
14500095	Alluvium	9	3	NA	NA	NA	NA
14500097	Alluvium	NA	12	NA	NA	NA	NA
14500098	Alluvium	10	NA	NA	NA	NA	NA
14500100	Alluvium	NA	12	NA	NA	NA	NA
14500110	Alluvium	NA	NA	9	NA	NA	NA
14500115	Alluvium	NA	NA	11	1	NA	NA
14500117	Alluvium	NA	NA	11	1	NA	NA
14510051	Alluvium	NA	3	3	5	NA	NA

NA = data not available
Data: Bioregional Assessment Programme (Dataset 2, Dataset 18)

2.1.3.3.4 Allocation

Groundwater allocation is discussed in the companion product 1.5 for the Clarence-Moreton bioregion (McJannet et al., 2015).

2.1.3.4 Gaps

Although there are many thousands of groundwater bores and a large number of groundwater observation bores in the Clarence-Moreton bioregion, there are some distinct data and knowledge gaps. The most significant gaps that could potentially influence achieving realistic simulation and modelling based analysis are:

- While some areas such as the Lockyer Valley in Queensland have a very good coverage with shallow groundwater observation bores, there is a general lack of groundwater observation bores in other parts of the Clarence-Moreton bioregion – most notably in the Clarence and Richmond river basins. This lack of data in some areas impacts on the uncertainty of recharge estimation for the sedimentary bedrock units.

- There is a general lack of deep groundwater observation bores, as most observation bores (and more generally the majority of all groundwater bores) are less than 100 m deep. While there are approximately 3000 bores in the bedrock aquifers, most are relatively shallow and located either in or near areas where the bedrock outcrops. However, as the Clarence-Moreton Basin is more than 1000 m deep throughout most of the basin and more than 3000 m in some areas, the existing groundwater monitoring network is likely to capture only a small component of the hydrodynamics of the Clarence-Moreton Basin. Critical hydraulic information including water level, hydraulic properties and water chemistry of bedrock aquifers is currently missing.
- There is a general lack of nested (multi-level) bore sites throughout the Clarence-Moreton bioregion. Although there are some nested bore sites in the Lockyer Valley, Bremer river basin and Warrill creek catchment (less than 20 in total), there are currently no multi-level monitoring sites in the Richmond or Clarence river basins. While groundwater dynamics in shallow alluvial aquifers are relatively well understood, there is very limited knowledge on characteristics such as groundwater flow direction or inter-aquifer head gradients throughout much of the bioregion.
- There are significant gaps in the groundwater databases. For example, there is no 'aquifer' layer where the screened interval of bores are assigned to a specific aquifer in the NGIS groundwater database. More information on hydraulic and petrophysical properties of key aquifer units need to be obtained. In particular, information for the Walloon Coal Measures and overlying stratigraphic units such as the Orara and Grafton formations are required for the numerical model development to assess the impacts associated with coal seam gas development.
- The hydraulic significance of faults is poorly understood due to the lack of nested (multi-level) groundwater monitoring sites. Only limited understanding exists on the role of faults as potential pathways or barriers for aquifer interconnectivity or groundwater flow to the surface. More work, such as the use of remote sensing to identify faults that penetrate to the surface, may be required in the future.

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2.1.4 Surface water hydrology and water quality

Summary

The existing streamflow gauging station data for the Richmond river basin of the Clarence-Moreton bioregion was analysed to assess its suitability for the surface water modelling that will be carried out for this part of the bioregion. There are 12 gauging stations with more than ten years reliable daily streamflow data between 1980 and 2012. The water quality aspects are discussed in companion product 1.5 for the Clarence-Moreton bioregion (McJannet et al., 2015). Also note that the analysis of surface water quality in order to determine surface water – groundwater interaction is described in Section 2.1.5.

2.1.4.1 Observed data

There are 12 stream gauging stations in the non-tidally influenced parts of the Richmond river basin with more than ten years of reliable daily streamflow data between 1980 and 2012 (Table 26). The location of these gauges is shown in Figure 62. Details and mean annual flows for these stations are summarised in Table 27. There are numerous minor tributaries which are ungauged or where the corresponding gauging station has now closed.

The Richmond River at Casino is the furthest point downstream on the main branch of the Richmond River above the influence of the tide. There are tidal influences in the Richmond River from around 4 km downstream of Casino (Manly Hydraulics Laboratory, 2006). The mean annual flow of the Richmond River at Casino is 591 GL.

Tidal influence also extends up the Wilsons River tributary upstream of the town of Lismore. The flow from the Wilsons River, which joins the Richmond River further downstream near Coraki is represented by Coopers Creek at Ewing Bridge (152 GL/year), Coopers Creek at Repentance (77 GL/year) and Wilsons River at Eltham (189 GL/year).

Table 26 Years of streamflow data for selected gauging stations in the Richmond river basin

Gauging station ID	Gauging station name	Number of years
203002	Coopers Creek at Repentance	32.8
203004	Richmond River at Casino	32.8
203005	Richmond River at Wiangaree	32.8
203010	Leycester Creek at Rocky Valley	31.9
203012	Byron Creek at Binnaburra	32.5
203014	Wilsons River at Eltham	32.6
203023	Ironpot Creek at Toonumbar	22.8
203024	Coopers Creek at Ewing Bridge	13.2
203030	Myrtle Creek at Rappville	32.1
203034	Eden Creek at Doubtful	11.3
203041	Shannon Brook at Yorklea	20.1
203900	Richmond River at Kyogle	20.1

Data: Bioregional Assessment Programme (Dataset 1)

Figure 62 Richmond river basin showing the locations of a selection of key stream gauging stations

Data: NSW Office of Water (Dataset 2)

Table 27 Mean annual streamflow for stations in the Richmond river basin that have more than ten years of available data between 1980 and 2012

Gauging station ID	Gauging station name	Mean annual streamflow (GL)
203002	Coopers Creek at Repentance	77
203004	Richmond River at Casino	591
203005	Richmond River at Wiangaree	250
203010	Leycester Creek at Rocky Valley	95
203012	Byron Creek at Binnaburra	42
203014	Wilsons River at Eltham	189
203023	Ironpot Creek at Toonumbar	35
203024	Coopers Creek at Ewing Bridge	152
203030	Myrtle Creek at Rappville	62
203034	Eden Creek at Doubtful	141
203041	Shannon Brook at Yorklea	98
203900	Richmond River at Kyogle	296

Data: NSW Office of Water (Dataset 3)

2.1.4.2 Statistical analysis and interpolation

No further analyses have been undertaken other than what was reported in the context information reported in the companion product 1.1 (Rassam et al., 2014) and companion product 1.5 (McJannet et al, 2015) for the Clarence-Moreton bioregion. The streamflow data that was deemed suitable here will be used to calibrate the surface water model reported in the companion product 2.6.1 for the Clarence-Moreton bioregion (Gilfedder et al., 2016).

2.1.4.3 Gaps

The stream gauge data analysis showed that there were only 12 gauges that have good quality records for at least ten years, making them suitable for river modelling purposes in this assessment.

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2.1.5 Surface water – groundwater interactions

Summary

Surface water – groundwater interactions were mainly investigated using water quality and chemistry data. Additionally, the response of alluvial water levels to climate variability was also used to determine the hydraulic relationships between bedrock aquifers, alluvial aquifers and streams.

Due to the spatial and temporal variability of surface water – groundwater interactions and the likely variable influence of different bedrock units, these interactions are best investigated using a wide range of independent but complementary techniques. This section discusses how multiple data sources such as groundwater quality, groundwater hydrographs and surface water hydrographs have been integrated with a preliminary three-dimensional geological model to develop an improved understanding of the major drivers of the hydraulic connectivity between these systems in the Clarence-Moreton bioregion.

From this analysis, two principal categories of surface water – groundwater interactions have been identified: stream–aquifer interactions, and aquifer–wetland interactions.

The analysis of stream electrical conductivity (EC) data measured irregularly at more than 190 streamflow sampling points demonstrated considerable spatial and temporal variability. This variability is driven by climate controls in addition to the nature of the bedrock underlying the alluvial aquifer systems.

Three examples are presented of how groundwater levels and streambed elevations are used as indicators to infer the degree of hydraulic connectivity between streams and aquifers. The three examples from the Richmond river basin, the Lockyer Valley and the Bremer river basin highlight some characteristic differences in the responses of different surface water – groundwater systems to droughts, the break of drought and subsequent flooding, with the local geology, geomorphology (valley characteristics) and in particular the bedrock geology identified as major drivers of these differences.

In addition to this local analysis of surface water – groundwater interactions, there are also processes that are likely to be controlled by regional characteristics of the geological Clarence-Moreton Basin, such as the geometry of aquifers or the presence of faults. This preliminary analysis indicates that there are areas where the presence of wetlands can be linked to the abutment of bedrock aquifers at the basin margins.

Surface water quality and chemistry data were used to identify areas where surface water systems are in connection with aquifers. Surface water quality data (i.e. EC) were used to infer areas where groundwater baseflow to the streams occurs.

In addition to the use of groundwater and surface water chemistry to assess surface water – groundwater interactions, alluvial groundwater levels representing different climate periods (i.e. climax of drought in 2007, after the break of the drought in 2008 and after the floods of 2010–11) were imported into the preliminary three-dimensional geological model. From the three-dimensional geological model, cross-sections were developed for selected transects in different river basins to determine the spatial and temporal variability of the hydraulic relationships between bedrock aquifers, alluvial aquifers and streams.

2.1.5.1 Observed data

The analysis of surface water – groundwater interactions is an essential part of the Clarence-Moreton Bioregional Assessment (the Assessment). Links between surface water and groundwater can be inferred from a range of different approaches (e.g. Martinez et al., 2015; Duvert et al., 2015); ideally, where available, multiple lines of evidence are integrated, which include:

- geological evidence (e.g. geomorphology of river valleys, sediment composition of aquifers or presence of geological structures that may induce connectivity to the surface)
- groundwater levels and streambed levels
- groundwater and surface water chemistry
- climate data
- wetland mapping
- remote sensing
- digital elevation models (DEMs)
- isotopic data
- streamflow time series data.

In the Assessment, the interactions between surface water and groundwater can be broadly grouped into two categories:

- stream–aquifer interactions
- aquifer–wetland interactions.

The analysis of surface water – groundwater interactions is an ongoing process, and it will be described in more detail during later stages of the Assessment and included in subsequent products (e.g. companion product 2.3 for the Clarence-Moreton bioregion (Raiber et al., 2016)).

2.1.5.1.1 Stream–aquifer interactions

As stream discharge volume is inherently related to stream water quality, relating stream discharge to EC can potentially provide an insight into baseflow contribution to streams and help with the identification of gaining or losing reaches.

There are two observed datasets on river and stream water quality in the Clarence-Moreton bioregion. These are datasets from the NSW Office of Water (Dataset 1) and the Queensland Department of Natural Resources and Mines (Dataset 2).

The NSW Office of Water dataset contains surface water quality data provided by the NSW Office of Water from 122 sampling sites within the Richmond and Clarence river basins (Table 28). Samples were collected at irregular intervals for a wide range of parameters including major ions, selected trace elements, turbidity and field parameters (e.g. EC and dissolved oxygen). EC is typically a good indicator of groundwater discharge to streams, as groundwater is often more saline than surface water due to processes such as evapotranspiration, which results in an increase in groundwater salinity during groundwater recharge. The NSW Office of Water dataset contains more than 7000 sampling records with EC readings for the Clarence-Moreton bioregion. The monitoring duration is highly variable with some sites having records of up to 40 years or more. The spatial distribution of sampling points is shown in Figure 63 and Figure 64.

The Queensland Department of Natural Resources and Mines (DNRM) dataset contains 75 sampling sites in Queensland for the Clarence-Moreton bioregion (Table 28) where water quality field parameters such as EC and dissolved oxygen were recorded during irregular sampling campaigns and where water chemistry was analysed in the laboratory. The total number of EC recordings (corresponding to individual sampling events) in this surface water dataset is more than 2800, but the number of measurements and their periods vary significantly among different sites. For example, a gauging station at the Logan River in Yarrahappini has 206 records collected from 1970 to 2013, whereas only few measurements were recorded at some other sites. The distribution of river and stream water quality sampling sites within the Clarence-Moreton bioregion in Queensland is shown in Figure 63 and Figure 64.

Streamflow data for the bioregion are readily available from DNRM (2014) and NSW Government (2014), and an overview on the active stream water monitoring sites and basic statistics are in companion product 1.1 for the Clarence-Moreton bioregion (Rassam et al., 2014). A comprehensive discussion of this relationship is outside the scope of this product and will be covered in more detail in companion products 2.3 (Raiber et al., 2016) and 2.6.1 (Gilfedder et al., 2016) for the Clarence-Moreton bioregion.

Table 28 Summary of stream water quality and chemistry sampling sites in the Clarence-Moreton bioregion

River basin	State	Number of sampling sites	First record	Latest record	Minimum observed EC (µS/cm)	Maximum observed EC (µS/cm)
Lockyer Valley	Queensland	32	1962	2013	71	8,100
Bremer river basin, Warrill Creek basin and Purga Creek basins	Queensland	12	1962	2013	67	12,966
Logan-Albert river basin	Queensland	20	1961	2013	90	5,200[a]
Mid- and Lower-Brisbane river basin	Queensland	11	1971	2013	36	1,700
Richmond river basin	NSW	72	1971	2013	32	25,400[b]
Clarence river basin	NSW	22	1970	2013	22	>50,000[b]

EC=electrical conductivity

[a]An unusually high electrical conductivity (38,000 µS/cm) was recorded at Teviot Brook in the Logan-Albert river basin at the 'Overflow' in 1974. However, as both previous and the following measurements as well as all other 97 measurements recorded at this site show maximum electrical conductivities of 5,200 µS/cm, it is assumed that this high reading was incorrect or that it is a spelling mistake.

[b]The very high electrical conductivity measurements in the Richmond river basin and Clarence river basin are limited to coastal areas (Figure 63 and Figure 64), and are likely to be linked to tidal influence or estuarine mixing.

Data: NSW Office of Water (Dataset 1), Queensland Department of Natural Resources and Mines (Dataset 2), Bioregional Assessment Programme (Dataset 3)

2.1.5.1.2 Locations of wetlands and relationship to geological characteristics

Analysis of surface water – groundwater interactions is an integral part of understanding the distribution, function and response of wetlands and groundwater-dependent ecosystems (GDEs). Geological structures such as faults can form pathways for inter-aquifer and inter-aquitard connectivity or for groundwater discharge to the surface, which can be manifested by the presence of wetlands or springs. For example, where aquifers are juxtaposed against low-permeability strata on opposing sides of a fault, this may induce inter-aquifer connectivity or upwards discharge of groundwater to the surface. In addition, geometric characteristics of aquifers and aquitards such as abutments of aquifers against basement highs or against the basin margin can also have a significant influence on aquifer and aquitard connectivity. The Clarence-Moreton bioregion is characterised by a complex geology, with many structural features such as faults which can form conduits that link aquifers, or create links between aquifers and the surface.

Observed datasets include mapped wetlands and GDEs, which are the surface expression of groundwater discharge. For the different river basins of the Queensland part of the Clarence-Moreton bioregion, GDEs can be accessed via the interactive Wetland*Info* website (DEHP, 2014). In NSW, recent mapping of GDEs in coastal river basins including the Clarence river basin and Richmond river basin is available from NSW Government (2014). The identification of wetlands within the Assessment was conducted in close collaboration with state government agencies, as discussed in more detail in companion product 1.3 for the Clarence-Moreton bioregion (Murray et al., 2015). The connectivity between surface water and aquifers will be considered in more detail in subsequent companion product 2.3 (Raiber et al., 2016).

2.1.5.2 Statistical analysis and interpolation

2.1.5.2.1 Surface water and groundwater chemistry as an indicator of connectivity

The spatial representation of the lowest and highest river and stream ECs on record at any site (Figure 63 and Figure 64) highlights that there is considerable spatial and temporal variability of salinities in the different river basins in the bioregion.

Generally for most sites, the lowest observed ECs represent periods of high stream discharge following high rainfall events or prolonged periods of above-average rainfall. For some sites, there is only limited variability between the lowest measured river or stream salinity and the highest salinity measurements. For example, while there is clearly some temporal variability of surface water salinity in the Richmond river basin (Figure 63 and Figure 64), the magnitude of observed variability is comparatively small at most sites. The highest surface water salinities observed in the Richmond river basin (25,400 µS/cm measured at the Richmond River at Woodburn (Figure 64) and up to 68,000 µS/cm at multiple sites in the Clarence river basin) are likely to represent a combination of tidal influence, estuarine mixing and open water evaporation. Saline ocean water enters the lower reaches of rivers during high tides. In these tidally influenced parts of the river, the boundary between fresh/brackish/ocean salinity levels (salt line) can move upstream or downstream. This movement of the salt line depends on the tides themselves, but also on the downstream flow of freshwater in the river. The lower parts of rivers can be fresh, and yet still exhibit tidal influence.

There is a significant difference between the lowest and the highest EC on record in many areas such as the Lockyer Valley, the Bremer river basin and the Warrill creek catchment in Queensland. At some sites, the difference between the lowest and highest salinity measurement on record is more than 10,000 µS/cm. In contrast to the Clarence river basin, there is no tidal influence in the bioregion in Queensland. The observed elevated surface water salinities instead mark the influence of baseflow from stratigraphic units such as the Gatton Sandstone, Walloon Coal Measures and Koukandowie Formation that occurs (all of these typically contain brackish or saline groundwater as discussed in Section 2.1.3.3.3) during periods of low surface water flows.

In order to illustrate the influence of low and high stream discharge volumes on river and stream salinity in these catchments, two examples of the temporal variability for Purga Creek in the Bremer river basin and Richmond River at Casino are shown in Figure 65. While the record at these sites is based on irregular measurements, there appears to be a clear relationship between the stream discharge rate and the EC for Purga Creek (Figure 65a). During periods of high flows, the salinity here is typically less than 1,000 µS/cm, but increases to up to 13,000 µS/cm following prolonged periods of low flow, which is in a similar range as the EC in the underlying bedrock (Walloon Coal Measures and Koukandowie Formation). Interestingly, the comparison of manual EC measurements with gauging site EC measurements at this site highlights the limitation of irregular manual measurement, which cannot capture the magnitude of variability to the same degree as regular measurements from automated gauging sites.

While there is also substantial variability of EC for the Richmond River (Figure 65b), the magnitude of this variability is much smaller (most samples range from 200–450 µS/cm) than in Purga Creek. This probably reflects the strong influence of the Lamington Volcanics, which predominantly contain fresh groundwater (Section 2.1.3.3.3), and other bedrock formations such as the Piora Member in this river basin. As these two bedrock formations, which underlie the alluvial aquifers throughout much of the Richmond river basin, predominantly contain fresh groundwater, EC alone may not be sufficient as a tracer of groundwater input into streams. Stream and groundwater surveys of other tracers such as ^{222}Rn would therefore be very useful; such measurements have been recently conducted by Southern Cross University at 29 creek and river sites in the Richmond river basin (Atkins, 2016), confirming the high spatial and temporal variability of surface water – groundwater interaction.

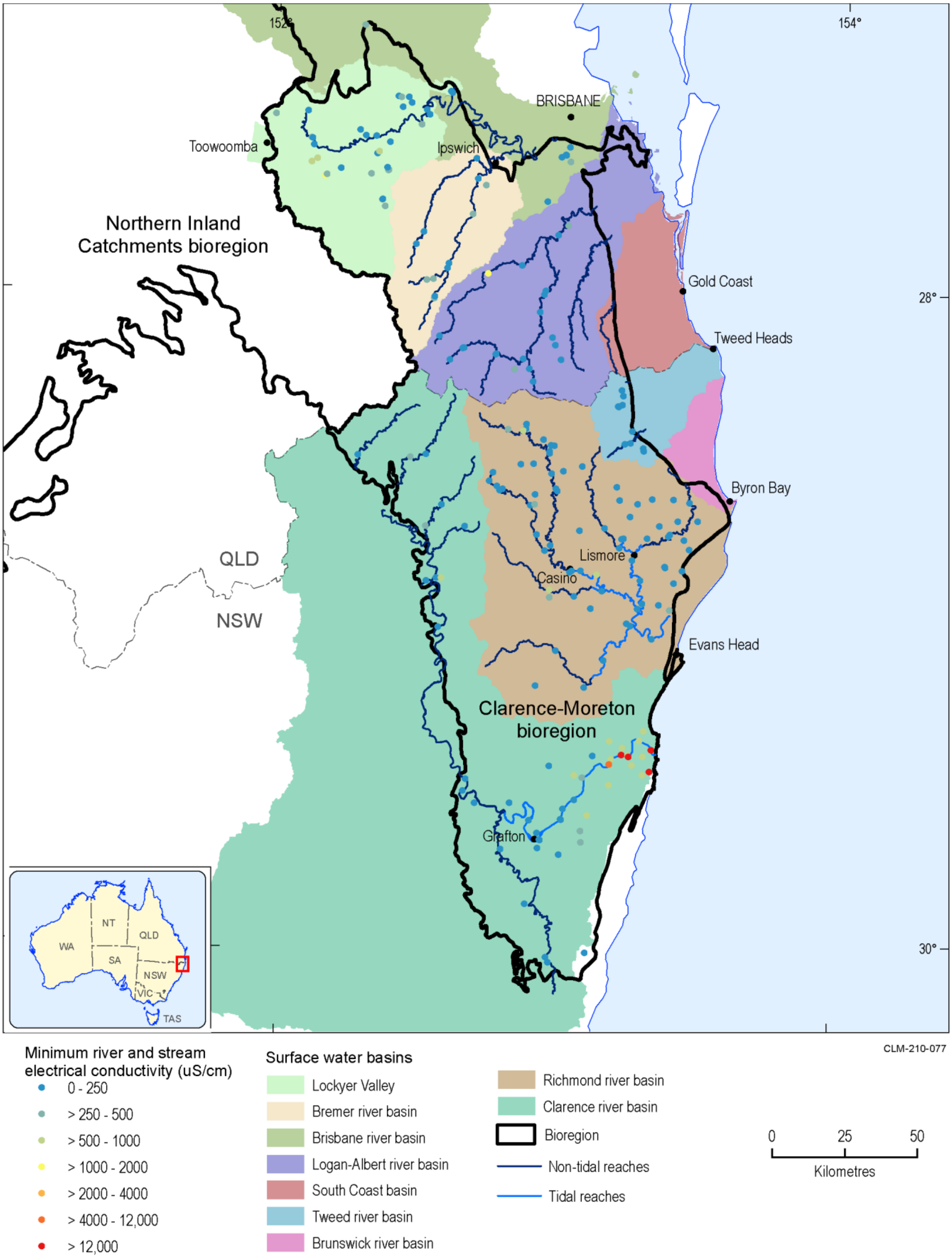

Figure 63 Minimum stream electrical conductivity representing conditions of high streamflow

Data: Bioregional Assessment Programme (Dataset 3)

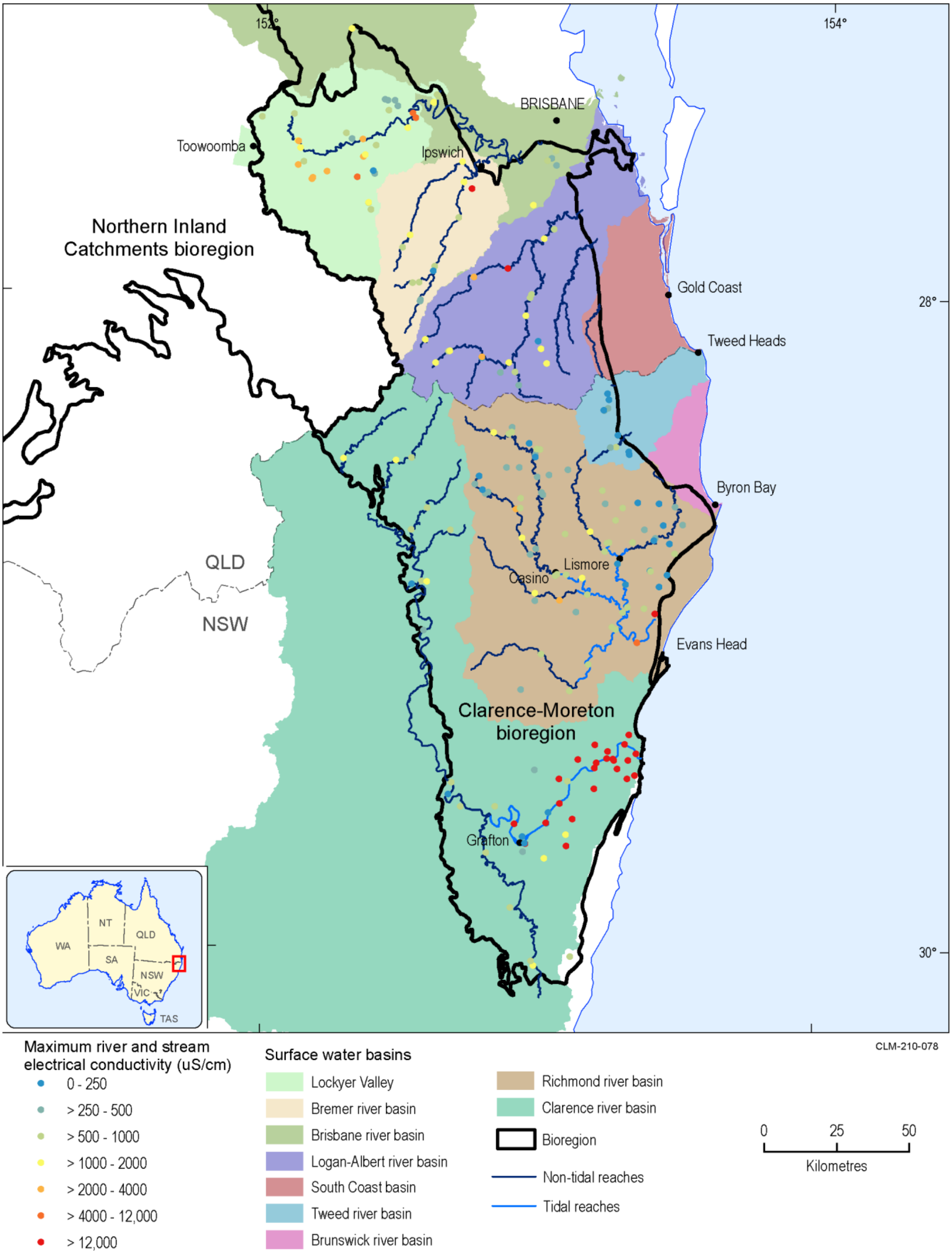

Figure 64 Maximum stream electrical conductivity as representation of low streamflow conditions

Data: Bioregional Assessment Programme (Dataset 3)

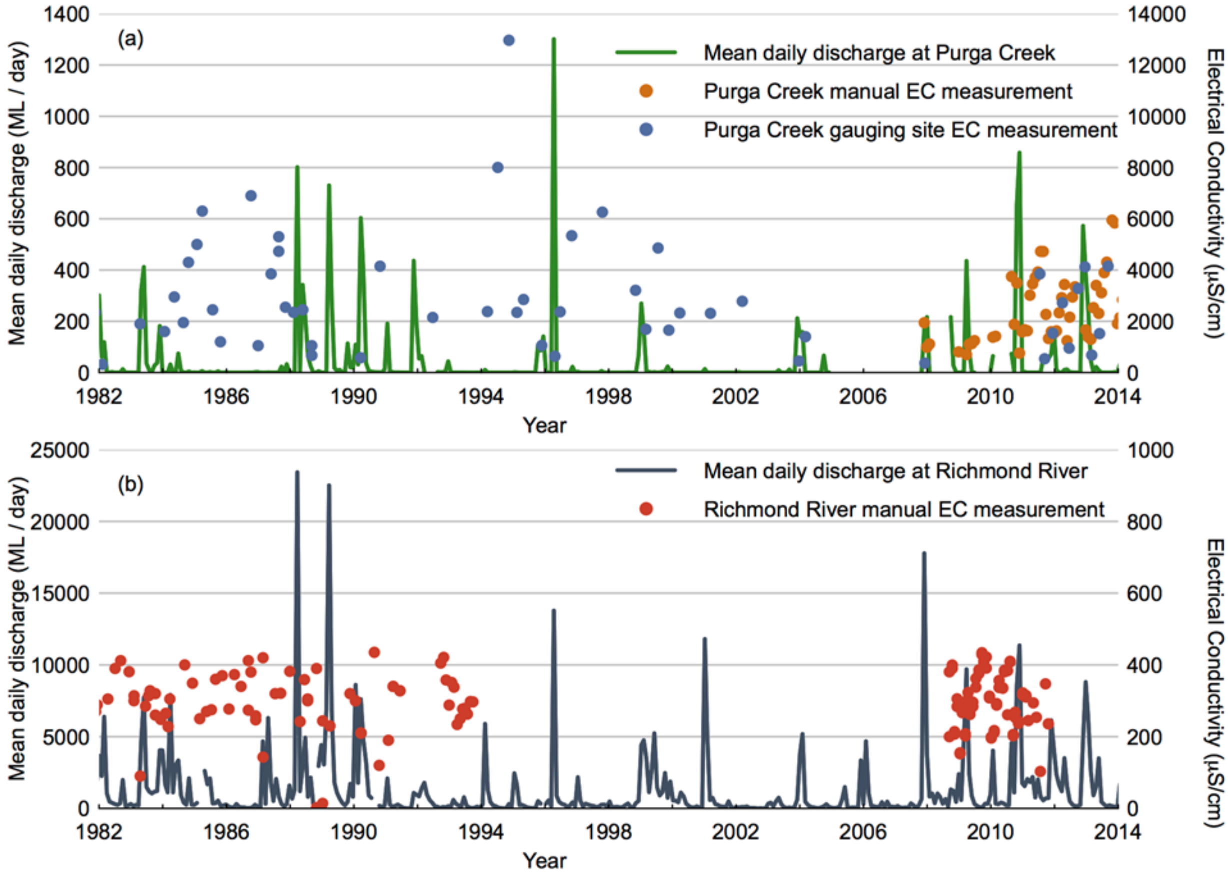

Figure 65 Electrical conductivity (EC) measurements and mean daily discharge at (a) Purga Creek at Loamside in the Bremer river basin and (b) Richmond River at Casino

Data: NSW Office of Water (Dataset 1), Queensland Department of Natural Resources and Management (Dataset 2)

2.1.5.2.2 Groundwater levels and streambed elevations as indicators of stream – aquifer connectivity

Groundwater level observations and their spatial interpolations were imported into the preliminary three-dimensional geological model in GoCAD to assess hydraulic relationships between aquifers and streams. Two-dimensional cross-sections were then created from the three-dimensional geological model at selected locations where observation bore transects exist.

Three examples are shown from different river basins within the bioregion to highlight the usefulness of this approach and also some of the limitations.

Lockyer Valley

Figure 66 shows a cross-section from the Laidley Creek, a tributary of the Lockyer Creek in the Lockyer Valley. This cross-section demonstrates the dynamic interaction during the drought (represented by the 2007 data), the subsequent break of the drought (represented by the 2009 data), and following the extreme flooding of 2011 (represented by the 2013 data). In addition, it shows the relationship to the potentiometric surface of the Gatton Sandstone and the groundwater level surface of the alluvial aquifer. The following can be concluded:

- During the drought, groundwater levels in the alluvial aquifer were generally low, and well below the streambed level. This suggests that there was probably no hydraulic connection between the stream and the underlying aquifer. Increasing groundwater ECs in the alluvial aquifer can be attributed to groundwater discharge from the bedrock to the alluvial aquifer (particularly at the edge of the alluvium), as the potentiometric surface of the Gatton Sandstone was considerably above the groundwater level of the alluvial aquifer (and therefore, there was strong potential for upwards discharge).
- Following a significant rise of water levels after the break of the drought, Figure 66 (2009 data) shows the changing nature of the hydraulic connection where the losing Laidley Creek has recharged the underlying alluvial aquifer.
- Following the extensive flooding of 2011, the groundwater levels continued to recover with groundwater level observations from 2013 indicating that Laidley Creek has turned into a gaining stream.

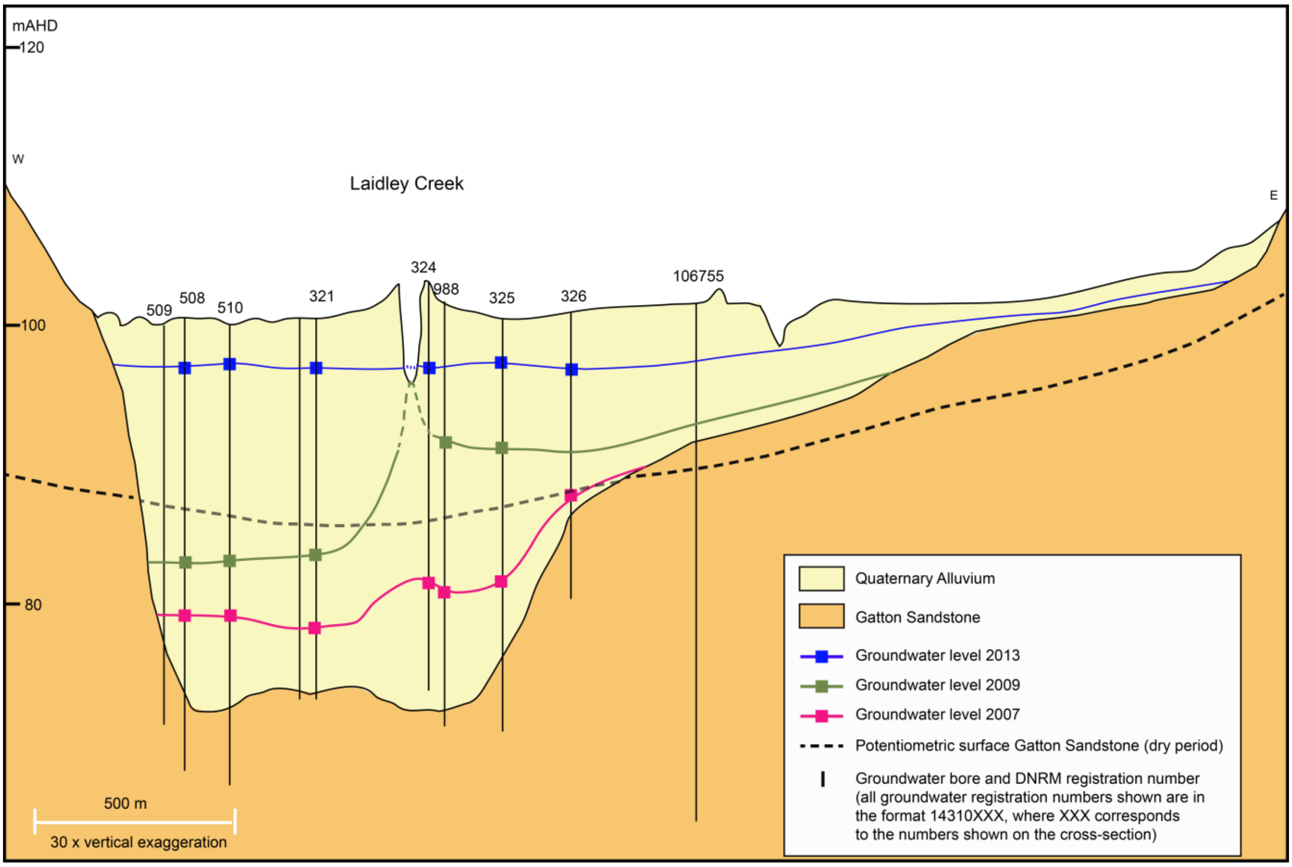

Figure 66 Geological cross-section through the Laidley Creek catchment (subcatchment of Lockyer Valley)

Note the spatial and temporal variability of the hydraulic relationships between the Lockyer Creek and the alluvial aquifer. With the exception of groundwater bore 106755, all groundwater registration numbers shown are in the format 14320XXX, where XXX corresponds to the three numbers shown on the cross-section (with exception of groundwater bore 106755, which follows a different numbering system). The potentiometric surface of the Gatton Sandstone is based on the kriging interpolation presented in Section 2.1.3.3.1.
Data: Geoscience Australia (Dataset 4), Bioregional Assessment Programme (Dataset 5, Dataset 6)

Bremer river basin

Groundwater levels of the alluvial aquifer and the potentiometric surface of the Walloon Coal Measures show that the response of the alluvial aquifer to drought and subsequent flooding and the nature of its hydraulic connectivity with the Bremer River are different to those observed for Laidley Creek.

- During the drought, groundwater levels decreased substantially. In some instances (i.e. bores near the Bremer River, such as bore number 14310051), the groundwater level in 2007 was very close to the base of the alluvium. This indicates a poor hydraulic connection between the aquifer and the river.
- Following the break of the drought, the groundwater level in the Bremer River alluvium recovered in bores near the Bremer River, probably due to recharge from the stream. However, in contrast to Laidley Creek, groundwater levels in bores distant from the river showed little or no recovery in groundwater levels after the break of drought and post the 2011 flooding, which suggests that stream recharge has a limited lateral extent and does not reach far across the floodplain at this location. In addition, this also suggests that rainfall recharge has a long delay time through the unsaturated zone.

The differences in the groundwater level response observed in the examples from Laidley Creek and the Bremer River are probably linked to the geology and geomorphology. The valley of Laidley Creek is considerably narrower than the broad valley of the Bremer River, and in contrast to the Bremer River, Laidley Creek is deeply incised into the alluvial aquifer, and has probably penetrated the clay-rich floodplain sediments that are present at the top of the alluvial sequence and can act as a seal that may limit groundwater recharge.

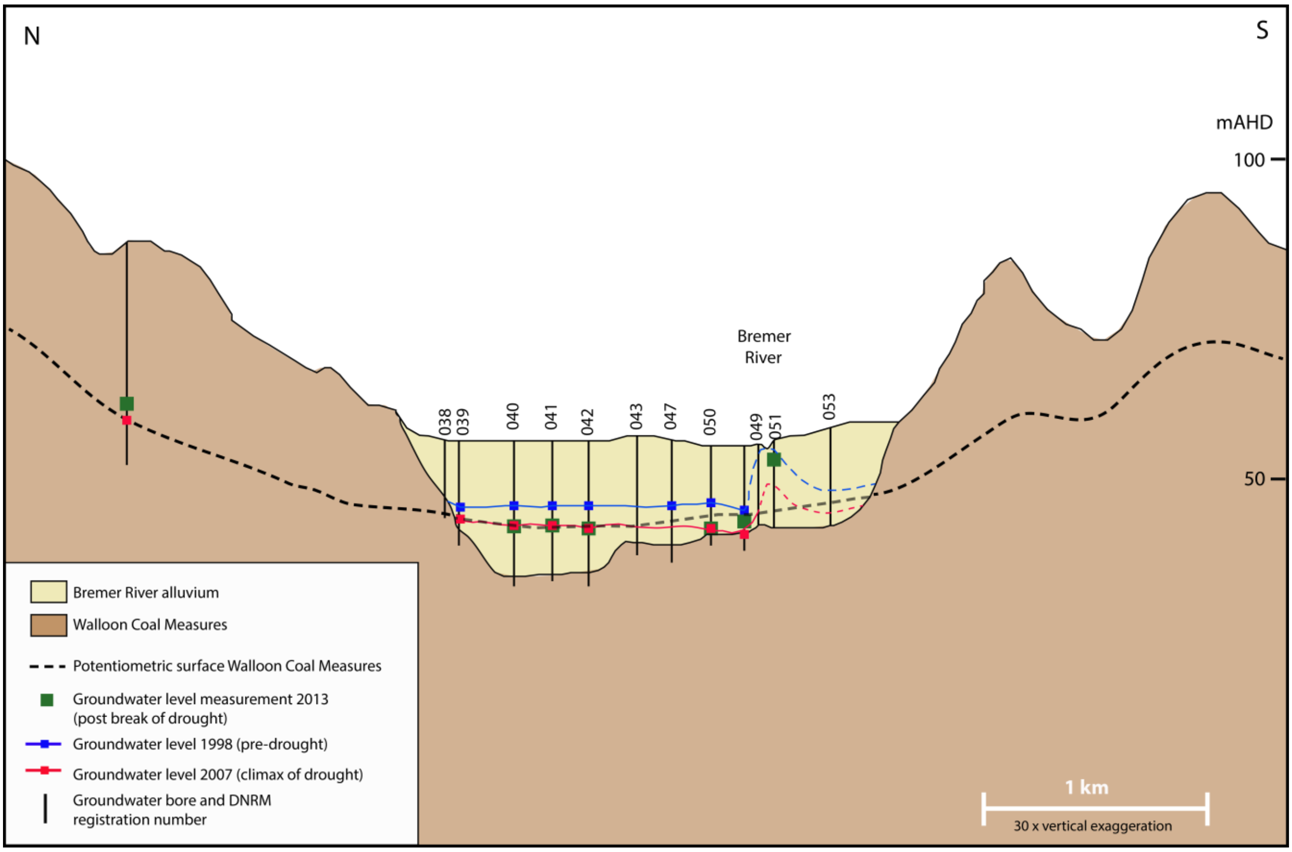

Figure 67 Geological cross-section through the Bremer river basin

Note the hydraulic relationships between the Bremer River and the alluvial aquifer. The topographic surface is based on the 1-second Shuttle Radar Topography Mission DEM data (Geoscience Australia and CSIRO Land and Water, 2010). The potentiometric surface of the Walloon Coal Measures is based on the kriging interpolation presented in Section 2.1.4. All groundwater registration numbers shown are in the format 14310XXX, where XXX corresponds to the numbers shown on the cross-section.
Data: Geoscience Australia (Dataset 4), Bioregional Assessment Programme (Dataset 5, Dataset 6)

Richmond river basin

The response of groundwater levels to rainfall events or longer-term climate variability in the Richmond river basin is not as well constrained as in the Queensland basins due to a lack of groundwater observation bores. However, the incorporation of groundwater level surfaces into the three-dimensional geological model suggests that there was a substantial change from the drought to post-drought.

Some observations based on the cross-section and water level fluctuation are:

- Groundwater levels in this central part of the Richmond river basin are generally shallow.
- During the drought, groundwater levels dropped to approximately 10 m below the ground surface, which may have resulted in a disconnection of the aquifers and streams.
- During normal conditions, the groundwater levels are shallow, and there is likely to be some connection between the alluvial aquifer and the streams, as indicated by the intersection of the water level surface with the ground surface.

However, the spatial modelling of groundwater levels (using kriging interpolation, Section 2.1.3.3.1) is based on a small number of groundwater level measurements in this area, and the uncertainty associated with the modelling is therefore high as indicated by a high standard deviation (Section 2.1.3.3.1). In addition, due to the low relief of the ground surface in this wide floodplain, the 1-second SRTM DEM data may not adequately capture the variability of the ground surface topography.

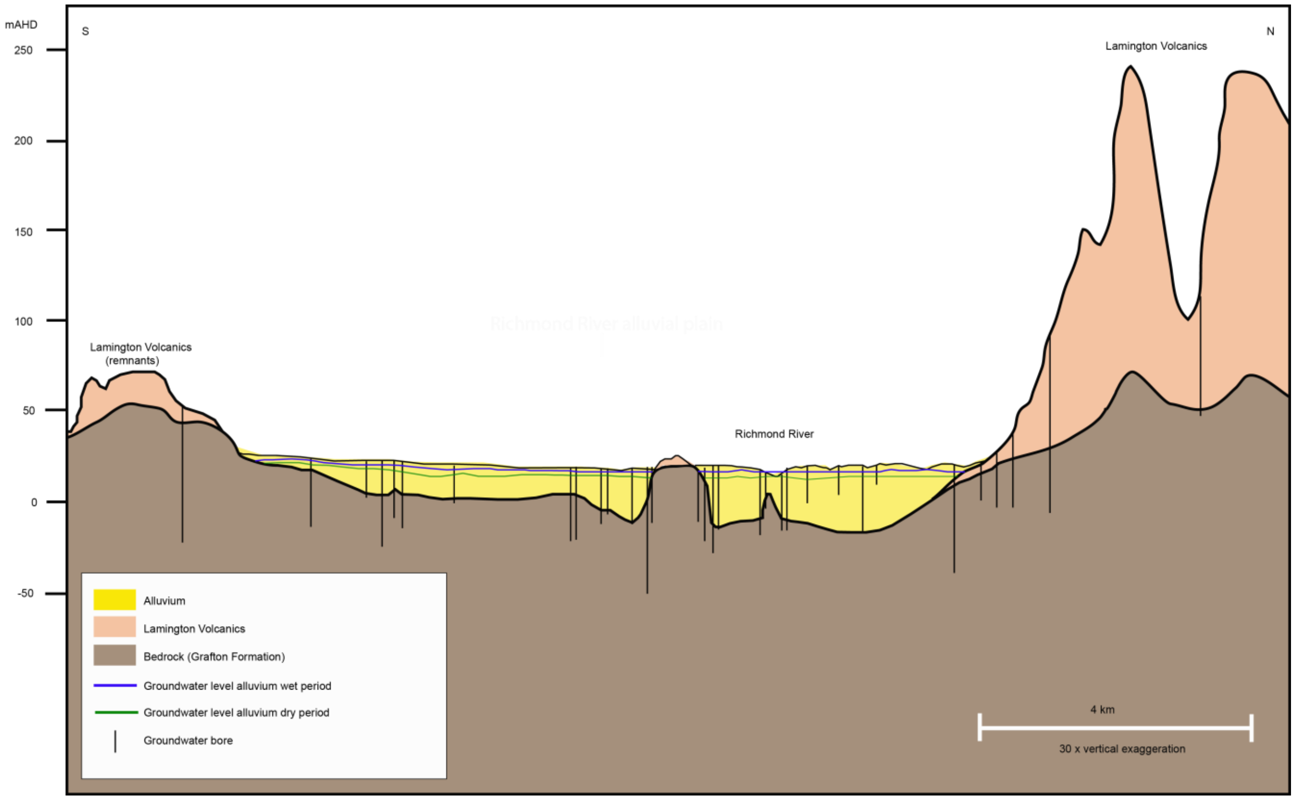

Figure 68 Geological cross-section through the Richmond river basin

Note the hydraulic relationships between the Richmond River and the alluvial aquifer and the change of the interpolated alluvial groundwater level during drought and post-drought conditions (Section 2.1.4). The topographic surface is based on the 1-second Shuttle Radar Topography Mission DEM data (Geoscience Australia and CSIRO Land and Water, 2010).
Data: Geoscience Australia (Dataset 4), Bioregional Assessment Programme (Dataset 6, Dataset 7)

2.1.5.2.3 Hydraulic relationships between wetlands and aquifers

In addition to stream–aquifer interactions, there are also interactions between aquifers and wetlands, controlled primarily by regional-scale geological features pertaining to the geometry of bedrock aquifers or structural features. A detailed identification of such interactions will be conducted and reported in later products. An example for the Bremer river basin is given here.

The Bremer river basin (Figure 69) overlies the geological Laidley sub-basin of the Clarence-Moreton Basin. The thickness of the Clarence-Moreton Basin sedimentary sequences here is likely to be more than 2000 m, of which the Walloon Coal Measures comprise the uppermost 400 to 600 m. At the eastern edge of this depositional centre, the Clarence-Moreton Basin sedimentary sequences terminate against basement rock near the West Ipswich Fault. The potentiometric surface map of the Walloon Coal Measures in this area shows that the groundwater flow direction is generally towards this eastern margin of the basin. As the basin sedimentary sequences thin from more than 2000 m to zero, and as groundwater is unlikely to penetrate the low-permeability basement rocks outside the basin, it is likely that groundwater discharges to the surface, which can be expressed either as discharge into the Bremer River or as wetlands and/or springs. The presence of wetlands in this area provides further evidence to support this hypothesis.

Similar links between the structural framework and the geometry of aquifers are likely to exist in other parts of the Clarence-Moreton Basin near the basin margins, for example, in the Lockyer Valley and the Richmond river basin and Clarence river basin.

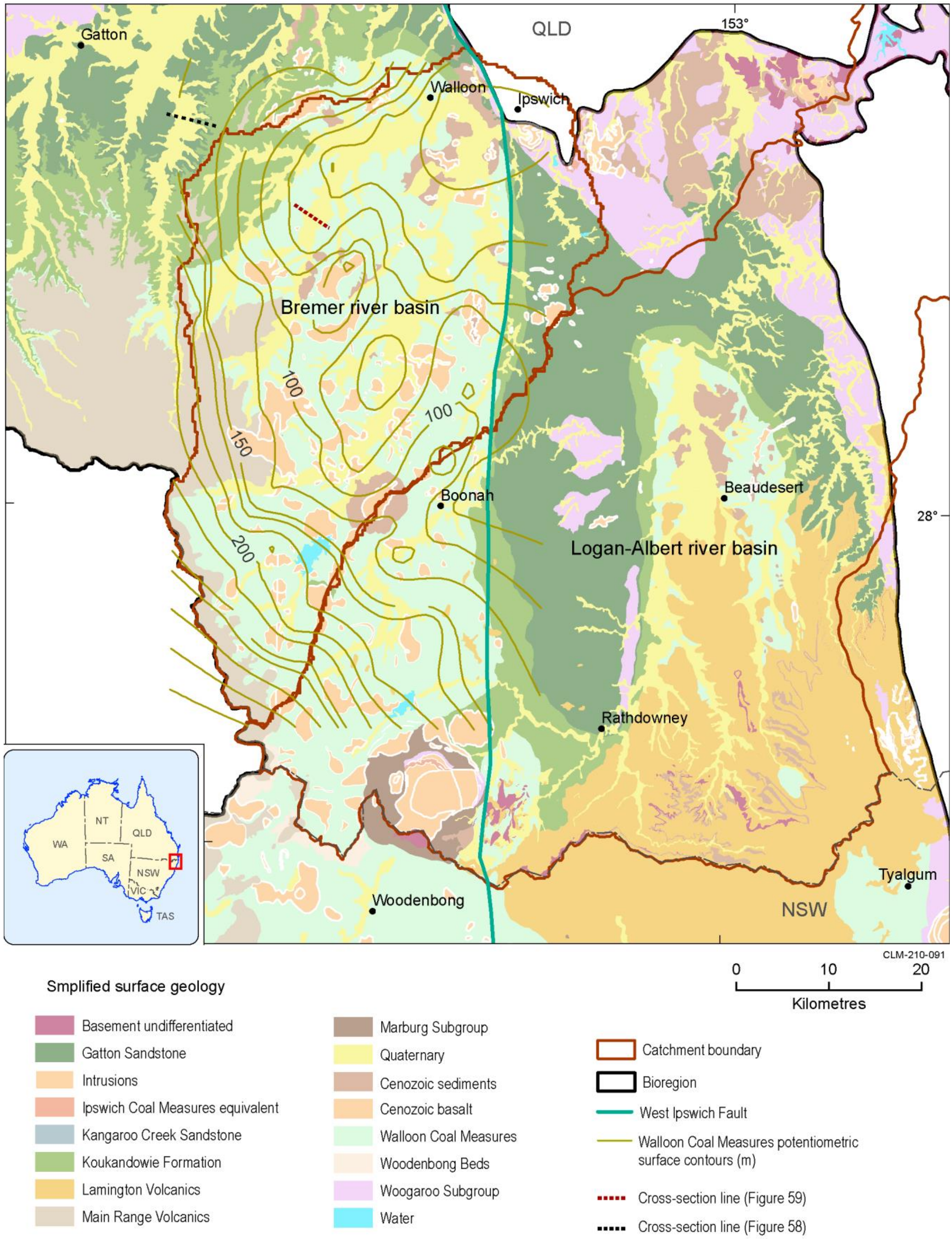

Figure 69 Piezometric surface map of Walloon Coal Measures in the Bremer river basin

Data: Bioregional Assessment Programme (Dataset 4)

2.1.5.3 Gaps

Some knowledge gaps in the existing datasets that have been identified so far include:

- There is a general lack of groundwater monitoring bores in the Richmond and Clarence river basins. This means that hydraulic gradients between streams and aquifers are often only inferred through interpolation of widely spaced data which significantly reduces the accuracy at which the riparian hydrological requirements and responses can be determined.
- Improving identification of gaining and losing reaches (where threatened by mining activity/modification of hydrology) is important in assessing risk to aquatic and hyporheic systems. Using EC as an indicator of baseflow to streams is more difficult in areas of low groundwater ECs such as the Richmond river basin and Clarence river basin due to the smaller contrast in EC during periods of low flow and high flow. This limitation can be mitigated through the assessment of additional chemical parameters and groundwater age tracers along stream transects. Tracers such as ^{222}Rn and groundwater age tracers could further help with the identification of gaining reaches.
- Lidar data are available for part of the bioregion, but have not been acquired to date due to the substantial cost. Lidar data would improve the accuracy of topographic representations. This would further help to determine the hydraulic relationships between creeks or rivers and the underlying aquifers, in particular in low-relief/low-lying areas such as in the floodplains of the Bremer River, Richmond River and Clarence River. In particular, lidar data would help to assess whether the creeks or rivers are incised deeply enough to intersect the basal coarser-grained alluvial sediments (i.e. sands and gravel). However, the usefulness of lidar data for assessment of surface water – groundwater interaction is limited in areas where only few monitoring bores exist.
- There is a lack of long-term surface water chemistry monitoring data in most areas.
- Stream-gauging stations are often not located in areas where stream-aquifer connectivity can be inferred (i.e. they are not close to existing groundwater monitoring network transects). As a result, hydraulic gradients between streams and aquifers can often only be inferred through interpolation of widely spaced data.
- In many parts of the bioregion, many wetlands are likely to be related to either upwelling of deep groundwater at the down-gradient end of flow paths within the basin or to faults where aquifers and aquitards are juxtaposed. However, there is a general lack of nested groundwater monitoring bore sites where stacked bedrock aquifers are screened. Having more nested bore sites would provide an improved understanding of vertical gradients between aquifers and therefore help with the identification of bedrock discharge areas.

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2.1.6 Water management for coal resource developments

Summary

As a result of the discontinuation of the Metgasco West Casino Gas Project, there will not be a water management plan for the project in the foreseeable future. Some relevant information can be found in Metgasco's water management plan (WMP) for the water and drilling fluids produced during exploration or pilot testing in Metgasco's three exploration permits, Petroleum Exploration Licence (PEL) 13, 16 and 426, in NSW. However, the plan is only applicable for the produced water during the exploration phase from 2012 to 2013.

2.1.6.1 Metgasco West Casino Project

As of January 2016, no water management plan existed for the West Casino Gas Project. The only relevant and publicly available information is Metgasco's water management plan (WMP) for its 2012 to 2013 exploration programme (Metgasco, 2012). The WMP was prepared for the management of produced water and drilling fluids in Metgasco's three exploration permits (PEL 13, 16 and 426) in NSW. The West Casino Gas Project is within the area covered by PEL 13 and 16. The WMP can be summarized as follows:

- Produced water is temporarily stored in a single dam with a capacity of approximately 3.8 ML.
- The produced water is treated by a Reverse Osmosis treatment plant for beneficial reuse.
- Treated water is stored in another dam (approximately 4.2 ML capacity) before being transported to an irrigation water storage dam.
- Brine concentrate from the water treatment plant is stored in fixed tanks temporarily and is then transported by water truck to a waste disposal facility.
- Drilling fluid is stored in a dam for reuse or transport to a waste disposal facility.
- The WMP is assessed on an ongoing basis.
- A monitoring network has been implemented to evaluate the integrity of the WMP at key control locations. The monitoring network consists of soil moisture level loggers, electrical conductivity loggers, dam piezometers, and monitoring bores and piezometers for groundwater.

In December 2015, Metgasco has decided to discontinue their proposed development of the West Casino Gas Project. This means that there will not be any future water management plans beyond what is described in Metgasco (2012).

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Glossary

The register of terms and definitions used in the Bioregional Assessment Programme is available online at http://environment.data.gov.au/def/ba/glossary (note that terms and definitions are respectively listed under the 'Name' and 'Description' columns in this register). This register is a list of terms, which are the preferred descriptors for concepts. Other properties are included for each term, including licence information, source of definition and date of approval. Semantic relationships (such as hierarchical relationships) are formalised for some terms, as well as linkages to other terms in related vocabularies.

aquifer: rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit quantities of water to wells and springs

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.

asset: an entity that has value to the community and, for bioregional assessment purposes, is associated with a subregion or bioregion. Technically, an asset is a store of value and may be managed and/or used to maintain and/or produce further value. Each asset will have many values associated with it and they can be measured from a range of perspectives; for example, the values of a wetland can be measured from ecological, sociocultural and economic perspectives.

bioregion: a geographic land area within which coal seam gas (CSG) and/or coal mining developments are taking place, or could take place, and for which bioregional assessments (BAs) are conducted

bioregional assessment: a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion, with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and coal mining development on water resources. The central purpose of bioregional assessments is to analyse the impacts and risks associated with changes to water-dependent assets that arise in response to current and future pathways of coal seam gas and coal mining development.

bore: a narrow, artificially constructed hole or cavity used to intercept, collect or store water from an aquifer, or to passively observe or collect groundwater information. Also known as a borehole or piezometer.

causal pathway: for the purposes of bioregional assessments, the logical chain of events either planned or unplanned that link coal resource development and potential impacts on water and water-dependent assets

component: for the purposes of Impact Modes and Effects Analysis (IMEA), a group of activities associated with a coal seam gas (CSG) operation or coal mine. For example, components during the development life-cycle stage of a coal mine include developing the mine infrastructure, the open pit, surface facilities and underground facilities. Components are grouped into life-cycle stages.

conceptual model: abstraction or simplification of reality connectivity: a descriptive measure of the interaction between water bodies (groundwater and/or surface water)

context: the circumstances that form the setting for an event, statement or idea

dataset: a collection of data in files, databases or delivered by services that comprise a related set of information. Datasets may be spatial (e.g. a shape file or geodatabase or a Web Feature Service) or aspatial (e.g. an Access database, a list of people or a model configuration file). In the BA Repository, datasets are guaranteed to have a metadata record in the Metadata Catalogue and to have their components (files, database interface) delivered via the Data Store. In semantic web terms, a BA dataset is defined as a subclass of DCAT Dataset and PROMS Entity and is described in the BA Ontology as a scope note in term record.

derived dataset: a dataset that has been created by the Bioregional Assessment Programme

discharge: water that moves from a groundwater body to the ground surface or surface water body (e.g. a river or lake)

ecosystem: a dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit. Note: Ecosystems include those that are human-influenced such as rural and urban ecosystems (i.e. humans are regarded as part of nature).

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), change in the quantity or quality of surface water or groundwater. An effect is a specific type of an impact (any change resulting from prior events).

extraction: the removal of water for use from waterways or aquifers (including storages) by pumping or gravity channels

formation: rock layers that have common physical characteristics (lithology) deposited during a specific period of geological time

groundwater: water occurring naturally below ground level (whether in an aquifer or other low permeability material), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.

groundwater-dependent ecosystem: ecosystems that rely on groundwater - typically the natural discharge of groundwater - for their existence and health

groundwater recharge: replenishment of groundwater by natural infiltration of surface water (precipitation, runoff), or artificially via infiltration lakes or injection

hydrogeology: the study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of interactions between water and rock impact: a change resulting from prior events, at any stage in a chain of events or a causal pathway. An impact might be equivalent to an effect (change in the quality or quantity of surface water or groundwater), or it might be a change resulting from those effects (for example, ecological changes that result from hydrological changes).

material: pertinent or relevant

permeability: the measure of the ability of a rock, soil or sediment to yield or transmit a fluid. The magnitude of permeability depends largely on the porosity and the interconnectivity of pores and spaces in the ground.

recharge: see groundwater recharge

runoff: rainfall that does not infiltrate the ground or evaporate to the atmosphere. This water flows down a slope and enters surface water systems.

saturated zone: the part of the ground in which all the voids in the rocks or soil are filled with water. The watertable is the top of the saturated zone in an unconfined aquifer.

source dataset: a pre-existing dataset sourced from outside the Bioregional Assessment Programme. This includes data sourced from the Programme partner organisations.

spring: a naturally occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool of water. Typically, it represents the point at which the watertable intersects ground level.

stratigraphy: stratified (layered) rocks

subregion: an identified area wholly contained within a bioregion that enables convenient presentation of outputs of a bioregional assessment (BA)

surface water: water that flows over land and in watercourses or artificial channels and can be captured, stored and supplemented from dams and reservoirs

uncertainty: the state, even partial, of deficiency of information related to understanding or knowledge of an event, its consequence, or likelihood. For the purposes of bioregional assessments, uncertainty includes: the variation caused by natural fluctuations or heterogeneity; the incomplete knowledge or understanding of the system under consideration; and the simplification or abstraction of the system in the conceptual and numerical models

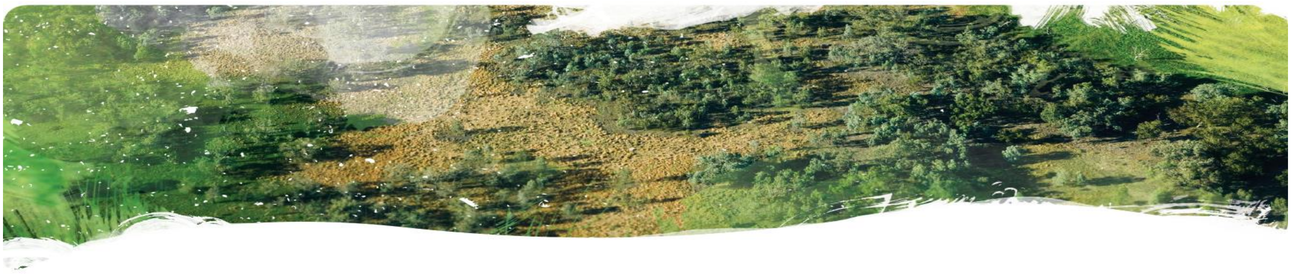
unsaturated zone: the zone in soils and rocks occurring above the watertable, where there is some air within the pore spaces

water allocation: the specific volume of water allocated to water access entitlements in a given season, defined according to rules established in the relevant water plan

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

watertable: the upper surface of a body of groundwater occurring in an unconfined aquifer. At the watertable, pore water pressure equals atmospheric pressure.

well: typically a narrow diameter hole drilled into the earth for the purposes of exploring, evaluating or recovering various natural resources, such as hydrocarbons (oil and gas) or water. As part of the drilling and construction process the well can be encased by materials such as steel and cement, or it may be uncased. Wells are sometimes known as a 'wellbore'.



2.2 Statistical analysis and interpolation

Originally the statistical analysis and interpolation was intended to be reported independently of the observations analysis. Instead it has been combined with the observations analysis as product 2.1-2.2 to improve readability. For statistical analysis and interpolation see Section 2.1 of this product.

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