Australian Government

BIOREGIONAL ASSESSMENTS

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

Conceptual modelling for the Clarence-Moreton bioregion

Product 2.3 from the Clarence-Moreton Bioregional Assessment

19 January 2017

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

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Authorship is listed in relative order of contribution.

Cover photograph

Rainforest waterfall in Border Ranges National Park, NSW, 2008

Credit: Liese Coulter, CSIRO

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Executive summary

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

Conceptual models are abstractions or simplifications of reality. During development of conceptual models, the essence of how the key system components operate and interact is distilled. In bioregional assessments (BAs), conceptual models are developed to describe the *causal pathways*, the logical chain of events – either planned or unplanned – that link coal resource developments to water and water-dependent assets. This product presents information about the conceptual model of causal pathways for the Clarence-Moreton bioregion.

2.3.1.1.1.1 Methods

The conceptual model of causal pathways for the Clarence-Moreton bioregion considers two potential futures:

- *baseline coal resource development (baseline)*: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012
- *coal resource development pathway (CRDP)*: a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in results between CRDP and baseline is the change that is primarily reported in a bioregional assessment. This change is due to the *additional coal resource development* (ACRD) – all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012. In the Clarence-Moreton bioregion, no new coal mines or expansions of existing mines are proposed.

Following the methods described in companion submethodology M05 (as listed in Table 1) on the development of conceptual models, this product includes:

- the key system components, processes and interactions
- ecosystem landscape classifications
- coal resource development baseline, CRDP and the ACRD
- potential hazards from coal resource development using the Impact Modes and Effect Analysis (IMEA) method
- the causal pathway groups from coal resource development to hydrological change for the Clarence-Moreton bioregion. The causal pathways have been discussed with stakeholders at a workshop in June 2015.

2.3.1.1.1.2 Summary of key system components, processes and interactions

Three-dimensional geological models were developed to improve the understanding of geology and hydrogeology, and explain spatial hydrological processes in the Clarence-Moreton bioregion.

The assessment of multiple lines of evidence confirmed the role of the Lamington Volcanics as the major preferential recharge area within the Clarence-Moreton bioregion – particularly in the Richmond river basin. Recharge rates to these volcanic aquifers are at least one order of magnitude higher than recharge rates to sedimentary bedrock units such as the Walloon Coal Measures. However, a large proportion of recharge to the Lamington Volcanics discharges into the streams or the alluvium locally following short flow paths and short lag times, with only a small proportion percolating to deeper sedimentary bedrock aquifers. The assessment of the spatial distribution of median streamflow rates and hydrochemical data further confirms the significance of the Lamington Volcanics as a major hydrological feature in the Richmond river basin, where most of the surface runoff is generated. Hydrochemical data also indicate that there is aquifer connectivity between alluvial and sedimentary bedrock aquifers in some areas within the Richmond river basin. However, ideally, this would need to be confirmed independently through the use of environmental tracers.

Although multiple lines of independent evidence have resulted in a sound understanding of most of the key hydrological processes, the assessment highlighted that there continues to be conceptual uncertainties regarding the role of faults that act as potential pathways linking deeper stratigraphic units such as the Walloon Coal Measures (the CSG target), to shallow aquifers and surface water features in the Richmond river basin. Furthermore, there continues to be uncertainty on the connectivity between deep and shallow aquifers due to a lack of nested groundwater monitoring sites where groundwater levels in different aquifers are monitored simultaneously to assess vertical groundwater fluxes between different stratigraphic units.

2.3.1.1.1.3 Ecosystems

The ecosystems of the Clarence-Moreton bioregion are classified in terms of landscape classes and their dependence on water. The classifications are based on key landscape properties related to patterns in geology, geomorphology, hydrology, ecology and human-modified land use.

These landscape classes are expressed as a percentage of the geographic area associated with the Clarence-Moreton bioregion in which the potential water-related impact of coal resource development on assets is assessed. This geographic area is called the preliminary assessment extent (PAE). Most of the PAE of the Clarence-Moreton bioregion (60.3 %) is modified landscape, with by far the largest landscape class being ‘Dryland agriculture’ (57.5%). Natural vegetation landscape classes cover 37.8% of the PAE, with the ‘Woodland’ landscape class being the most prevalent of these (23.3%), then ‘Open forest’ landscape class (8.0%) and ‘Rainforest’ landscape class (5.2%).

2.3.1.1.1.4 Coal resource development

As of mid-2015, the baseline includes one existing coal mine (Jeebropilly Mine, west of Ipswich) and the CRDP includes the Jeebropilly Mine and one additional CSG development (Metgasco Limited’s West Casino Gas Project). This CSG development is located in the Richmond river basin near Casino, NSW. The focus on this area is due to the presence of highly gas-saturated coal seams that have a relatively high permeability, which are located along the western side of the Casino Trough at depths as shallow as 250 m. A recent decision by Metgasco (16 December 2015) to sell back their petroleum exploration licences (PELs) and petroleum production license application (PPLA) to the NSW Government effectively means that future development of any CSG resources in the Clarence-Moreton bioregion is highly uncertain. However, as per companion submethodology M04 for developing a coal resource development pathway, once the CRDP is determined, it is not changed for BA purposes, even in cases such as this where Metgasco have discontinued their operations in the Clarence-Moreton bioregion.

2.3.1.1.1.5 Hazard analysis

Identification of potential hazards followed the IMEA method. IMEA is used to systematically identify activities that may initiate hazards, defined as events, or chains of events that might result in an effect (a change in the quality and/or quantity of surface water or groundwater).

The hazard analysis for the Clarence-Moreton bioregion is based on the proposed CSG operations and associated water management. The assessment of geology and hydrogeology demonstrated that there is no hydraulic connection between the Richmond river basin and the Bremer river basin, where the only existing baseline coal mine (Jeebropilly Mine) is located. Consequently, potential hazards associated with coal mines are not considered in the Clarence-Moreton BA. A large number of potential hazards associated with CSG operations are identified; some of these are beyond the scope of a BA and others are adequately addressed by site-based risk management processes and regulation.

Hazards associated with coal mines and CSG operations that are considered to be in scope for BAs are grouped into four main causal pathway groups (refer to Appendix B in companion submethodology M05 for developing a conceptual model of causal pathways):

- ‘Subsurface depressurisation and dewatering’
- ‘Subsurface physical flow paths’
- ‘Surface water drainage’
- ‘Operational water management’.

These causal pathway groups are used generally across BAs; however, for the ‘Subsurface depressurisation and dewatering’ causal pathway group, no further discussion on dewatering will occur in relation to the Clarence-Moreton bioregion as dewatering applies to coal mining activities only and there are no coal mines being modelled in the baseline or CRDP for the Clarence-Moreton bioregion.

2.3.1.1.1.6 Causal pathways

The ‘Subsurface depressurisation and dewatering’ causal pathway group includes coal mine and CSG operations that intentionally dewater and depressurise subsurface hydrostratigraphic units (such as coal seams and aquifers) to permit coal resource extraction. Subsurface depressurisation associated with CSG development has the potential to directly affect the regional groundwater system at point, local or regional scales. In the Richmond river basin, there are several aquitards that can potentially prevent the wider impacts of depressurisation on overlying aquifers. However, if these aquitards were compromised by faults, the pressure change could be transmitted much faster with potential impacts extending to the uppermost aquifers.

The 'Subsurface physical flow paths' causal pathway group involves physical modification of the rock mass or geological architecture by creating new physical paths that water may potentially infiltrate and flow along. The extent of these changes is likely to be minor and limited to the vicinity of the compromised well (<1 km) or the location where hydraulic fracturing occurs.

'Surface water drainage' is the most common causal pathway group for CSG operations in the Clarence-Moreton bioregion. Subsidence, diverting site drain lines, rainwater and runoff diversion, levee bunds and creek crossings can change, or disrupt, surface water drainage. Effects on surface water direction, volume and quality can have medium-term (5 to 10 years), to long-term (10 to 100 years) cumulative effects on watercourses within and downstream of the CSG development.

The 'Operational water management' causal pathway group involves the modification of water management systems and may have a cumulative effect on surface water catchments and stream networks, surface water – groundwater interactions, and groundwater conditions. Effects are likely to be in the medium to long term and include watercourses in aquifer outcrop areas that are within and downstream of the CSG development.

A synthesis section summarises how all sections of this product link together, and how the conceptual model framework presented in this product will inform subsequent companion products of the BA. A qualitative assessment indicated that 21 of the 35 landscape classes identified in the Clarence-Moreton bioregion are unlikely to be impacted by any of the four causal pathway groups. The criteria adopted to undertake this assessment related to the spatial scale associated with the impact, geological and hydrogeological settings, tidal influence, the explicit location of the landscape class relative to the West Casino Gas Project, and the type of water dependency. This initial qualitative assessment will be tested in product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling) for the Clarence-Moreton bioregion where numerical modelling outcomes are reported. This means that even if the initial qualitative assessment suggests that a causal pathway does exist, the groundwater numerical model may indicate otherwise; note that the opposite scenario is also possible.

2.3.1.1.1.7 Gaps

Knowledge gaps for the conceptual model of causal pathways in the Richmond river basin are primarily related to geological and hydrogeological data gaps (e.g. the general lack of deep groundwater monitoring bores, the lack of hydraulic property data of aquifers and aquitards and the lack of nested groundwater monitoring sites), data quality issues and the complex nature of the geological and hydrogeological setting. Furthermore, the assessment of landscape classes showed that not all landscape classes may be represented in the groundwater modelling area and not all spatial data may be obtained for each landscape class (spatial data was either non-existent or non-accessible within the window of data collection for the BA analysis).

2.3.1.1.1.8 Further work

The causal pathways described in this product guide how the modelling (product 2.6.1 (surface water numerical modelling) and 2.6.2 (groundwater numerical modelling) is conducted for the Clarence-Moreton bioregion.

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This technical product was reviewed by several groups:

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- Senior Science Leaders: David Post (Projects Director), Steven Lewis (Science Director, Geoscience Australia), Brent Henderson (Science Director, CSIRO), Becky Schmidt (Products Manager)
- Technical Assurance Reference Group: Chaired by Peter Baker (Principal Science Advisor, Department of the Environment and Energy), this group comprises officials from the NSW, Queensland, South Australian and Victorian governments.

Valuable information and data on three-dimensional geological models and groundwater and surface water conceptualisation were provided by Max Milz (Metgasco), Felipe Oliveira and Kevin Ruming (both NSW Department of Trade and Investment), Brad Pinder (Arrow Energy), John McKellar (Geological Survey of Queensland) and Richard Green and Chris Rumpf (both NSW Department of Primary Industry (Water)).

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.

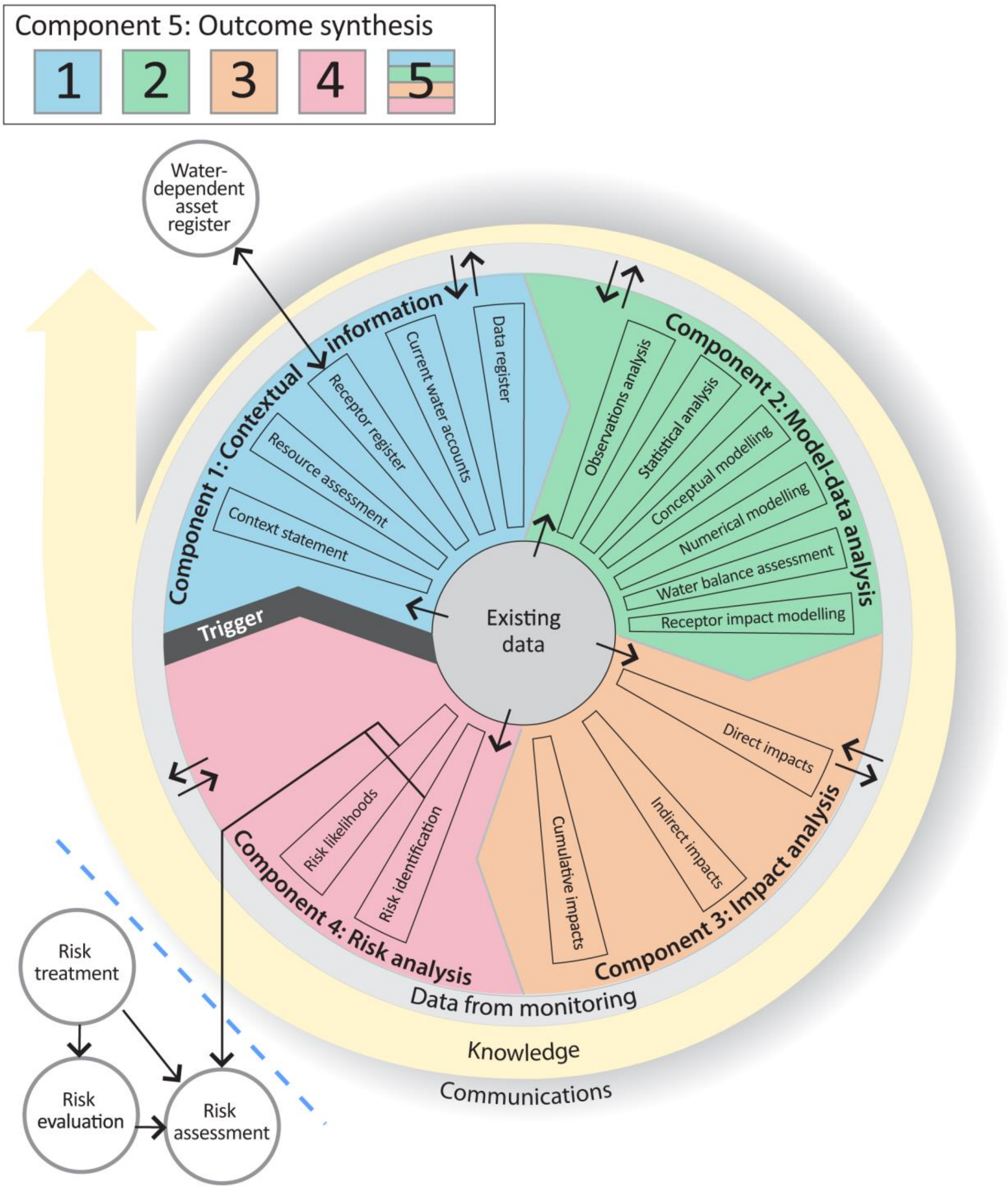

Figure 1 Schematic diagram of the bioregional assessment methodology

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), in the first instance, to 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.

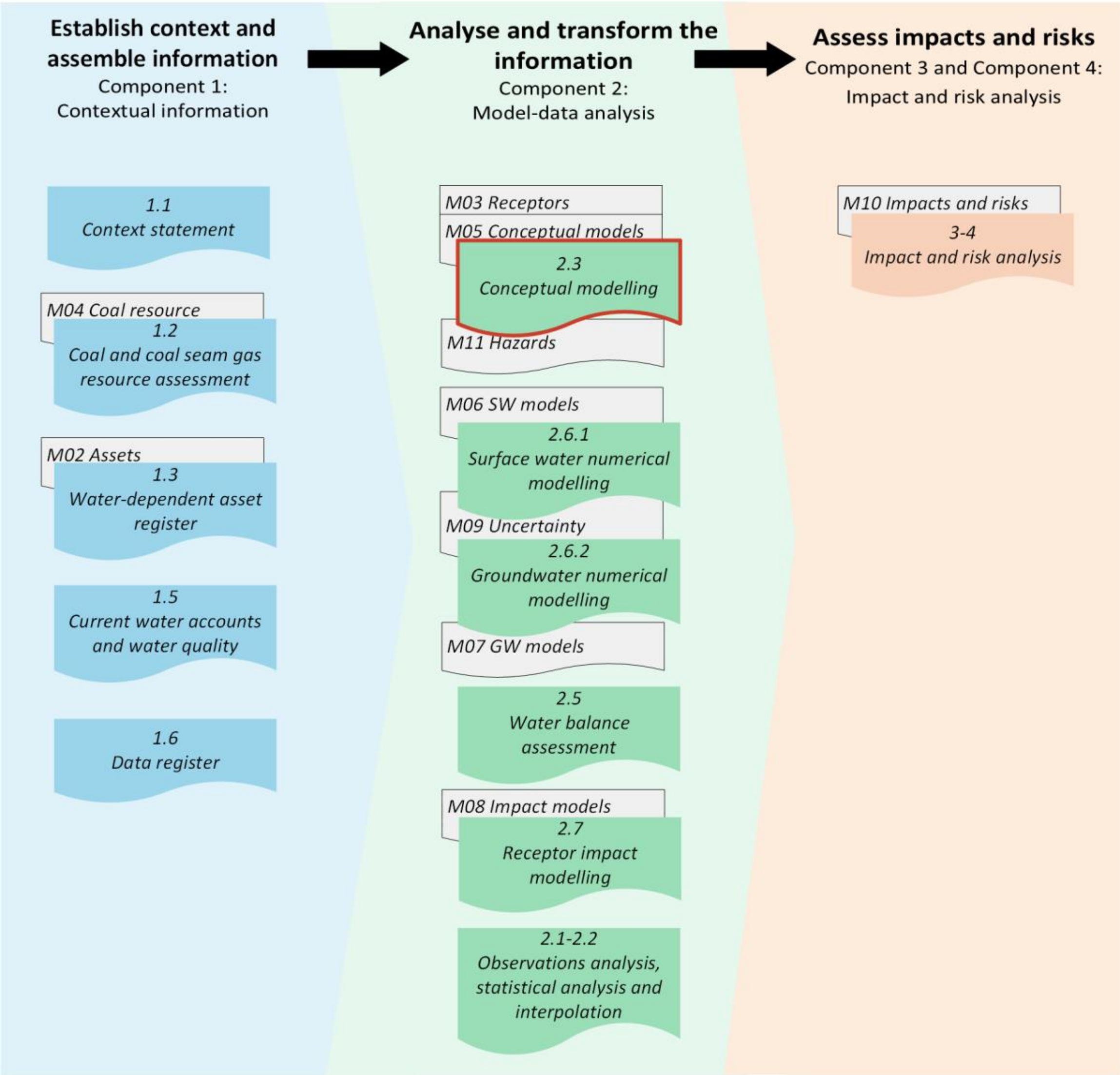

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical 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°.
- Visit http://bioregionalassessments.gov.au to access metadata (including copyright, attribution and licensing information) for datasets cited or used to make figures in this product.
- In addition, the datasets are published online if they are unencumbered (able to be published according to conditions in the licence or any applicable legislation). The Bureau of Meteorology archives a copy of all datasets used in the BAs. This archive includes datasets that are too large to be stored online and datasets that are encumbered. The community can request a copy of these archived data at http://www.bioregionalassessments.gov.au.
- The citation details of datasets are correct to the best of the knowledge of the Bioregional Assessment Programme at the publication date of this product. Readers should use the hyperlinks provided to access the most up-to-date information about these data; where there are discrepancies, the information provided online should be considered correct. The dates used to identify Bioregional Assessment Source Datasets are the dataset's published date. Where the published date is not available, the last updated date or created date is used. For Bioregional Assessment Derived Datasets, the created date is used.

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2.3 Conceptual modelling for the Clarence-Moreton bioregion

This product firstly summarises key system components, processes and interactions for the geology, hydrogeology and surface water in the Clarence-Moreton bioregion. It describes its ecosystems using a landscape classification.

The product then characterises the two potential futures considered in bioregional assessments:

- *baseline coal resource development (baseline)*: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012
- *coal resource development pathway (CRDP)*: a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in results between CRDP and baseline is the change that is primarily reported in a bioregional assessment. This change is due to the *additional coal resource development* – all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012.

The Impact Modes and Effects Analysis method is then used to identify *hazards*, defined as events, or chains of events, that might result in an *effect* (change in the quality and/or quantity of surface water or groundwater).

Next are presented causal *pathways,* the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. Causal pathways for hazards are identified by considering coal resource development activities, impact causes, impact modes and the resulting water-related effects. This product describes the causal pathways from the coal resource development to the hydrological changes (represented by hydrological response variables).

The product concludes by describing the causal pathways for the baseline and CRDP, which guide how the modelling (product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling)) is conducted.

2.3.1 Methods

Summary

The conceptual model of causal pathways characterises the *causal pathway*, the chain of logic or activities – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. This section details the specific application to the Clarence-Moreton bioregion of methods described in the companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016).

Key concepts and terminology are also explained, and the overall steps are summarised: (i) synthesis of key system components, processes and interactions for the geology, hydrogeology and surface water of the bioregion; (ii) landscape classification; (iii) definition of the coal resource development pathway; (iv) hazard analysis; (v) identification of causal pathways from the coal resource development to hydrological changes; and (vi) description of the resulting coal resource development pathway (CRDP) conceptual model of causal pathways.

Geology is a major landscape-forming driver, and four major categories of geology were identified for the purpose of landscape classification: fractured rock, consolidated sedimentary rock, unconsolidated sediments – alluvium and unconsolidated sediments – estuarine and coastal. The three-dimensional geological model for the bioregion enabled the development of detailed geological cross-sections of the Richmond river basin, which extend from the shallow alluvial aquifers to the deep coal-bearing layers. The causal pathways were finalised following discussion with stakeholders at the 'Conceptual modelling of causal pathways' workshop held in June 2015.

2.3.1.1 Background and context

Conceptual models are abstractions or simplifications of reality. A number of conceptual models are developed for a bioregional assessment (BA), including conceptual models for geology, groundwater and surface water, which underpin the numerical modelling. Another type of conceptual model is a conceptual model of causal pathways, which characterises the *causal pathway*, the chain of logic or activities – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. The conceptual model of causal pathways brings together a number of conceptual models developed in a BA, and might be expressed in a variety of ways, with narrative, pictorial graphics, and influence diagrams all important. This product presents information about the conceptual model of causal pathways for the Clarence-Moreton bioregion, which was developed using the methods outlined in the companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016). The application to the Clarence-Moreton bioregion is described in Section 2.3.1.2, with more specific details found in the individual sections that follow.

The causal pathways play a critical role in focusing the BA on the most plausible and important *hazards*, defined as events, or chains of events, that might result in an *effect* (change in the quality and/or quantity of surface water or groundwater). The causal pathways associated with these hazards underpin the construction of groundwater and surface water models, and frame the assessment of the *severity* and *likelihood* of impacts to water-dependent assets. A *water-dependent asset* is an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development. Some assets are solely dependent on incident rainfall and will not be considered as water dependent if evidence does not support a linkage to groundwater or surface water that may be impacted by coal resource development.

The construction of causal pathways requires the Assessment team to first synthesise and summarise the key system components, processes and interactions for the geology, hydrogeology and surface water of the bioregion (as presented in Section 2.3.2). Emphasising gaps and uncertainties is as important as summarising what is known about how various systems work.

Section 2.3.3 presents the development of a *landscape classification*, which aims to systematically simplify a complex system that contains a large number of assets identified by the community. The landscape classification describes the main biophysical and human ecosystems, and provides a high-level conceptualisation of the bioregion at the surface. Most assets are related to one or more *landscape classes*, which are defined for BA purposes as ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. Landscape classes are present on the landscape across the entire bioregion and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of *ecosystem assets*, which are ecosystems that may provide benefits to humanity (Bureau of Meteorology, 2013; United Nations et al., 2014).

Section 2.3.4 then defines two potential futures (Figure 3), namely the:

- *baseline coal resource development* (baseline), a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012
- *coal resource development pathway* (CRDP), a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in results between CRDP and baseline is the change that is primarily reported in a BA. This change is due to the *additional coal resource development* (ACRD) – all coal mines and CSG fields, including expansions of baseline operations that are expected to begin commercial production after December 2012.

Figure 4 illustrates this fundamental comparison of these futures, with the baseline in the top half of the figure and the CRDP in the bottom half of the figure. It demonstrates that in order to assess potential impact on assets, it is important to compare the changes of two types of variables at specific points in space and time:

- *hydrological response variables*, the hydrological characteristics of the system that potentially change due to coal resource development (for example, drawdown (Figure 3) or the annual streamflow volume)
- *receptor impact variables*, the ecological characteristics of the system that, according to the conceptual modelling, potentially change due to changes in hydrological response variables (for example, condition of breeding habitat for a given species, or biomass of river red gums).

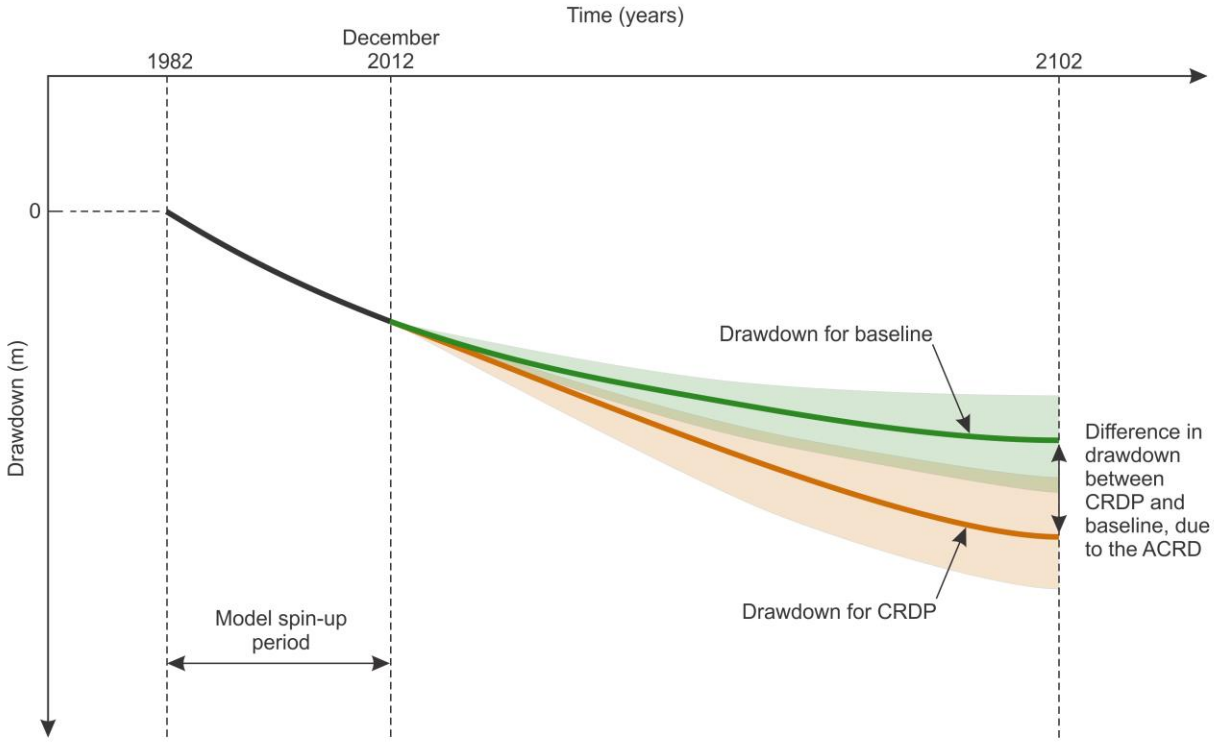

Figure 3 Generic example of drawdown at a specific location over time for the baseline coal resource development (baseline) and coal resource development pathway (CRDP). The difference in drawdown between CRDP and baseline is due to the additional coal resource development (ACRD)

The lighter shades indicate the uncertainty in results. Model spin-up period is a warm-up period for the models.

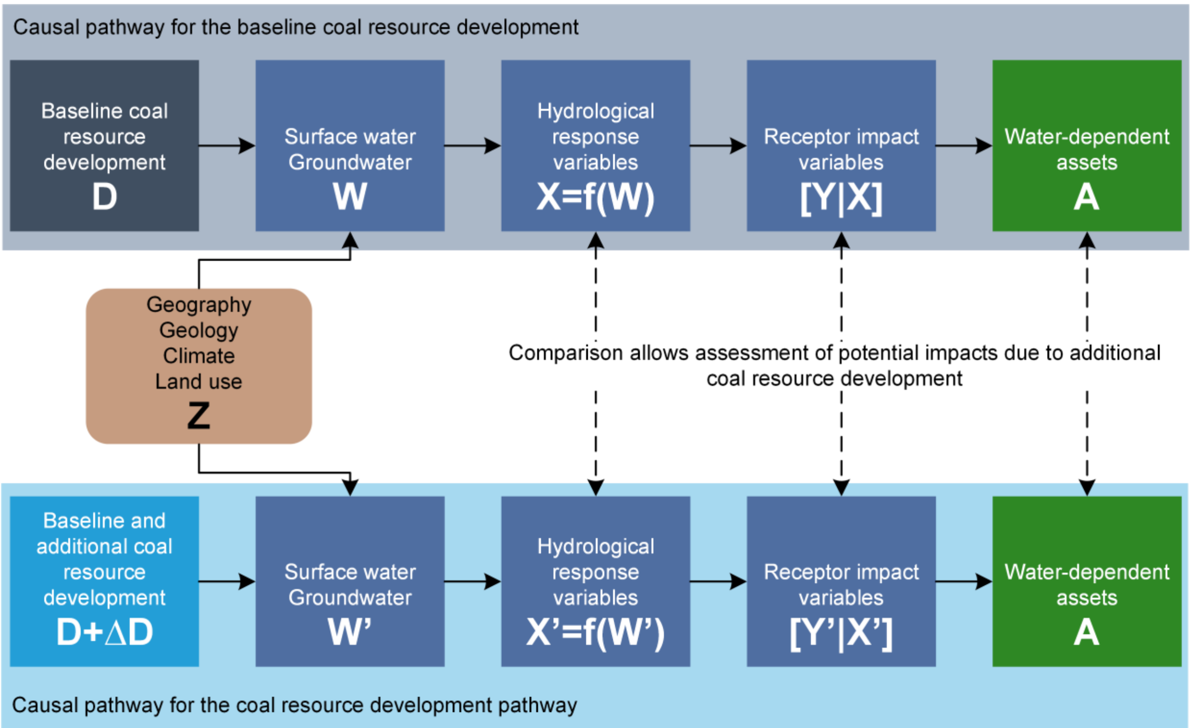

Figure 4 The difference in results between the coal resource development pathway (CRDP) and the baseline coal resource development (baseline) provides the potential impacts due to the additional coal resource development (ACRD)

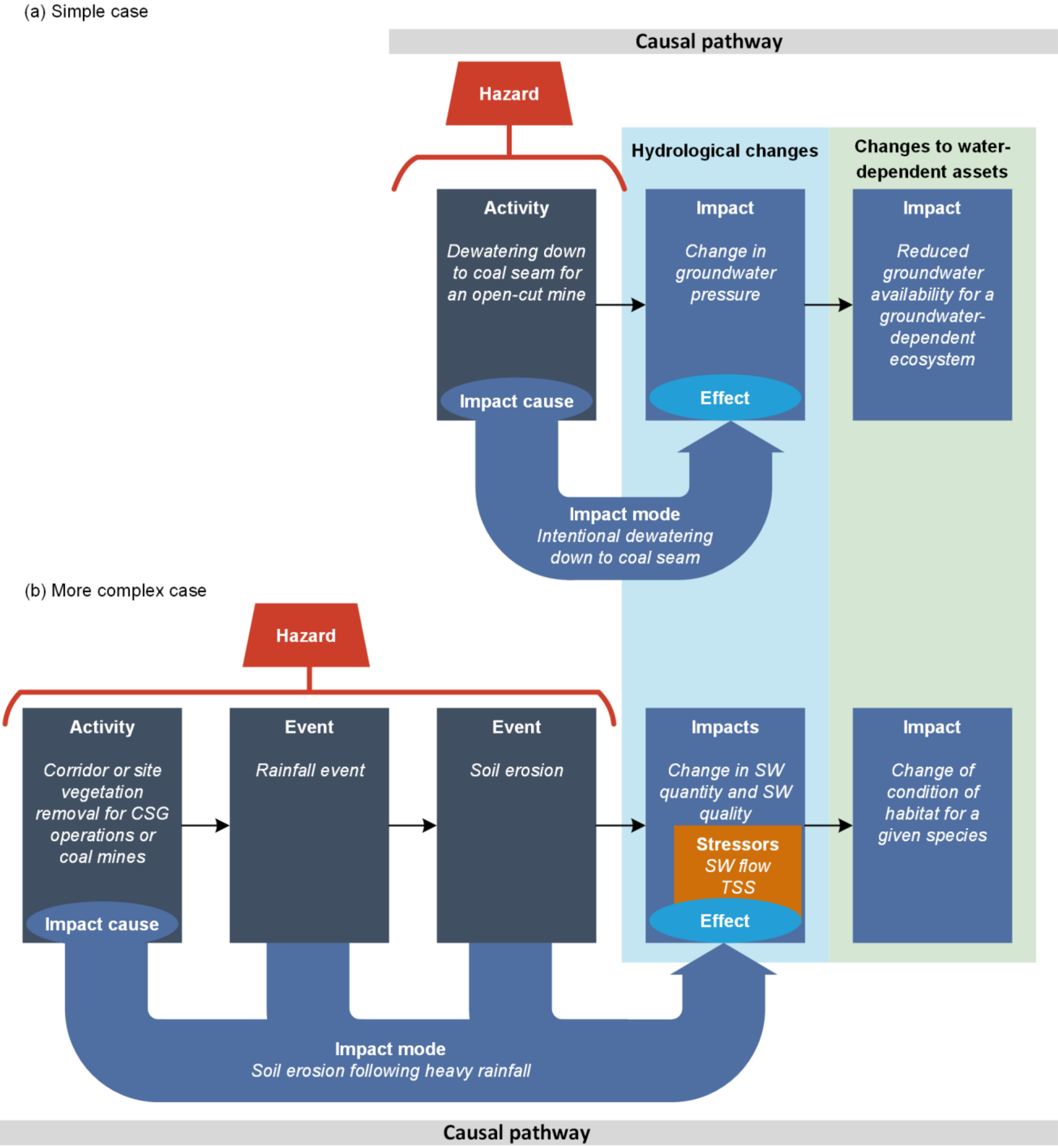

Figure 5 Hazard analysis using the Impact Modes and Effects Analysis. This figure shows how hazards identified using IMEA are linked to changes in hydrology and water-dependent assets via causal pathway

The italicised text is an example of a specified element in the Impact Modes and Effects Analysis. (a) In the simple case, an activity related to coal resource development directly causes a hydrological change which in turn causes an ecological change. The hazard is just the initial activity that directly leads to the effect (change in the quality and/or quantity of surface water or groundwater). (b) In the more complex case, an activity related to coal resource development initiates a chain of events. This chain of events, along with the stressor(s) (for example, surface water (SW) flow and total suspended solids (TSS)), causes a hydrological change which in turn causes an ecological change. The hazard is the initial activity plus the subsequent chain of events that lead to the effect.

Section 2.3.5 details the hazard analysis, using the Impact Modes and Effects Analysis (IMEA) method, as described in companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016), and illustrated in Figure 5. Potential causal pathways for both baseline and CRDP are identified by considering:

- *activities* – planned events associated with a CSG operation or coal mine. For example, activities during the exploration and appraisal life-cycle stage in a CSG operation include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into components, which are grouped into life-cycle stages
- *impact causes* – activities (or aspects of an activity) that initiate a hazardous chain of events
- *impact modes* – the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events
- *effects* – changes in the quantity and/or quality of surface water or groundwater. An effect is a specific type of an *impact* (any change resulting from prior events).

This product only specifies the causal pathways from coal resource development to hydrological response variables (see Figure 4). For BAs undertaking receptor impact modelling, the subsequent causal pathways (from hydrological response variables to impacts on landscape classes and water-dependent assets) are reported in the companion product 2.7 (receptor impact modelling). The Clarence-Moreton bioregion will not have a product 2.7 (receptor impact modelling) or a product 3-4 (impact and risk analysis). These causal pathways are reported for only those landscape classes with potential hydrological changes, as reported in product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling).

2.3.1.2 Developing causal pathways

The 'Conceptual modelling of causal pathways' workshop was held in Sydney in June 2015. The key components of the three-dimensional geological model for the Clarence-Moreton bioregion were described with emphasis on the Richmond river basin. This is attributed to the fact that the ACRD in the Clarence-Moreton bioregion is restricted to a potential CSG development near Casino, NSW. Detailed cross-sections showing the underlying geological stratigraphy in the Richmond river basin were presented; those cross-sections constituted the main underpinning for conceptualising the causal pathway. The landscape classification of the Clarence-Moreton bioregion is underpinned by the comprehensive understanding of the geology, which was achieved through the development of the three-dimensional geological model for the bioregion (Section 2.3.2 of this product). As the surface geology is an important influence on the landscapes of the Clarence-Moreton bioregion, the four main types of surface geology were used to classify landscapes in the bioregion. They are: fractured rock, consolidated sedimentary rock, unconsolidated sediments – alluvium and unconsolidated sediments – estuarine and coastal. The development of the Clarence-Moreton landscape classification is outlined in detail in Section 2.3.3.1.

There are no pre-existing CSG developments in the bioregion, and therefore, there is no baseline CSG development in the CRDP. There is one currently operating coal mine (Jeebropilly Mine in the Bremer river basin) in the baseline. Furthermore, one potential CSG development (the Metgasco West Casino Gas Project in the Richmond river basin) is included in the CRDP as an ACRD. As there is no hydraulic connection between the Richmond river basin and the Bremer river basin due to a prominent basement high that separates the hydrostratigraphic units, the groundwater model does not include the Bremer river basin and hence modelling focuses on the ACRD component of the CDRP in the Richmond river basin.

The potential causal pathways considered the CSG development included in the groundwater model, the impact causes and modes, the activities and the resulting water-related effects identified by the IMEA. The resulting water-related effects were grouped into four main causal pathways groups, which are described in detail in Section 2.3.5. Throughout the interactive presentations and consultation process with the key stakeholders, the Assessment team was able to refine their understanding of the key processes thus resulting in a better conceptualisation of the causal pathways. Discussions with the stakeholders also focused on knowledge gaps and uncertainties identified by the Assessment team.

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2.3.2 Summary of key system components, processes and interactions

Summary

The geological setting has a major influence on many hydrological and ecological processes, and is one of the main drivers that form the landscape. It controls key processes such as groundwater recharge and discharge as well as inter-aquifer interaction. It also significantly influences the interaction between the surface water and groundwater systems.

The aim of this section is to describe the conceptual understanding of how key system components such as geology, hydrogeology and surface hydrology operate and interact in the Clarence-Moreton bioregion. In addition to drawing on existing literature and information, new analyses conducted as part of the Clarence-Moreton Bioregional Assessment have greatly enhanced the knowledge of geology, hydrogeology and surface water in the bioregion.

For example, three-dimensional geological models were developed to improve the understanding of geology and hydrogeology in the Clarence-Moreton bioregion, and explain spatial hydrological processes. These were supplemented by the use of existing pictorial conceptual models developed by the Queensland Department of Environment and Heritage Protection. The two-dimensional and three-dimensional representations of geology facilitated the identification of pathways between different system components of the hydrological cycle, which explained the spatial relationships between different stratigraphic units and the Walloon Coal Measures (the main target of coal seam gas (CSG) exploration in the Clarence-Moreton bioregion).

Based on available information (as of 25 February 2016), the assessment of the baseline and the coal resource development pathway (CRDP) outlined in Section 2.3.4 of this product suggested that only one coal mine (Jeebropilly Mine) exists in the baseline coal resource development (baseline) with no future plans for new coal mine development in the Clarence-Moreton bioregion. Furthermore, the assessment suggested that only one CSG development may potentially proceed (West Casino Gas Project), and is therefore considered as an additional coal resource development (ACRD) in the Richmond river basin. A recent decision by Metgasco Limited (Metgasco) (16 December 2015) to sell back their petroleum exploration licenses (PELs) and petroleum production license application (PPLA) to the NSW Government effectively means that future development of any CSG resources in the Clarence-Moreton bioregion is highly uncertain. However, as per the CRDP methodology (companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014)), once the CRDP is determined, it is not changed for BA purposes, even in cases such as this where Metgasco have now discontinued their operations in the Clarence-Moreton bioregion.

The basin-wide three-dimensional geological model demonstrated that a basement high separates the Richmond river basin and the Bremer river basin (where the Jeebropilly Mine is located). This lack of hydraulic connection between the Bremer and Richmond river basins led the Assessment team to only focus on modelling impacts for the West Casino Gas Project,

thus excluding the Jeebropilly Mine during the development of the groundwater model. Consequently, Section 2.3.2 focuses on the geological, hydrogeological and hydrological characteristics of the Richmond river basin to support the development of the groundwater model. However, geological similarities within many parts of the Clarence-Moreton bioregion mean that the conceptual models of hydrological processes in the Richmond river basin could be adopted from other parts of the Clarence-Moreton bioregion such as the adjoining Logan-Albert river basin, the Lockyer Valley and the Brisbane river basin.

Conceptual hydrogeological models that integrate information from geology, hydrogeology and surface water hydrology are subject to uncertainties, particularly in data-scarce areas or in regions with complex geology. The uncertainties resulting from data gaps, data-quality issues and complex geological and hydrogeological settings are discussed in Section 2.3.2.6. This section highlights the fact that there are significant conceptual uncertainties regarding the role of faults as potential pathways linking deeper stratigraphic units such as the Walloon Coal Measures to shallow aquifers and surface water features in the Richmond river basin. Furthermore, there continues to be considerable uncertainty on the connectivity between deep and shallow aquifers in general. Due to the lack of nested bore sites where different aquifers are monitored simultaneously to assess vertical fluxes, other auxiliary data such as hydrochemistry were used to infer connectivity. The hydrochemical data suggest that there is likely to be aquifer connectivity in some areas within the Richmond river basin.

In contrast to the uncertainties regarding the role of faults and connectivity between shallow and deep aquifers, the role of the Lamington Volcanics as the major preferential recharge area within the Clarence-Moreton bioregion and in particular the Richmond river basin is well understood and supported by multiple lines of evidence. Recharge rates to these volcanic aquifers are at least one order of magnitude higher than recharge rates of sedimentary bedrock units such as the Walloon Coal Measures (the main target of CSG exploration). However, a large proportion of recharge to the Lamington Volcanics discharges into the stream locally with short lag times and following short flow paths; only a small proportion of this recharge percolates to deeper aquifers. The assessment of the spatial distribution of median streamflow rates further underpins the significance of the Lamington Volcanics as a major hydrological feature in the Richmond river basin, where most of the surface runoff is generated. The recharge assessment also confirmed that there are significant spatial variations in recharge rates to the alluvium in the headwaters (upper catchment), mid and lower catchment of the Richmond river basin. Hydrochemical data and analogues from data-rich parts of the Clarence-Moreton bioregion such as the Lockyer Valley or Bremer river basin indicate that sedimentary bedrock discharge to shallower aquifers or surface water is likely to be overwhelmed by the contribution from the Lamington Volcanics. However, in some areas and during periods of low flow (i.e. droughts), the contribution from the sedimentary bedrock may become more significant at the local scale.

Though various data sources representing multiple lines of evidence underpinned the current conceptual hydrogeological model, this model may not be unique. That is, there may be alternative models that adequately describe the geology, hydrogeology and hydrology of the Richmond river basin, and still honour the currently available data.

The detailed conceptual understanding presented in this section also underpins many activities including the landscape classification (Section 2.3.3) and the identification of causal pathways (Section 2.3.5), and thus provides the framework for the numerical groundwater model presented in companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016b).

2.3.2.1 Scope and overview

This section summarises the conceptual geological and hydrogeological understanding of deep and shallow rock units in the Clarence-Moreton bioregion and how they interact with each other, building on knowledge reported in companion products 1.1, 1.2, 1.5 and 2.1-2.2 (Rassam et al., 2014; Raiber et al., 2014; McJannet et al., 2015; and Raiber et al., 2016, respectively). It describes the connectivity between deep and shallow aquifer systems as well as their interaction with the surface water system, thus highlighting the possible pathways through which water-dependent assets may ultimately be impacted by potential coal seam gas (CSG) developments in the bioregion. Section 2.3.5 discusses specific causal pathways in the context of CSG operations.

Open-cut coal mine operations have occurred in both the Queensland and NSW parts of the Clarence-Moreton bioregion. However, coal mines in north-eastern NSW were generally small operations and have closed decades ago. As of early 2016, there is only one operational coal mine (Jeebropilly Mine) in the Clarence-Moreton bioregion in Queensland. The analysis of the CRDP for the Clarence-Moreton bioregion (Section 2.3.4) suggests that based on current information no new coal mines are expected in this area in the foreseeable future. CSG development is likely to be restricted to the Richmond river basin of north-eastern NSW (Figure 6 and Figure 7) (Section 2.3.4; companion product 1.2 for the Clarence-Moreton bioregion (Raiber et al., 2014)). Hence, the groundwater model developed to predict potential impacts of CSG activities on water-dependent assets (described in companion product 2.6.2 of the Clarence-Moreton bioregion (Cui et al., 2016b)) only focuses on the Richmond river basin in the Clarence-Moreton bioregion.

This section therefore focuses on the geological, hydrogeological and hydrological characteristics of the Richmond river basin to support the development of the groundwater model. However, many of the conceptual models presented for different geological units in the Richmond river basin are applicable across other parts of the Clarence-Moreton bioregion such as the adjoining Logan-Albert river basin, the Lockyer Valley and the Brisbane river basin (Figure 6) due to geological similarity. Such similarities across different parts of the Clarence-Moreton bioregion in NSW and Queensland mean that conceptual models developed by the Queensland Department of Environment and Heritage Protection for south-east Queensland, available on their Interactive Wetland*Info* website (Department of Environment and Heritage Protection, 2013), can be adopted for this bioregional assessment (BA). Combining those pictorial conceptual models with the two-dimensional and three-dimensional representations of the Richmond river basin underpin the current conceptual understanding of how different components of the hydrological cycle interact.

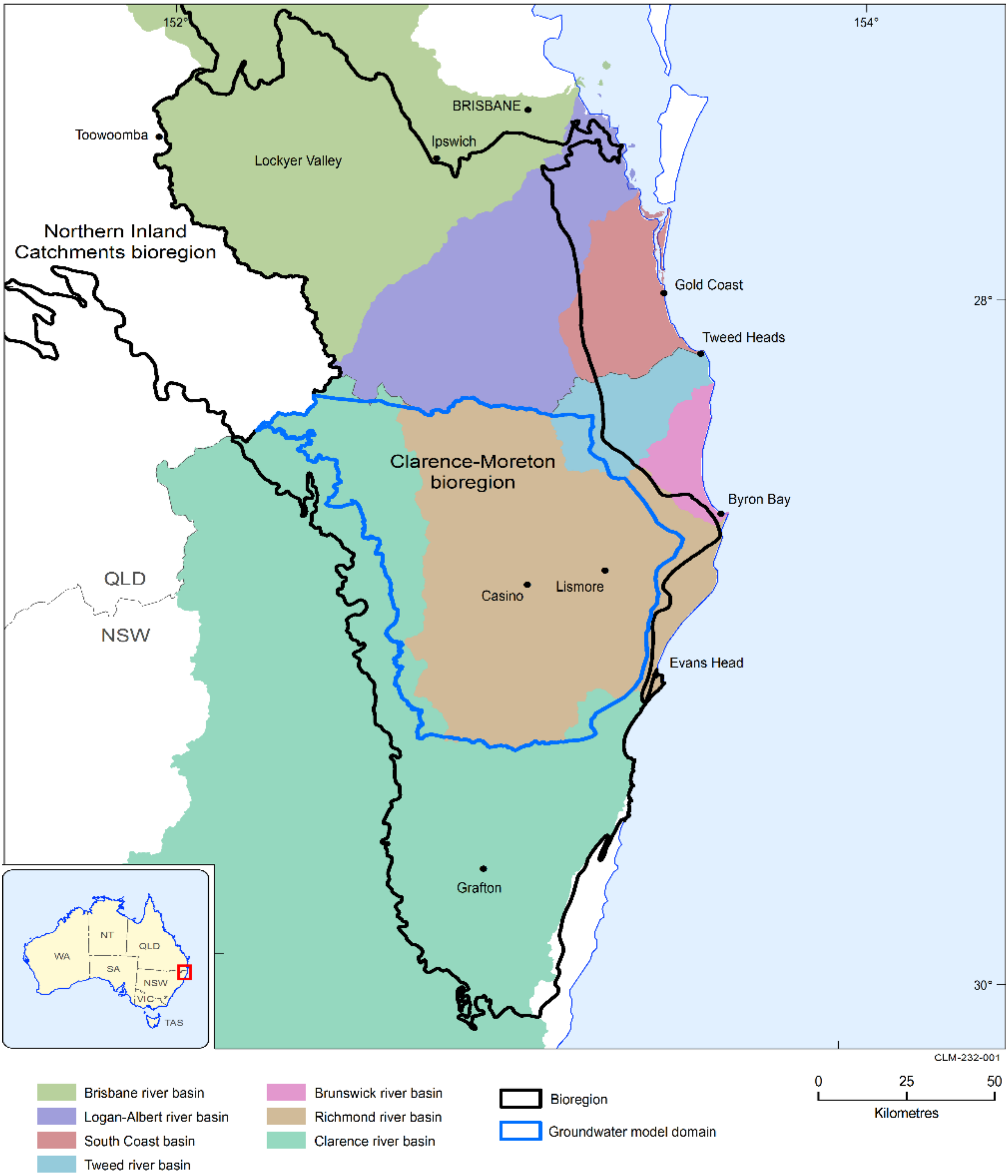


Figure 6 Richmond river basin and spatial relationship to Richmond River groundwater model domain

A three-dimensional geological model was developed for the entire Clarence-Moreton bioregion.
Data: Bioregional Assessment Programme (Dataset 1)

2.3.2.2 Geology and hydrogeology

2.3.2.2.1 Three-dimensional geological model of the Clarence-Moreton bioregion

A three-dimensional geological model of the Clarence-Moreton bioregion and regional models were developed as part of this BA (Figure 7), as described in companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016). In the Clarence-Moreton bioregion, geology has a major influence on many hydrological and ecological processes, and geological processes such as tectonic uplift and erosion shape terrain development and are major landscape-forming drivers. Geology also controls groundwater recharge and aquifer interaction and it also has a major influence on surface water – groundwater interactions.

The three-dimensional geological models have many applications to the Assessment. They highlight the spatial extent of alluvial, volcanic and sedimentary bedrock aquifers, and their structural and stratigraphic relationships. The models also include important topographic features such as Lamington National Park in southern Queensland, the Border Ranges National Park in northern NSW and the Main Range Volcanics in south-east Queensland. These are of great significance for hydrological processes and ecosystems as they are preferential groundwater recharge areas and also generate large volumes of surface water runoff. The bioregion-wide three-dimensional geological model also shows the five major regional alluvial aquifer systems that cover a substantial part of the Clarence-Moreton bioregion. These major alluvial systems are the Lockyer Valley alluvium, Bremer River/Warrill Creek alluvium and Logan-Albert River alluvium in Queensland, and the Richmond River and Clarence River alluvia in NSW (Figure 7). In the Richmond and Clarence river basins, estuarine and coastal sediments were deposited near the coast during the Quaternary. These can be identified in some bore logs, but their representation as separate layers in a three-dimensional geological model requires development of finer-scale models that focus exclusively on these areas, a task beyond the scope of this Assessment. Consequently, no differentiation was made in the three-dimensional geological model among different types of Quaternary unconsolidated sediments (i.e. alluvial, coastal or estuarine sediments).

Four higher resolution three-dimensional geological models were developed for the following river basins within the Clarence-Moreton bioregion:

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

These allow closer examination of local hydrological processes and regional groundwater dynamics, and provide the model structure for the numerical groundwater model of the Richmond river basin (discussed in companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016b)). In this product, the focus is on hydrological processes limited to the area covered by the Richmond river basin three-dimensional geological model domain (Figure 8) to provide the structure that underpins the numerical groundwater model.

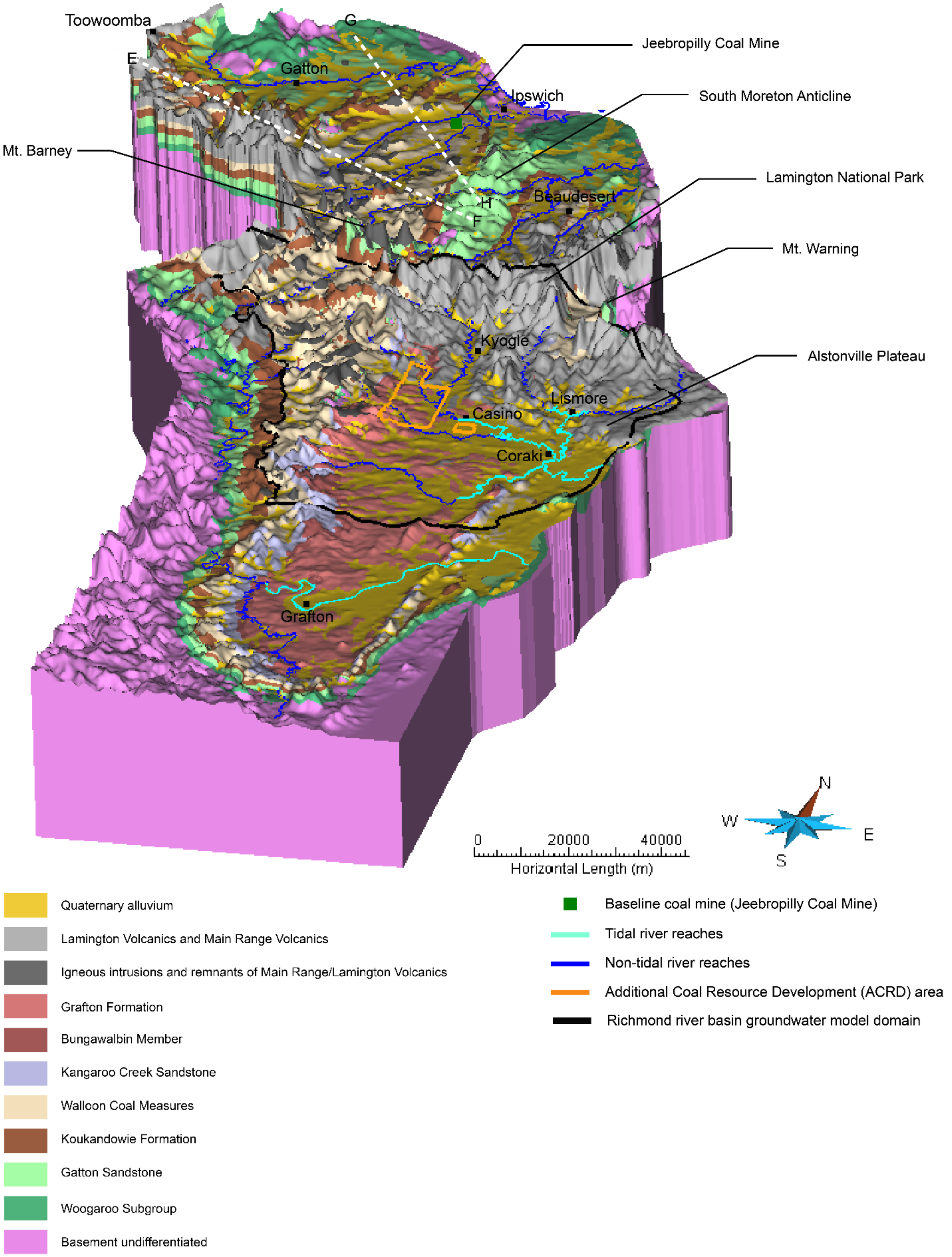


Figure 7 Three-dimensional geological model of the Clarence-Moreton bioregion

Viewed from the south-east; the vertical extent is from –2500 to +1400 m Australian Height Datum (AHD); the north-south extent is 320 km; the maximum east-west extent is 140 km; the vertical exaggeration is 10. The dashed lines E to F and G to H show the orientation of cross-sections Figure 14 and Figure 15.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3); NSW Trade and Investment (Dataset 4)

2.3.2.2.2 Three-dimensional geological model of the Richmond river basin

The three-dimensional geological model of the Richmond river basin (Figure 8 and Figure 9) highlights geological and topographic features. It shows the spatial distribution and geometry of alluvia, volcanic and sedimentary bedrock stratigraphic units. Major structural features were projected onto the three-dimensional geological model, and major permanent or near-permanent streams are shown. Two major regional fault systems with potentially significant influence on groundwater flow are the East Richmond and Coraki faults. Another important structural feature is the mid-basin high, which separates the Casino Trough (where most CSG exploration has occurred and where the West Casino Gas Project is located) from the Lismore Trough. A further depositional centre is the Grafton Trough. Fault displacements are not modelled in this version of the three-dimensional geological model, but faults will be incorporated in a future model realisation as part of a CSIRO strategic funding 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'). Thick sequences of basalts, which are part of the Lamington Volcanics, occur in the northern part of the Richmond river basin (discussed in more detail in Section 2.3.2.2.6). The headwaters of the major rivers in the Richmond river basin (the Richmond and Wilsons rivers) are located in the steeper upper parts of the volcanics. Further downstream, these rivers are tidal-influenced. The Walloon Coal Measures, the major target for CSG exploration in the Clarence-Moreton bioregion, outcrop in the western part of the Richmond river basin. In the centre of the Richmond river basin and in the West Casino Gas Project area, they are covered by several hundred metres of younger sedimentary bedrock units and alluvial aquifers (discussed in more detail in subsequent sections).

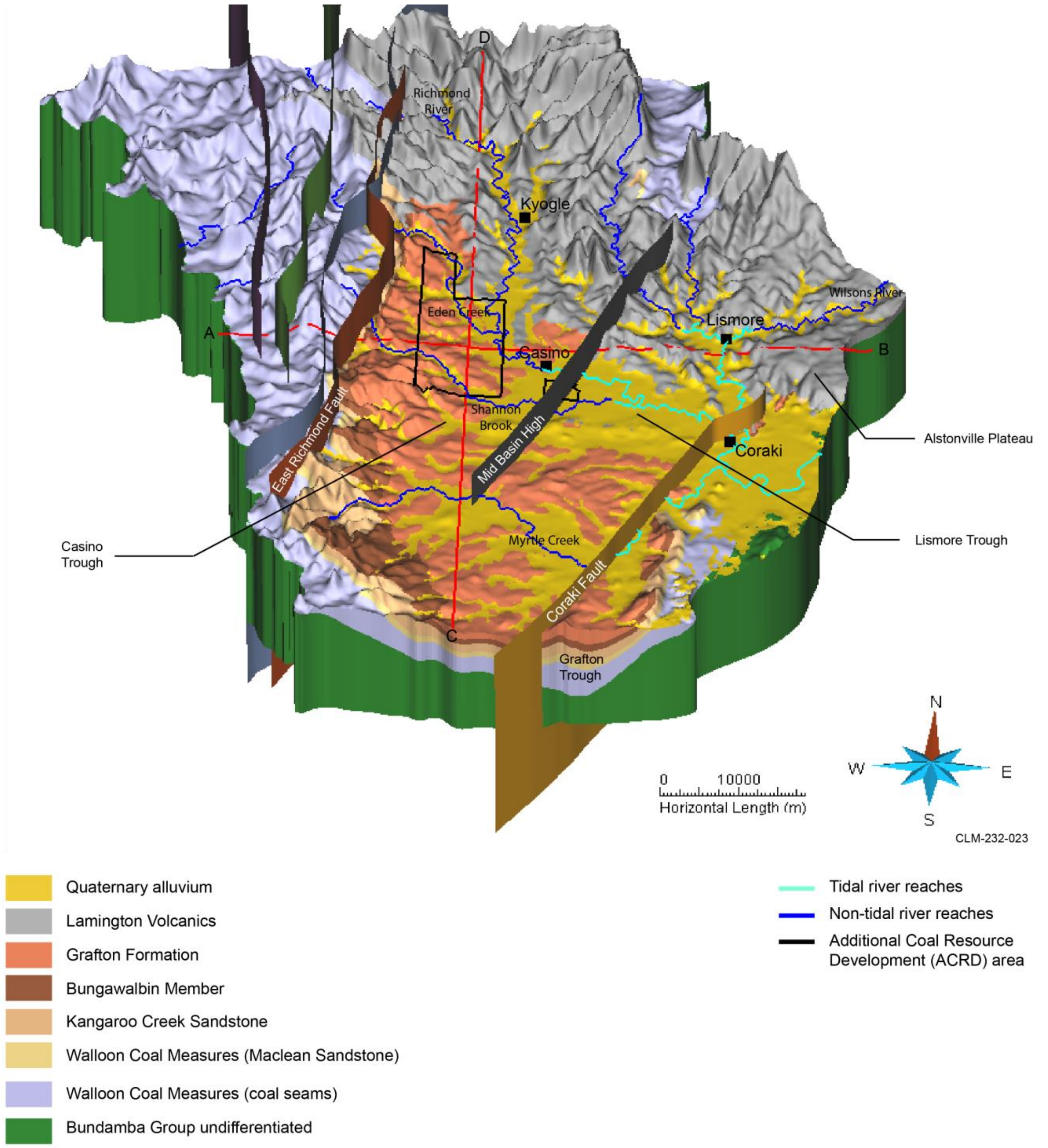


Figure 8 Three-dimensional geological model of the Richmond river basin; the extent of this model corresponds to the extent of the Richmond river basin groundwater domain

Viewed from the south; the vertical exaggeration is 12. Lines A to B and C to D show the orientation of the fence diagram (Figure 9) and cross-section (Figure 24). Faults and other structural elements are projected as vertical surfaces on the three-dimensional geological model.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 3, Dataset 5); NSW Trade and Investment (Dataset 4)

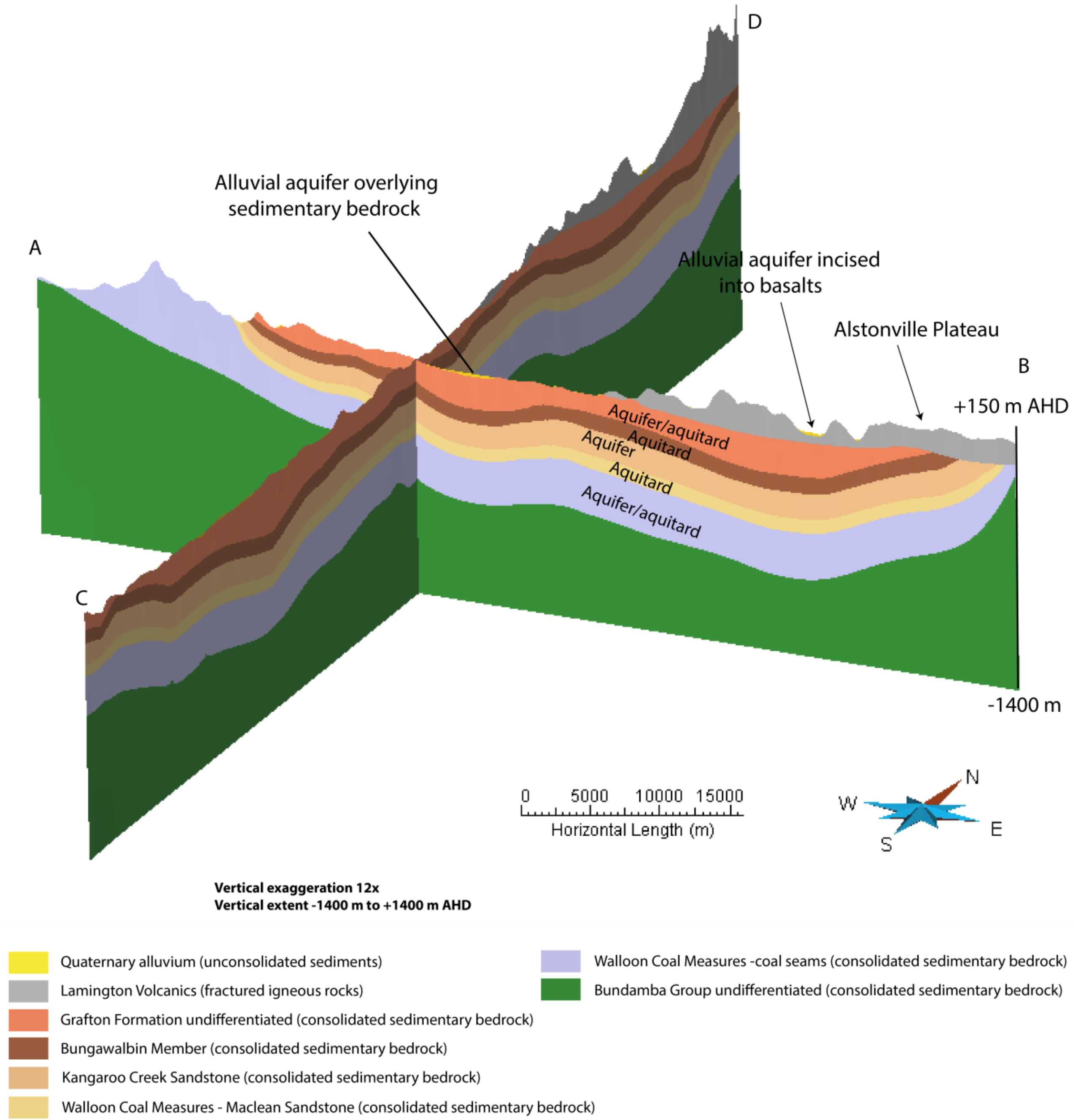


Figure 9 Fence diagram through the Richmond river basin showing geometric and thickness relationships between alluvial, volcanic and sedimentary bedrock hydrostratigraphic units

In brackets in the legend, the assignment of each unit to the four major hydrostratigraphic groups or geology types is shown. A–B and C–D refer to the orientation of the cross-section line in Figure 8.
Data: Bioregional Assessment Programme (Dataset 5)

For the purpose of landscape classification (described in detail in Section 2.3.3.1), all geological units within the Clarence-Moreton bioregion were assigned to four major geology types:

- unconsolidated sediments – alluvium (surface alluvium up to approximately 40 m thick, representing an unconfined to semi-confined aquifer)
- unconsolidated sediments – estuarine and coastal

- fractured igneous rock – in the Clarence-Moreton bioregion, this category relates mostly to volcanic (extrusive) rocks. Fractured intrusive rocks also exist (e.g. Figure 10), but are only of minor significance for hydrological or ecological processes in the Richmond river basin due to their areally limited extent
- consolidated sedimentary rock – this category includes all the Clarence-Moreton Basin sedimentary units (e.g. corresponding to Grafton Formation, Bungawalbin Member, Kangaroo Creek Sandstone, Walloon Coal Measures and Bundamba Group in Figure 10).

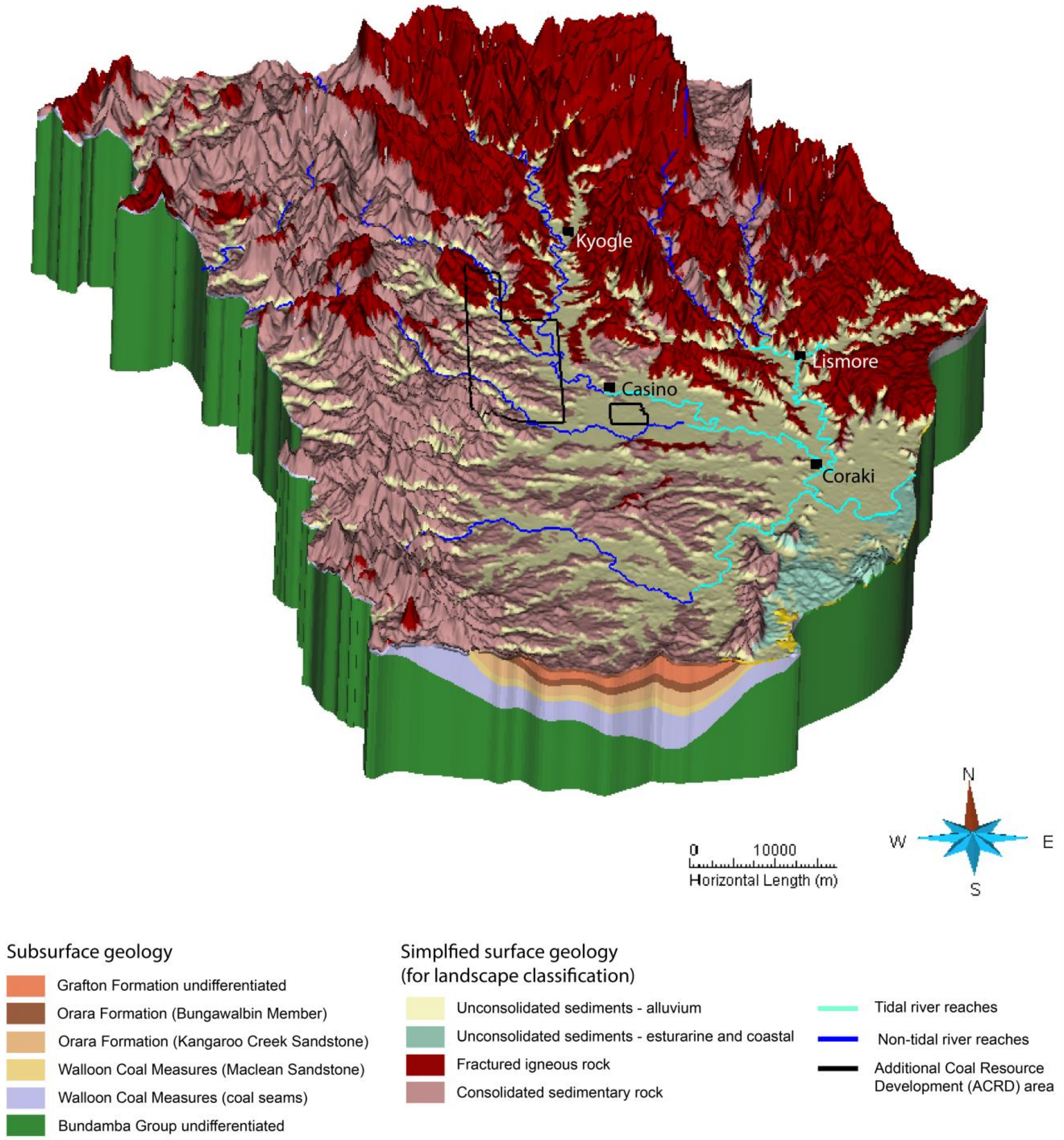


Figure 10 Three-dimensional geological model of Richmond River basin and four major simplified surface geology types

Data: Bioregional Assessment Programme (Dataset 1, Dataset 3, Dataset 5); NSW Trade and Investment (Dataset 4)

2.3.2.2.3 Groundwater flow directions, groundwater recharge and discharge

Groundwater recharge is one of the most important hydrogeological processes, as it has a major impact on the flow and composition of groundwater in aquifer systems. Having reliable information on the amount of recharge, as well as on its temporal variability and the spatial distribution of preferential recharge areas, is critical in water resource assessments and the development of groundwater models. Due to the spatial heterogeneity of geological materials, climatic variability and the scarcity of hydrogeological data in many regions, groundwater recharge is also one of the most difficult processes to estimate (e.g. Raiber et al., 2015).

For this BA, groundwater recharge to the aquifers of the Clarence-Moreton bioregion was estimated using chloride mass balance for the fractured volcanic rock and sedimentary bedrock aquifers for the entire bioregion, complemented by an assessment of the relationship between soils, vegetation and rainfall for alluvial aquifers (companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016)). Groundwater recharge occurs via different mechanisms, including diffuse rainfall recharge and surface water recharge.

Diffuse rainfall recharge occurs where stratigraphic units are exposed at the surface. The three-dimensional representation of groundwater recharge in the Richmond river basin shows high spatial variability in recharge rates due to the variable hydraulic properties of the sediments and rocks.

The recharge assessment conducted as part of this BA suggests that there are several preferential recharge areas in the Clarence-Moreton bioregion (Figure 11 and Figure 12):

- the entire extent of Main Range Volcanics and Lamington Volcanics
- Woogaroo Subgroup outcrop in the Lockyer Valley (at the northern margin of the Clarence-Moreton bioregion)
- the western margin of the Clarence-Moreton bioregion in NSW, where the sedimentary bedrock units are topographically elevated, is considered a major area of recharge to the sedimentary bedrock aquifers in NSW
- Cenozoic intrusions – hydrochemical data and groundwater mounding near Cenozoic intrusions in the Bremer river basin and Warrill creek basin (Figure 11) suggests that these act as preferential recharge areas for the Walloon Coal Measures. Elsewhere within the Clarence-Moreton bioregion (e.g. Richmond river basin), there are relatively few Cenozoic intrusions and their influence on regional groundwater recharge processes is therefore likely to be very limited.

Although these areas are all considered as preferential recharge areas for specific aquifers, the recharge assessment indicates that recharge rates to the Main Range Volcanics and Lamington Volcanics are at least one order of magnitude larger than to most sedimentary bedrock units. The three-dimensional geological model shows that the Walloon Coal Measures, the primary CSG target, is exposed over extensive areas in both Queensland and NSW. However, the recharge assessment highlights that recharge rates to this unit are comparatively small.

Inferred groundwater flow directions of the sedimentary bedrock units are shown in Figure 11. In the Richmond river basin in NSW, the bedrock topographic gradients suggest that groundwater in the sedimentary bedrock likely flows from the elevated western margin towards the lower-lying eastern basin margin.

The three-dimensional representation of formation bases (Figure 13), where each formation base corresponds to the formation top of the underlying stratigraphic unit, highlights that there is no hydraulic connection between the Casino Trough and the Warrill Creek Syncline (which underlies the Bremer river basin, where the only operating coal mine in the Clarence-Moreton bioregion is located) due to the presence of two basement highs (Mount Barney basement high and South Moreton Anticline).

As outlined in companion products 2.1-2.2 and 1.3 for the Clarence-Moreton bioregion (Raiber et al., 2016; Murray et al., 2015, respectively), the Lockyer Valley was not included in the preliminary assessment extent (PAE). This is because the Walloon Coal Measures are not present in approximately 80% of the Lockyer Valley (Figure 14). Furthermore, where the Walloon Coal Measures are present in the Lockyer Valley, they are only very thin (0 to 100 m) and covered by thick sequences of the Main Range Volcanics (Figure 15). Together with the location at the basin margin where coal thickness and gas saturation are likely to be very small, there is sufficient evidence to indicate that there is unlikely to be any potential for CSG development in the Lockyer Valley.

The assessment of geology and hydrogeology conducted during this BA suggests that throughout the Clarence-Moreton bioregion in Queensland and NSW, there are several areas where upward leakage occurs from the sedimentary bedrock to the shallow aquifer and to the surface at the down-gradient end of the flow paths. An example of a sedimentary bedrock discharge area in the Clarence-Moreton bioregion that is best constrained by monitoring data is located at the eastern boundary of the Bremer river basin (Figure 11). The potentiometric surface of the Walloon Coal Measures in this discharge area suggests that groundwater flows towards a relatively small area at the eastern margin of the basin south-west of Ipswich, where it is likely to discharge into the alluvium and to the surface (Figure 11). In other areas such as the Richmond river basin where less groundwater monitoring data exist, the bedrock topographic gradient is derived from the three-dimensional geological model; this suggests that, similar to the Bremer river basin, groundwater in the sedimentary bedrock flows towards the lowest point in the eastern part of the Richmond river basin near Coraki (e.g. Figure 12 and Figure 13), where it is likely to discharge into the alluvial aquifers.

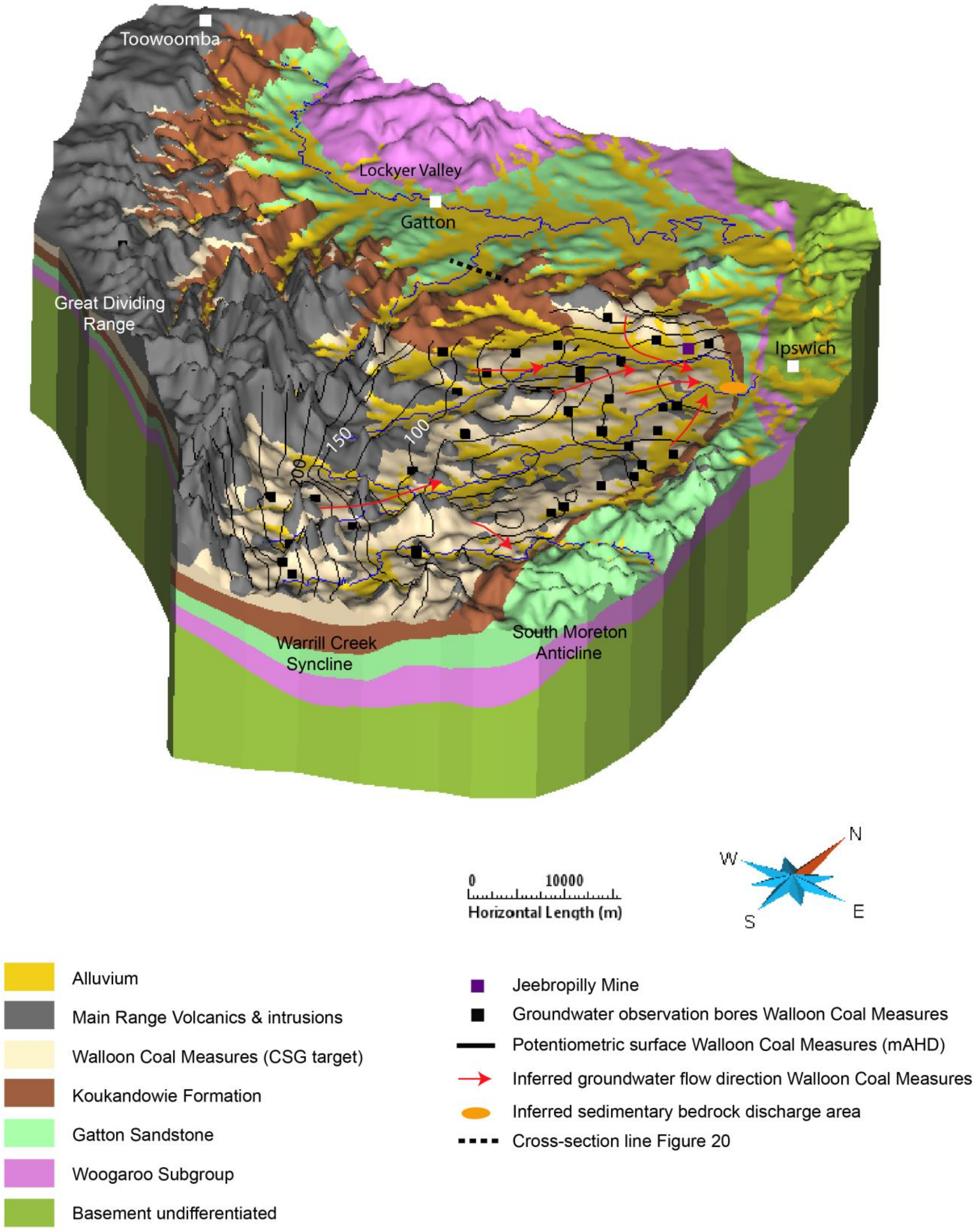


Figure 11 Three-dimensional geological model of the Bremer river basin, Warrill creek catchment and Lockyer Valley

Superimposed are the potentiometric surface map, inferred groundwater flow directions and discharge areas of Walloon Coal Measures in the Bremer river basin and Warrill creek catchment.
The vertical extent is from –2000 to +1200 m AHD; the north-south extent is 100 km; the maximum east-west extent is 95 km; the vertical exaggeration is 10.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3)

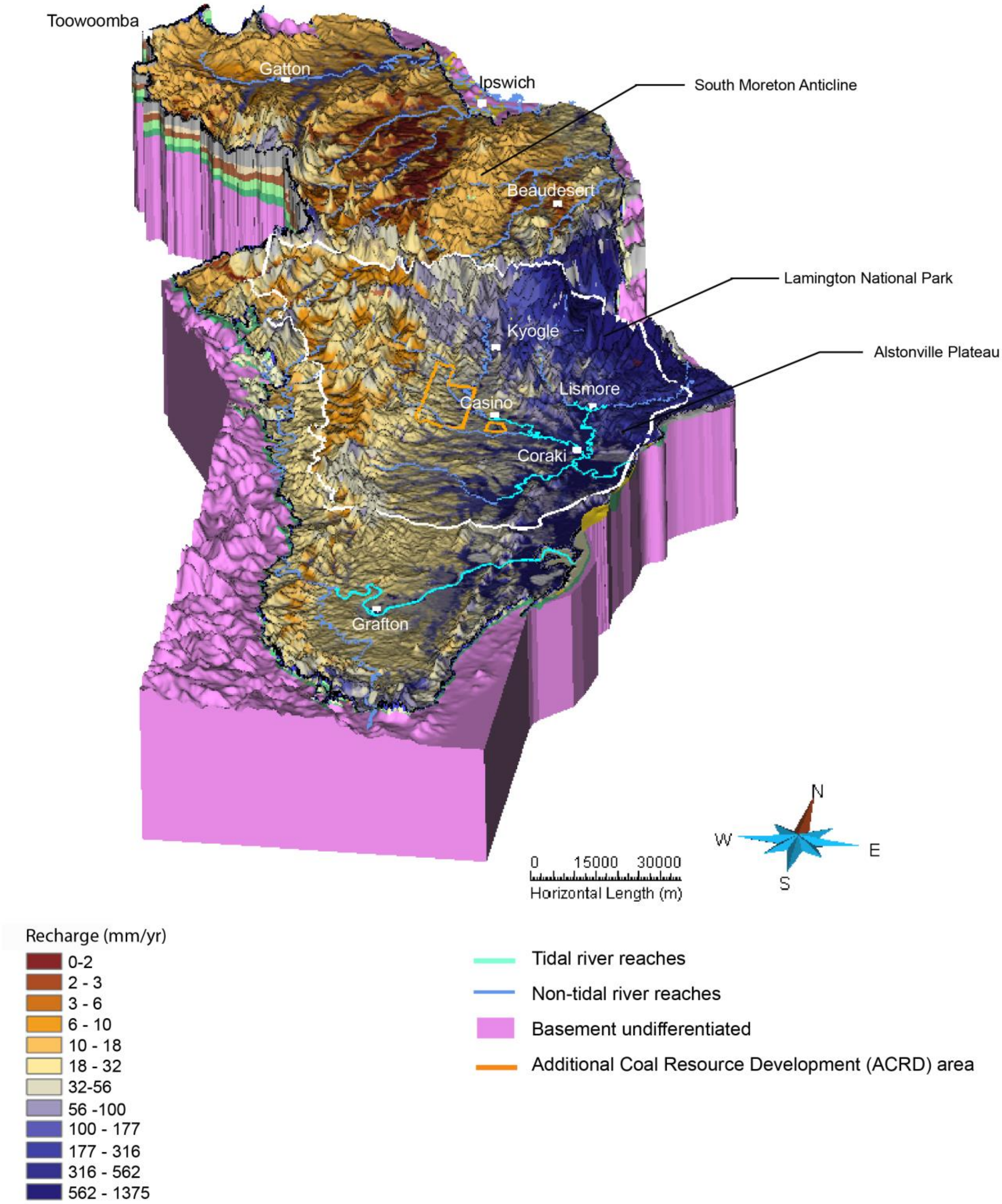


Figure 12 Three-dimensional representation of groundwater recharge distribution in the Clarence-Moreton bioregion

The vertical extent is from –2500 to +1400 m AHD; the north-south extent is 320 km; the maximum east-west extent is 140 km; the vertical exaggeration is 10.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3, Dataset 6); NSW Trade and Investment (Dataset 4)

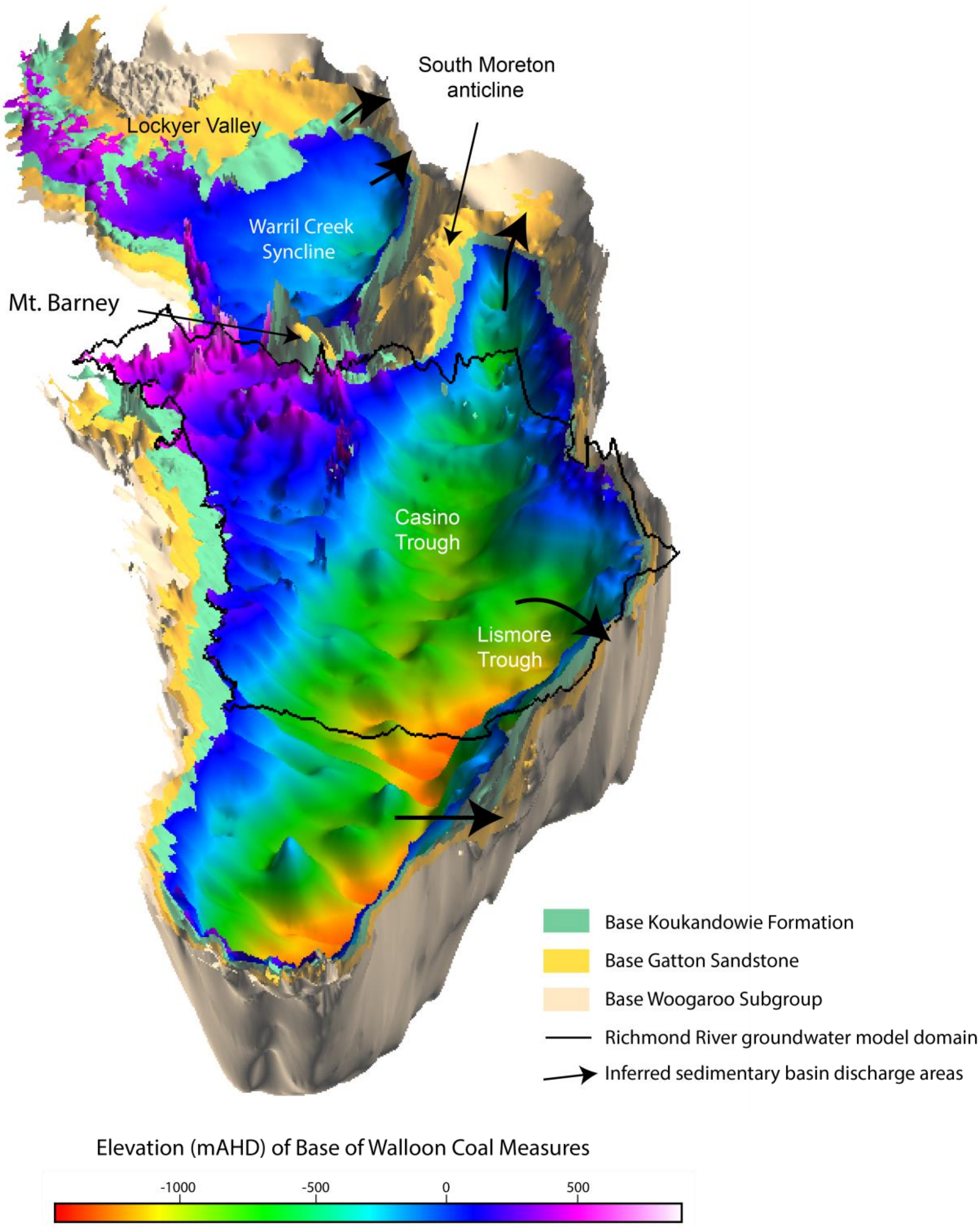


Figure 13 Three-dimensional representation of formation bases of Walloon Coal Measures (shown as colour-coded elevation), Koukandowie Formation, Gatton Sandstone and Woogaroo Subgroup

Geological structures and Richmond River groundwater model domain are also shown.
The north-south extent is 320 km; the maximum east-west extent is 140 km; the vertical exaggeration is 12.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2)

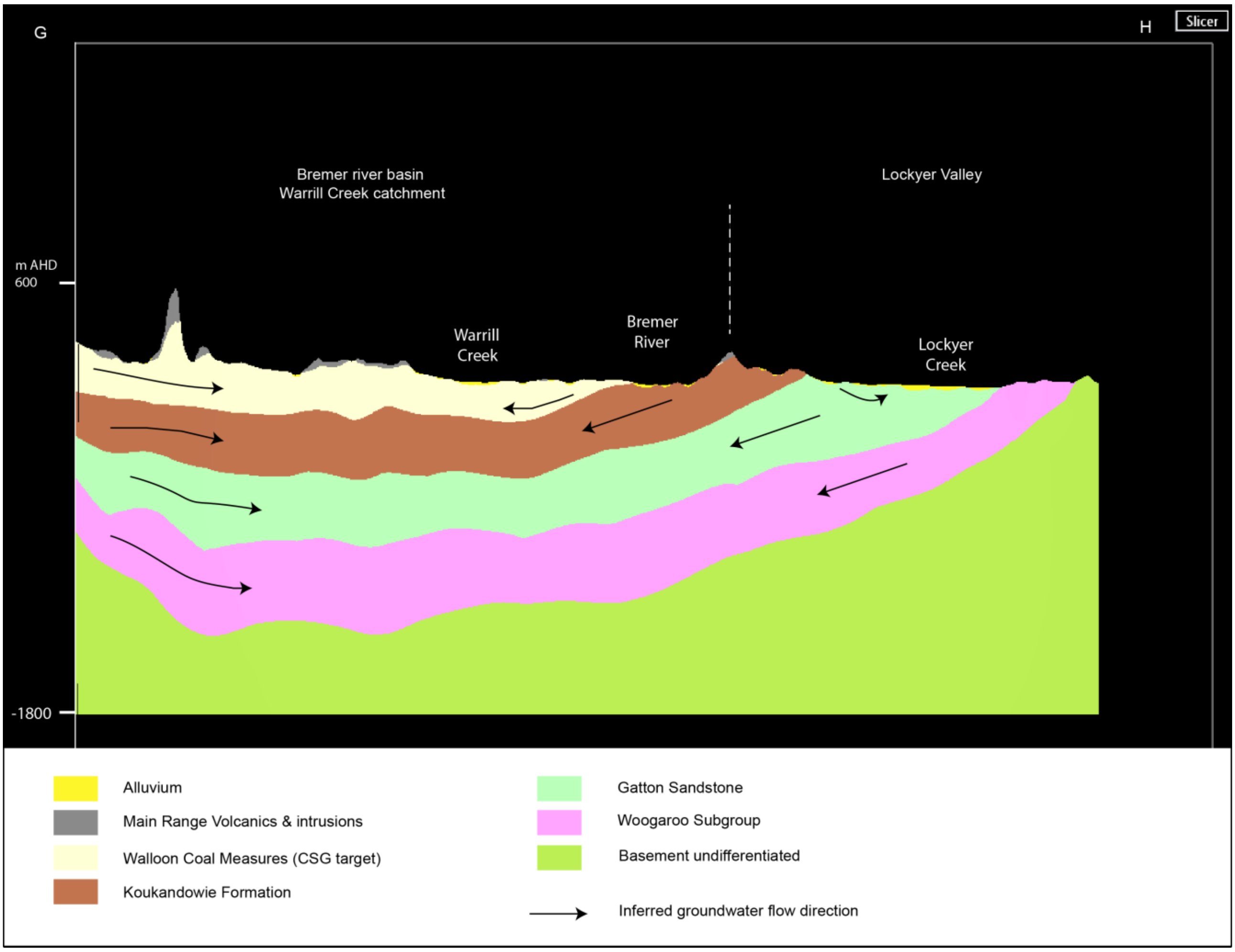


Figure 14 Cross-section G–H through the Bremer river basin, Warrill creek catchment and the Lockyer Valley, highlighting the absence of the Walloon Coal Measures in the Lockyer Valley

For orientation of cross-section, see Figure 7.
Data: Bioregional Assessment Programme (Dataset 2)

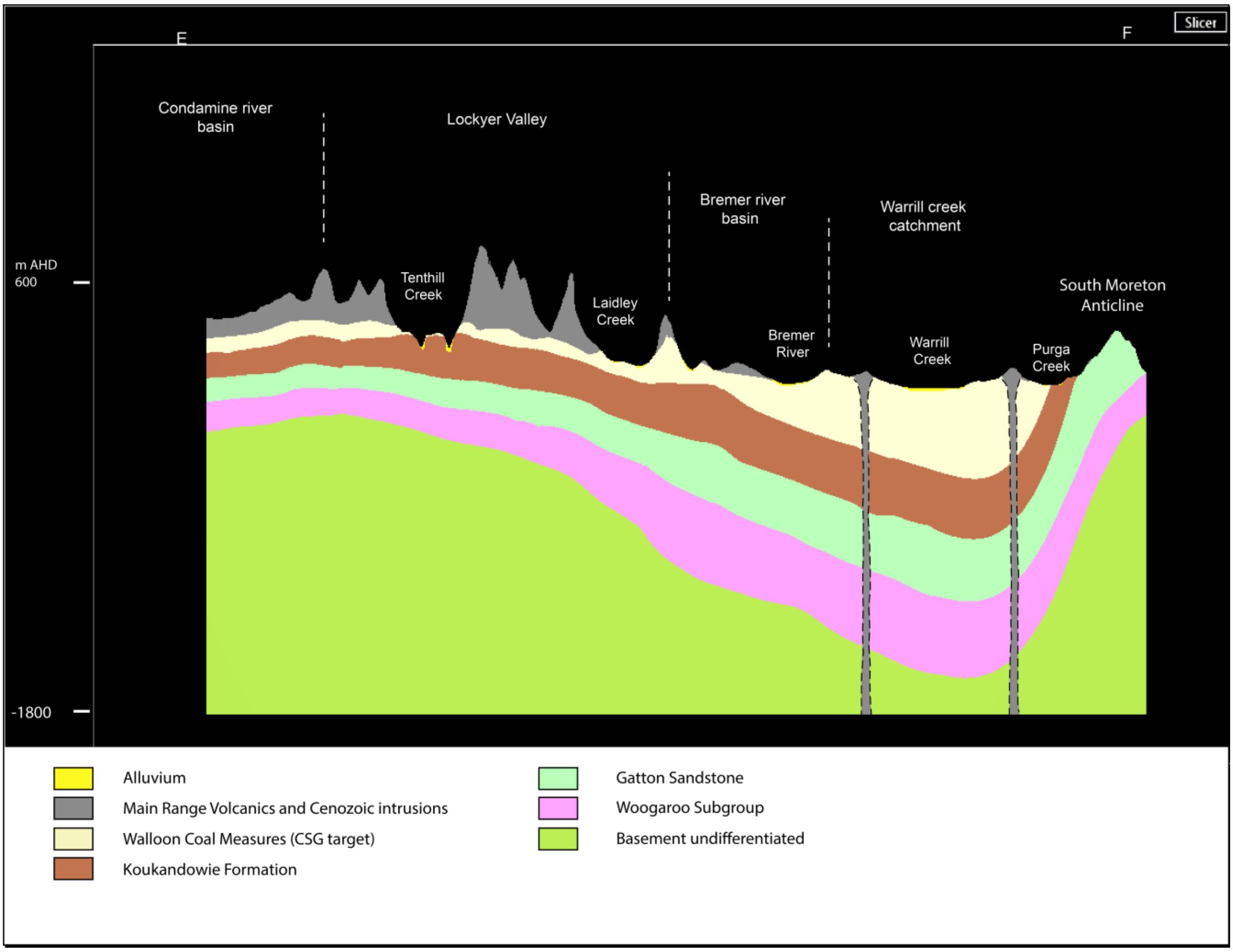


Figure 15 Cross-section E–F through the Bremer river basin, Warrill creek catchment and the Lockyer Valley, highlighting the spatial relationship of the Walloon Coal Measures and the Main Range Volcanics in the Lockyer Valley

For orientation of cross-section line, see Figure 7.
The dashed line at the interface of the intrusions and the sedimentary bedrock indicates that the subsurface geometry of these intrusions is unknown. Consequently, they have not been modelled in the three-dimensional geological model and were instead added subsequently to the cross-section.
Data: Bioregional Assessment Programme (Dataset 2)

2.3.2.2.4 Unconsolidated sediments – alluvium

2.3.2.2.4.1 Alluvia overview

Alluvial aquifer systems host many important water-dependent assets in the Clarence-Moreton bioregion. Throughout the Clarence-Moreton bioregion, alluvial depositional and aquifer systems follow a generalised pattern of upper, mid and lower catchment alluvial development (Figure 16).

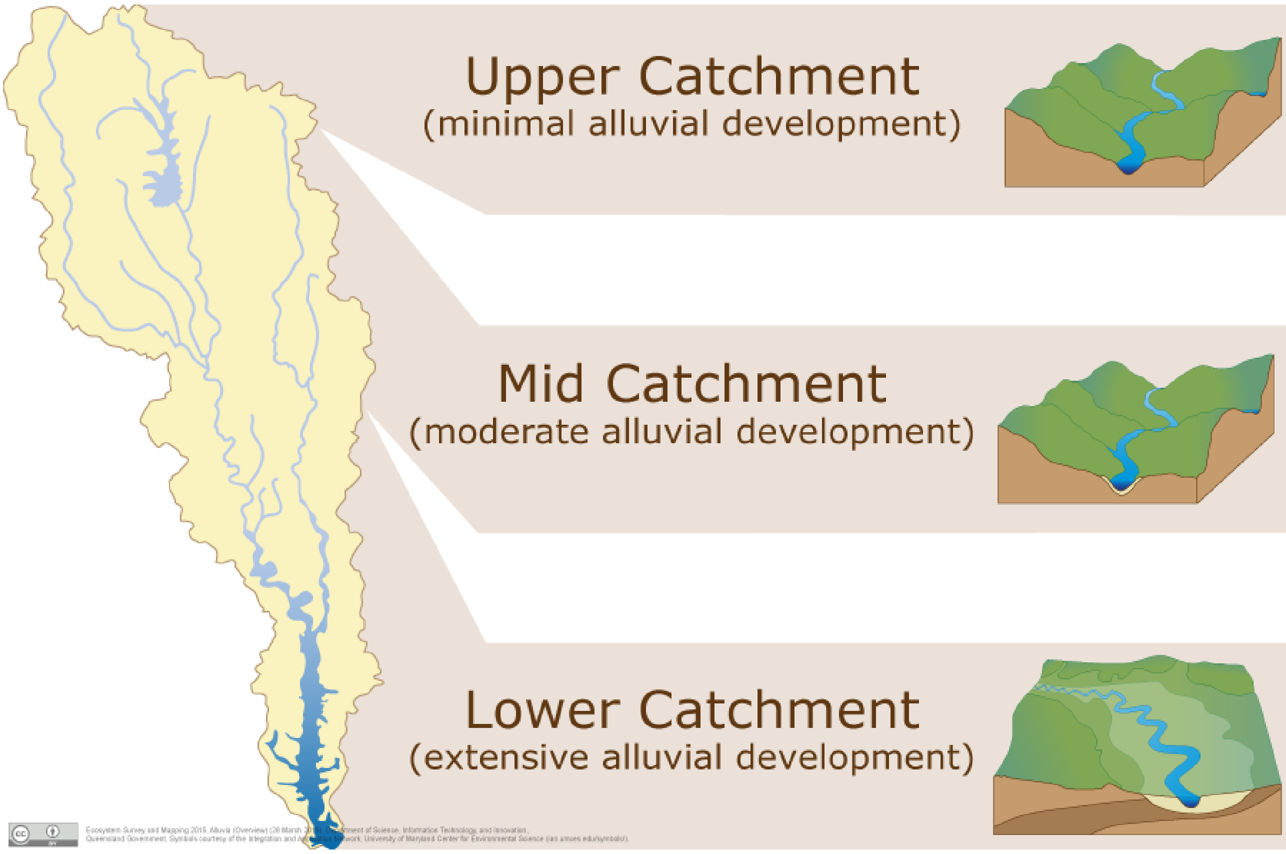


Figure 16 Different alluvial systems recognised in upper, mid and lower zones for a generalised catchment in the Clarence-Moreton bioregion in south-east Queensland

See Queensland Government (2015a) for more information.
Data: Adapted from DSITI (Dataset 7), © The State of Queensland (Department of Science, Information Technology and Innovation), 2015

2.3.2.2.4.2 Upper catchment

Alluvial sediments in the topographically higher upper catchment (headwaters) of the Richmond river basin (and in other similar catchments within the Clarence-Moreton bioregion) are relatively thin (typically less than 15 m thick) and are composed mostly of unconsolidated coarse-grained sediments such as boulders, gravel and sand (Figure 17). These have been derived from erosion of the Lamington Volcanics and deposited in a high-energy fluvial environment. Streams in the upper catchment erode deeply into the surrounding basaltic landscape, thus forming narrow (typically less than 500 m wide) and steep v-shaped valleys. Due to the coarse composition of the alluvial sediments of the upper catchment, groundwater in these unconfined aquifers is stored and transmitted rapidly through relatively large intergranular voids between boulders, gravel and sand. In the alluvial channels in the upper catchment, only thin clay and soil profiles overlie the alluvial sequences as sediments are frequently re-worked during high-energy rainfall and flow events. Due to the absence of an overlying confining layer, the alluvial aquifers in the upper catchment are unconfined, thus resulting in high infiltration and recharge rates (Figure 12), and consequently lower groundwater salinity of less than 1000 µS/cm (Raiber et al., 2015; Figure 18). As a result of the limited alluvial development and the predominance of coarse-grained alluvial sediments in these upper reaches, rapid discharge from the basalts to the thin and areally restricted alluvial deposits occurs due to a close hydraulic connection with short flow paths (commonly only hundreds of metres) and short residence times (likely to range from days to months). The response of water levels to rainfall is near-instantaneous, suggesting that most of the alluvial aquifer is saturated during wet conditions particularly following episodic high rainfall events (Figure 17(a)). Conversely, groundwater levels in the upper alluvium rapidly decline during drier climate periods or persistent droughts, when much of the alluvial aquifer becomes unsaturated (Figure 17(b)).

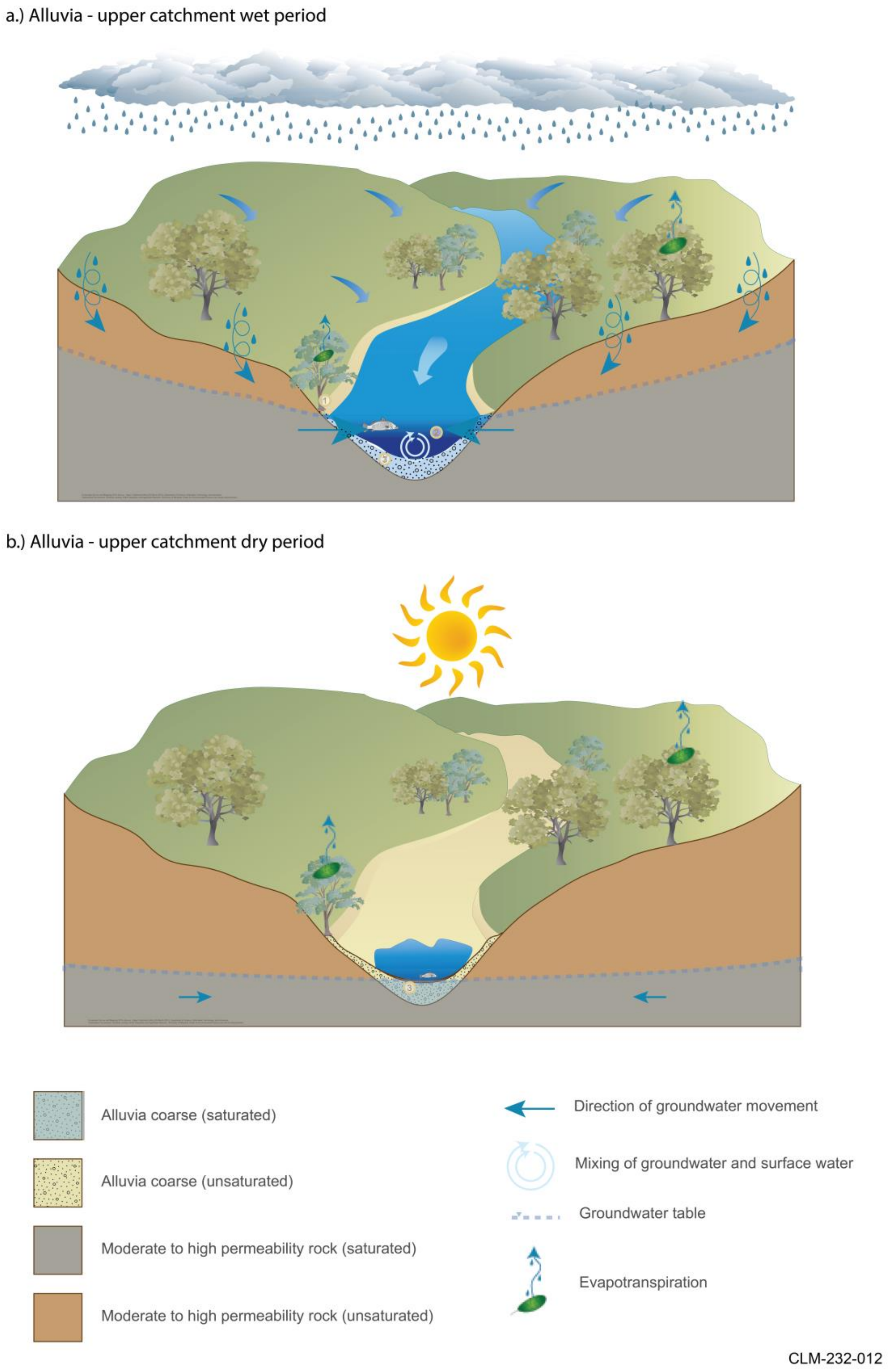


Figure 17 Hydrological conceptual model of alluvia in the upper reaches during (a) wet and (b) dry periods

See Queensland Government (2015b) for more information.
Source: Adapted from DSITI (Dataset 7), © The State of Queensland (Department of Science, Information Technology and Innovation), 2015

2.3.2.2.4.3 Mid-catchment

The mid-catchment of the Richmond river basin and other similar areas within the Clarence-Moreton bioregion are characterised by wider floodplains (approximately 0.5 to 2 km wide) and thicker alluvial sequences (approximately 15 to 30 m thick) compared to the upper alluvium (Figure 19). The relative proportion of finer-grained sediments such as clay and silt increases, and there is greater likelihood of soils forming above the alluvial sequences. The greater abundance of fine-grained sediments and the presence of clays or soils on top of the alluvium potentially result in lower recharge rates when compared to the upper catchment, though recharge rates are still considered to be high.

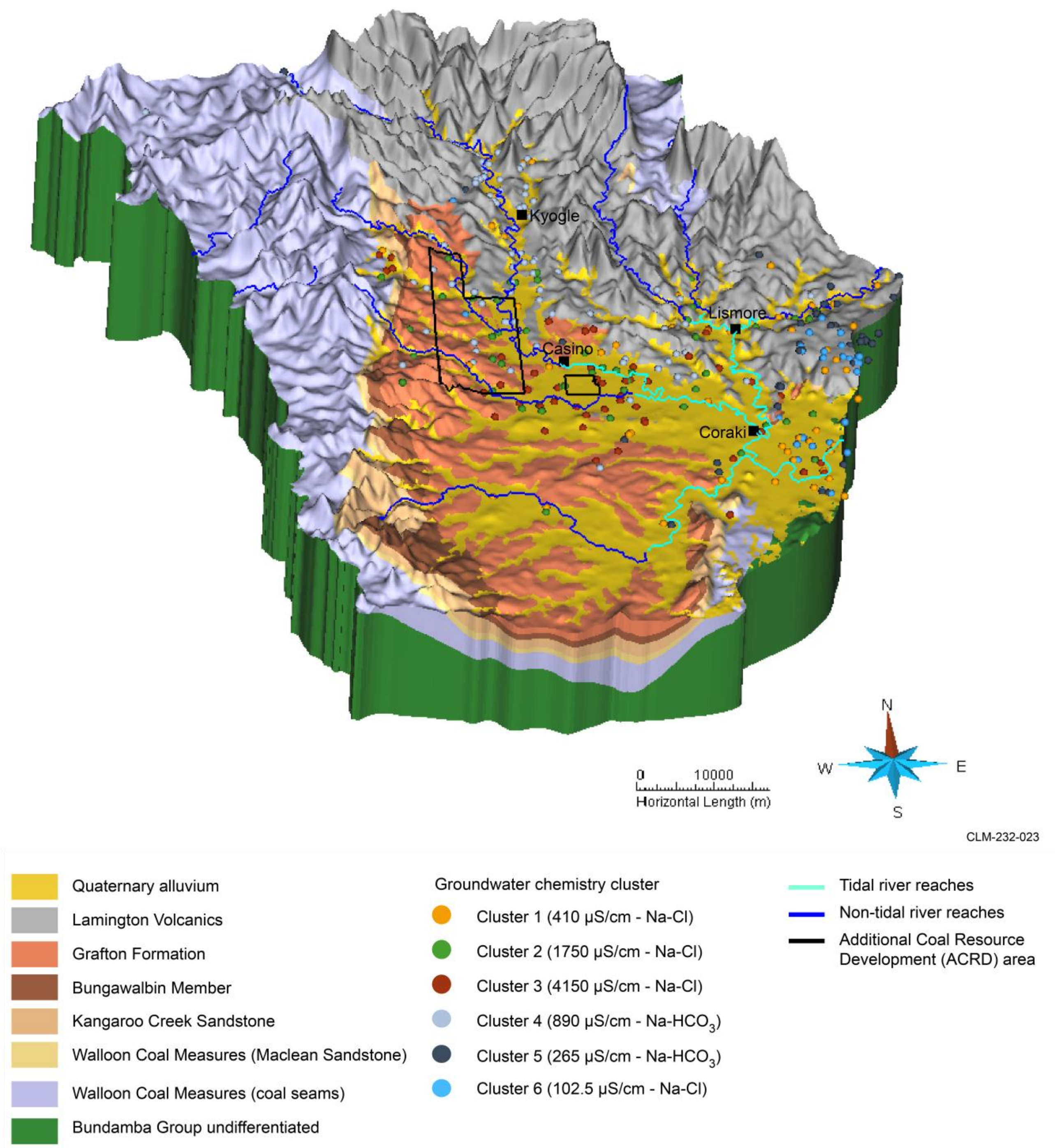
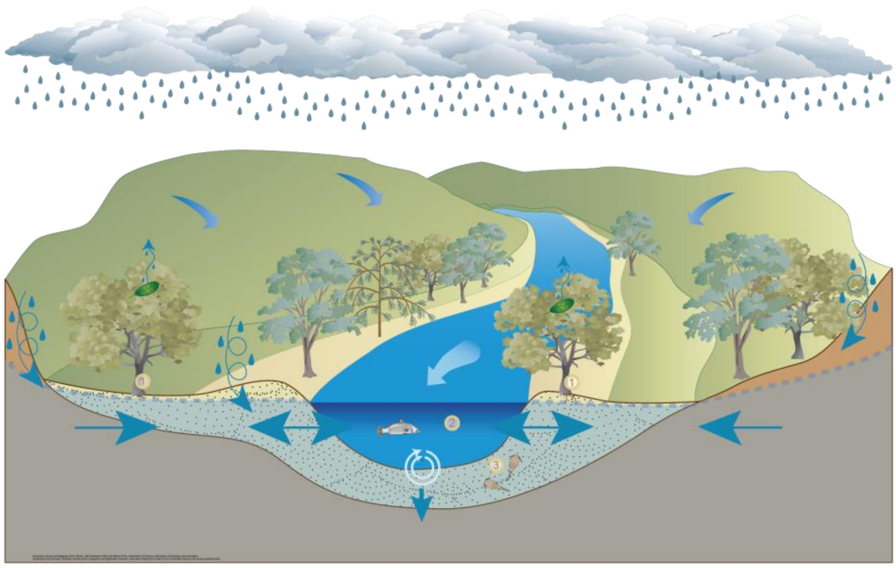


Figure 18 Groundwater chemistry clusters, median electrical conductivities and hydrochemical water type in the Richmond river basin

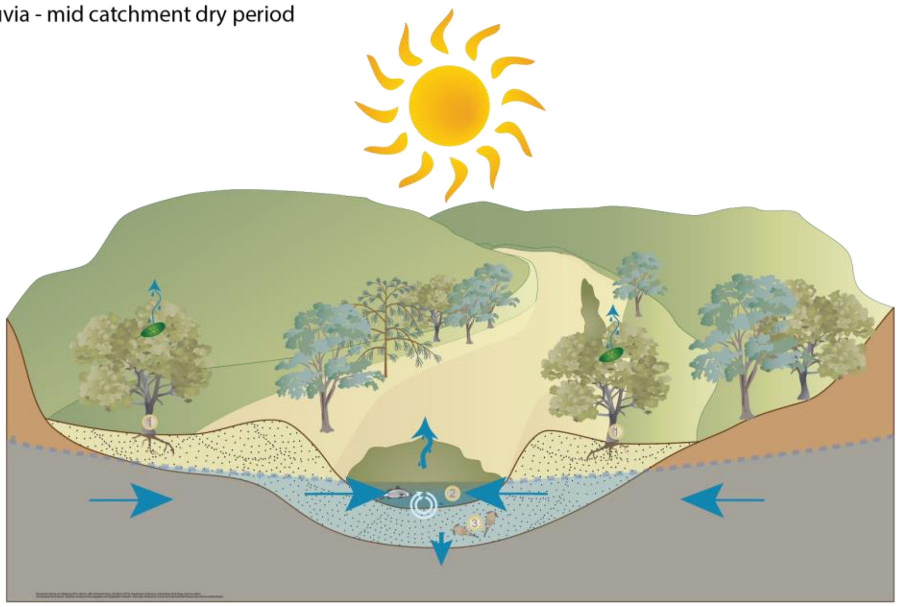
Additional information on groundwater chemistry in the Richmond river basin is available in companion products 1.5 (McJannet et al., 2015) and 2.1-2.2 (Raiber et al., 2016) for the Clarence-Moreton bioregion.
Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5, Dataset 8)

The change from a sedimentary composition dominated by coarse-grained sediments in the upper alluvium to a dominance of finer sediments in the lower catchment is associated with the change to the lower-energy meandering fluvial system for the latter. Unlike the upper catchment where the alluvium is exclusively underlain by highly fractured and hydraulically transmissive basalts of the Lamington Volcanics, the alluvium in the mid-catchment is more likely to be underlain by sedimentary bedrock units, which are hydrostratigraphic units with significantly lower hydraulic conductivities than the Lamington Volcanics. Due to a larger thickness and a different sediment composition, the alluvial aquifers in the mid-catchment respond differently to climatic extremes. During wet periods (Figure 19(a)), they have shallow water levels and are close to full saturation. However, during drier months or periods of severe drought, the larger aquifer thickness and the higher degree of aquifer confinement means that the alluvial aquifers have a larger 'buffering' capacity compared to the alluvial aquifers in the upper catchment (Figure 19(b)). As a result, they have more consistent groundwater levels even during extensive drought periods, and support a wider range of ecosystems and ecological processes. Furthermore, due to the more complex recharge processes, the groundwater chemical composition becomes more variable in comparison to the upper catchment, as represented by a wider range of electrical conductivities and variable groundwater chemistry (Figure 18).

a.) Alluvia - mid catchment wet period



b.) Alluvia - mid catchment dry period



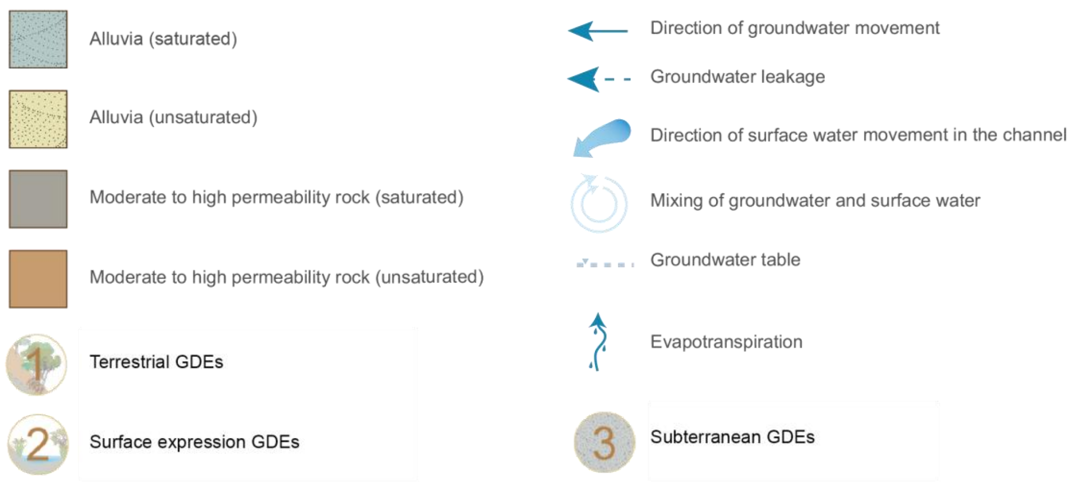


Figure 19 Hydrological conceptual model of alluvia in the mid-catchment reaches during (a) wet and (b) dry periods

See Queensland Government (2015c) for more information.
Data: Adapted from DSITI (Dataset 7), © The State of Queensland (Department of Science, Information Technology and Innovation), 2015

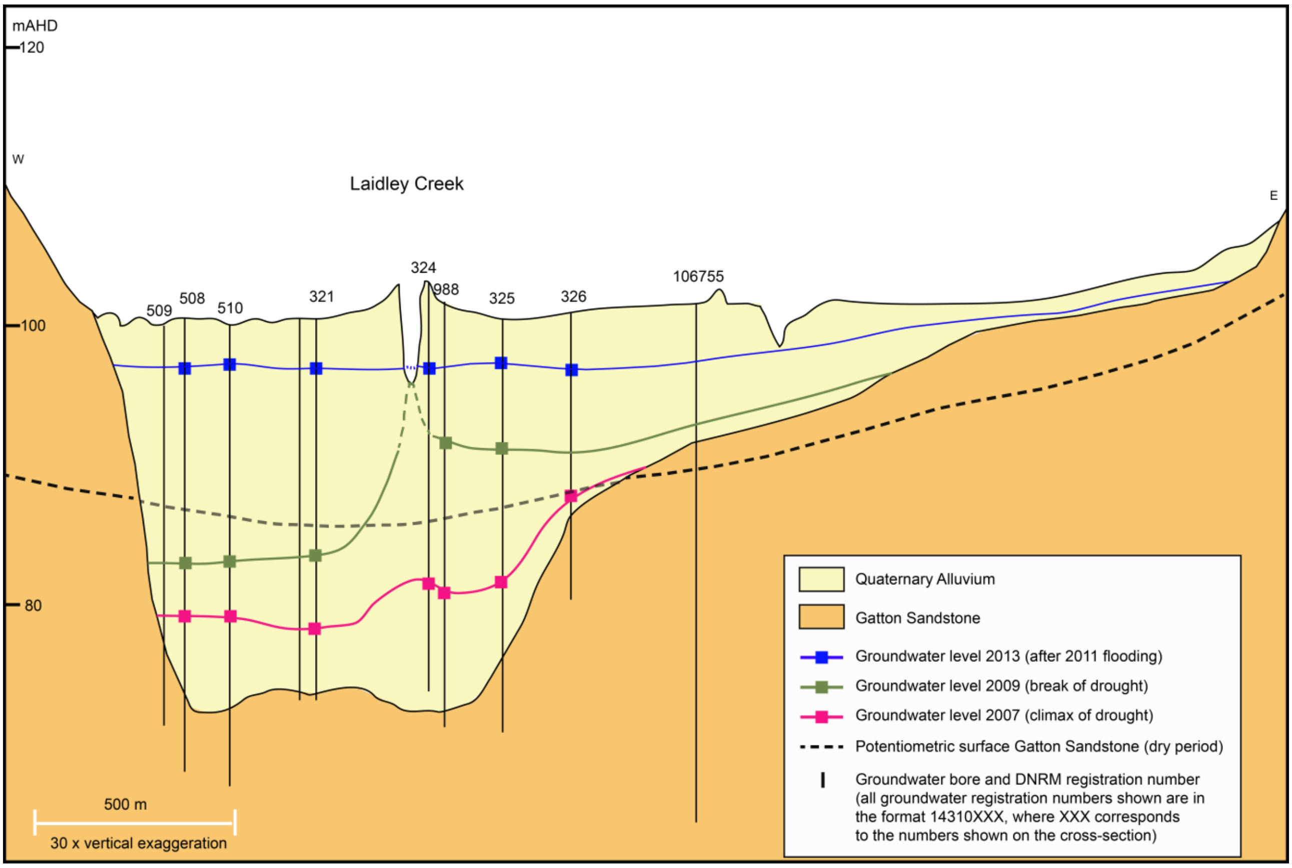


Figure 20 Example of temporal variability of groundwater levels in an alluvial aquifer overlying sedimentary bedrock in a mid-catchment location in the Lockyer Valley in the Clarence-Moreton bioregion in Queensland

For orientation of cross-section line, see Figure 11.

2.3.2.2.4.4 Lower catchment

Alluvial aquifers in the lower catchment of the Richmond river basin (i.e. down-gradient of Casino) and other similar areas within the Clarence-Moreton bioregion tend to be significantly wider (up to approximately 15 km) and deeper (ranging mostly between approximately 25 to 50 m) than those in the upper and mid-catchment (Figure 21). Typically, the alluvial sediments in the lower catchment are fining-upward sequences of unconsolidated and, less commonly, semi-consolidated sediments. Within these alluvial sequences, gravel- and sand-rich layers occur near the base, overlain by thick deposits of finer-grained floodplain silts and clays that have been deposited in a low-energy floodplain environment. Throughout the Quaternary, the Richmond River frequently changed its course across the floodplain of the lower catchment. Abandoned stream channels are now preserved in the landscape as paleochannels. As these paleochannels consist mainly of coarse-grained sediments (sand and gravel) relative to surrounding finer-grained material, they can transmit groundwater faster and can form perched aquifers.

Surface water in the Richmond river basin is generally fresh (Raiber et al., 2016). The observed higher groundwater salinities in the alluvium of the lower Richmond river basin down-gradient of Grafton suggest that river recharge to the alluvium is likely to be less significant (Raiber et al., 2015; Figure 18) than in the upper catchment. Diffuse recharge from precipitation seems to be the more dominant recharge process in the lower catchment. The presence of low permeability silt and clay at the top of the alluvia means that the aquifer is commonly semi-confined, and recharge rates are substantially lower than those in the alluvium of the upper catchment. However, near the coastal eastern part of the Richmond river basin, recharge rates to the alluvium are higher than those in the central part of the catchment due to the predominance of sandy soils that facilitate rapid recharge, as supported by the prevalence of lower groundwater salinities in these coastal areas.

Unlike the upper and mid-catchments, the lower Richmond river alluvia are underlain mostly by sedimentary bedrock units such as the Grafton Formation (Figure 10). In comparison to the Lamington Volcanics, sedimentary bedrock units such as the Grafton Formation are less permeable, and there is likely to be a smaller degree of hydraulic connection across the interface between the sedimentary bedrock and the alluvium. This suggests that the relative contribution of the sedimentary bedrock discharge to the overall alluvial water balance is small during normal climatic conditions. However, examples from other parts of the Clarence-Moreton bioregion show that during prolonged drought periods, the relative water level difference (head gradient) between the alluvial and sedimentary bedrock aquifers can increase (Figure 20) due to a more rapid and pronounced drop in the alluvium water level compared to that of the sedimentary bedrock aquifers (Raiber et al., 2015). As a result of the increasing head gradient, there is a higher potential for discharge from the sedimentary bedrock to the alluvium in some areas during dry periods. Strongly elevated groundwater salinities of more than 20,000 µS/cm observed in the alluvial aquifer in some areas in the Clarence-Moreton bioregion (e.g. Lockyer Valley) suggest that locally, and particularly at the edge of the alluvium and at the down-gradient end or regional flow paths of the sedimentary bedrock, a considerable proportion of the alluvial groundwater in these zones is sourced from the underlying bedrock (which often contains highly saline groundwater; McJannet et al., 2015) during drought conditions.

An example from the Bremer river basin (Figure 22) where no or only small watertable rises were recorded two years after high rainfall and flooding highlights that unlike in the upper or mid-reaches, there is a considerable time lag between rainfall or flooding and the water level response in the lower alluvia.

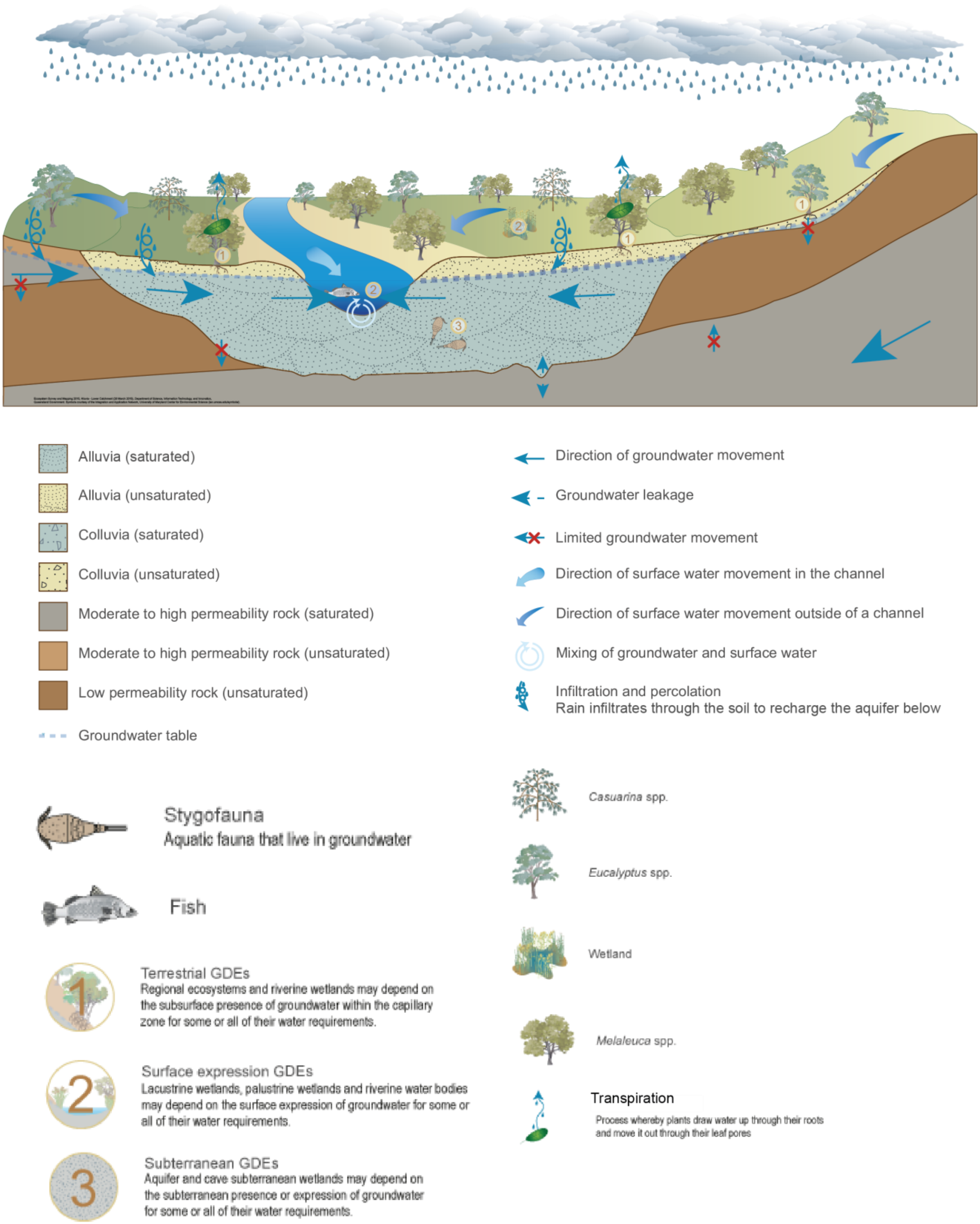


Figure 21 Hydrological conceptual model of alluvia in the lower catchment reaches

See Queensland Government (2015d) for more information.
Data: Adapted from DSITI (Dataset 7), © The State of Queensland (Department of Science, Information Technology and Innovation), 2015

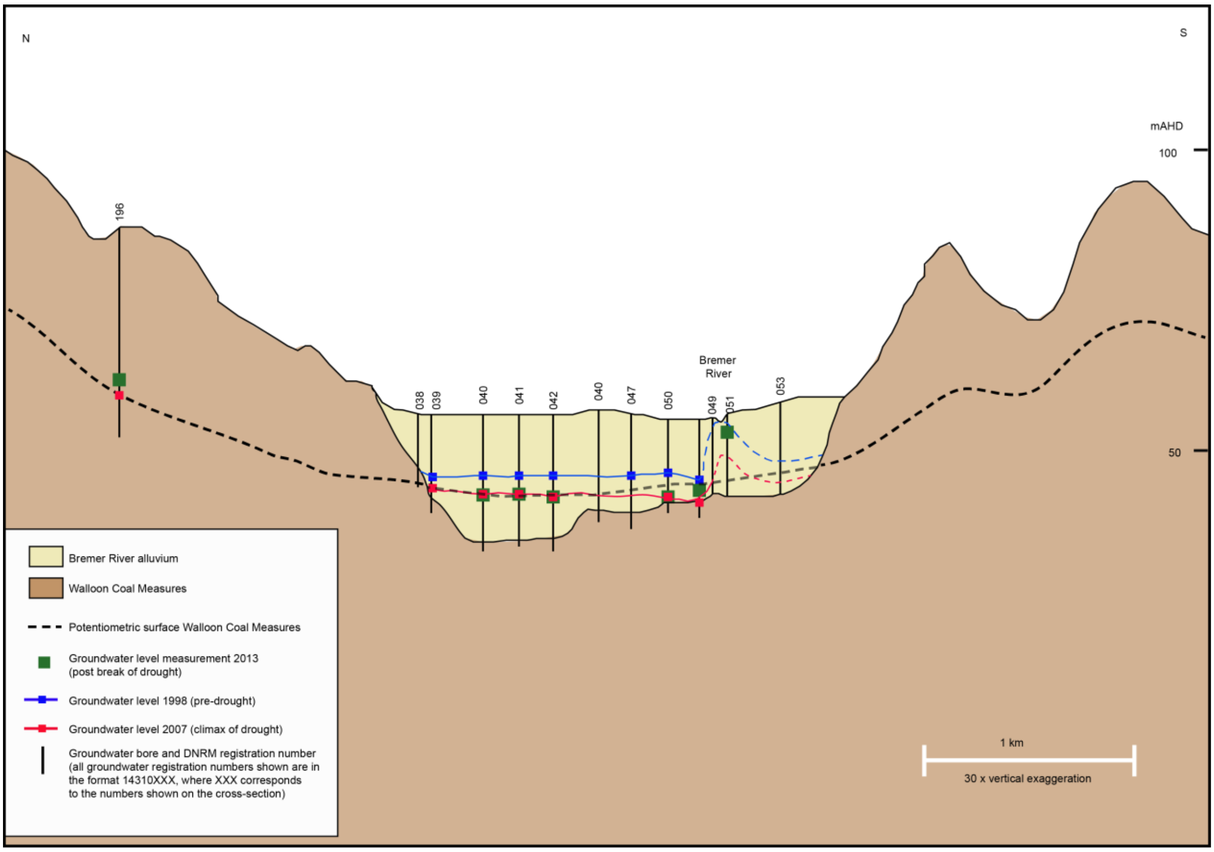


Figure 22 Temporal variability of groundwater levels in the lower catchment (example from Bremer river basin)

2.3.2.2.5 Unconsolidated sediments – estuarine and coastal

Estuarine zones are the interface between fresh water and marine environments. The Richmond River estuary includes the tidal reaches of the Richmond River from the coast to Casino, Wilsons River to Boatharbour, Bungwalbin Creek and North Creek (Aquatic Biogeochemical & Ecological Research, 2008; Hydrosphere Consulting, 2011).

Estuarine sediments consist of unconsolidated sediments such as clay and sand. In lithological logs from groundwater bores, marine influence is commonly recognised by the presence of 'shells'. In the three-dimensional geological model, the estuarine and coastal sediments are not differentiated from alluvial sediments. A subdivision of the unconsolidated sediments in the three-dimensional geological model is possible, but it would require a finer-scale three-dimensional model of the coastal area within the Richmond river basin which was beyond the scope of the Assessment. However, the extent of the estuarine and coastal sediments superimposed onto the three-dimensional geological model of the Richmond river basin is shown in Figure 10.

Interaction between seawater and freshwater can occur far inland in the Richmond river basin due to the small topographic gradient. Sampling by Hydrosphere Consulting (2011) suggested that an oligohaline salinity environment (corresponding to a brackish surface water salinity of up to approximately 9 mS/cm) within the Richmond River estuary exists beyond Coraki (Figure 18).

2.3.2.2.6 Fractured igneous rocks

Fractured igneous rocks in the Clarence-Moreton bioregion consist mostly of extrusive volcanic rocks such as the basalts of the Lamington Volcanics, which cover large surface areas in the northern part of the Richmond river basin and the Main Range Volcanics in Queensland (Figure 8). Recharge and groundwater flow processes, as well as hydrological features associated with the basalts such as streams and springs are represented by the 'permeable rock' conceptual model (Figure 23). The median thickness of the Lamington Volcanics and Main Range Volcanics determined from the three-dimensional geological model for the Clarence-Moreton bioregion is 128 m, and its maximum thickness is 825 m near the crest of the volcanics in topographically elevated areas (e.g. close to the border between Queensland and NSW). Within the Richmond river basin, the median thickness of the Lamington Volcanics estimated from the three-dimensional geological model is 105 m. However, these volcanic rocks do not consist of a single homogeneous basalt flow or one single aquifer. Rather, the basalt sequence consists of many overlapping basalt flows with a maximum thickness of approximately 10 m each (e.g. Brodie and Green, 2002). These are stacked together and commonly separated by lower-permeability layers including the clay-rich weathering profiles developed during a depositional hiatus between periods of volcanic activity. In addition, groundwater bore logs show that fluvial paleodrainage systems and lacustrine sediments covered by subsequent basalt flows exist in some areas of the Lamington Volcanics, as also previously indicated by Brodie and Green (2002).

These different zones of varying rock permeability affect the capacity of different basalt flows to store and transmit groundwater. At the top and the base of the basalt flows, zones consisting of broken vesicles commonly occur, and these provide considerable primary pore space that can store and transmit groundwater. Vesicular zones of different basalt flows in the Lamington and Main Range volcanics are likely to be connected by well-developed fracture networks (representing secondary porosity) (Figure 23), resulting in high recharge rates and low salinity of groundwater (Brodie and Green, 2002; McJannet et al., 2015; Raiber et al., 2015). Rainwater infiltrates rapidly through the fractures of the highly elevated areas near the NSW–Queensland border where soil profiles are thin and aerially-extensive outcrops of fresh and unweathered basalt occur. These form preferential recharge areas of the Clarence-Moreton bioregion (Figure 12). At the edge of the basalt flows, at the interface of the higher-permeability basalts and the lower-permeability overlying alluvial aquifers, groundwater discharges to the surface as springs, and these may feed streams such as those on the Alstonville Plateau (Figure 12) (Brodie and Green, 2002).

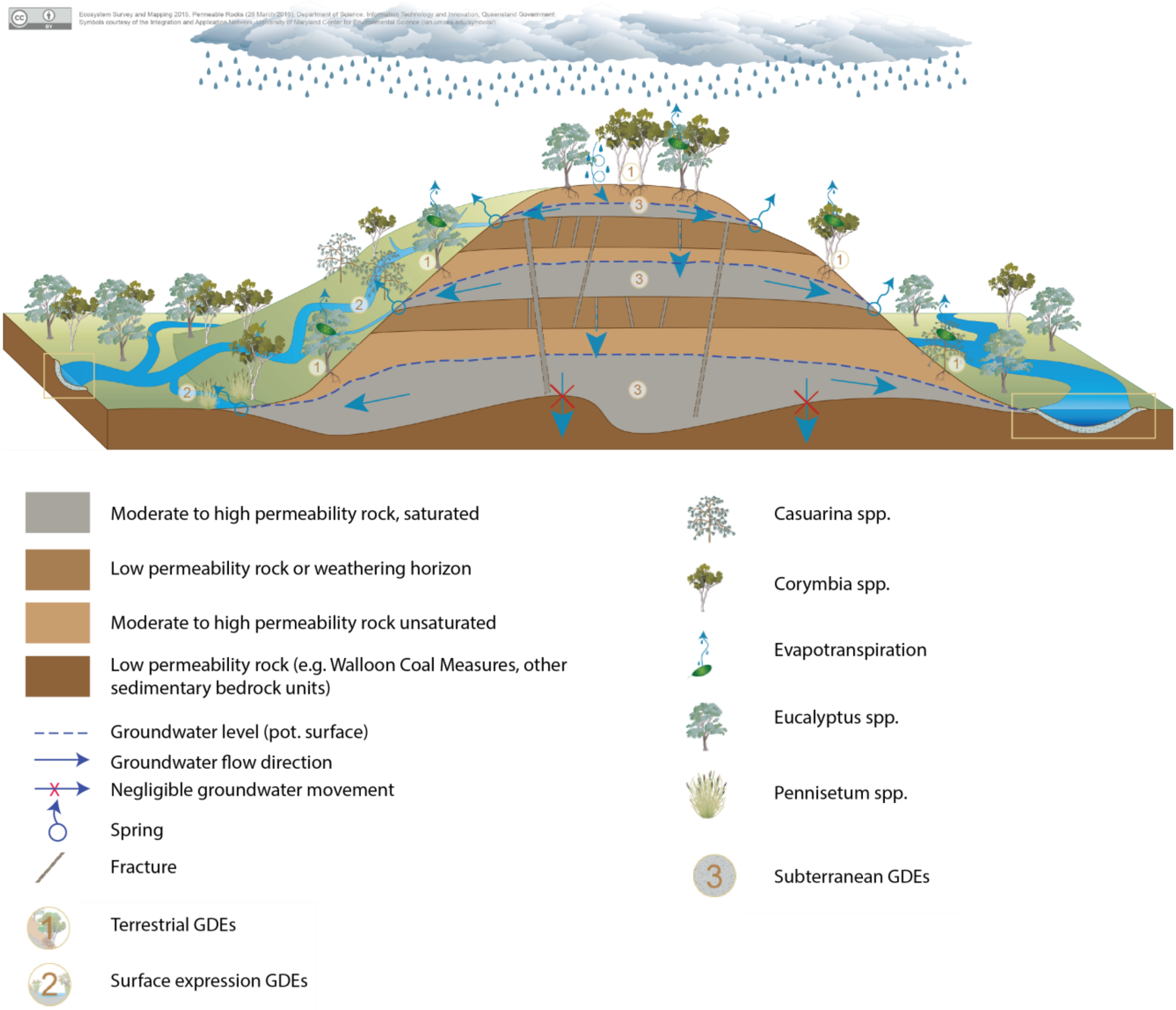


Figure 23 Conceptual model of volcanic rocks and their interaction with underlying sedimentary bedrock in the Clarence-Moreton bioregion; hydrological features associated with the volcanic rocks are also shown

See Queensland Government (2015e) for more information.
Data: Adapted from DSITI (Dataset 7), © The State of Queensland (Department of Science, Information Technology and Innovation), 2015

2.3.2.2.7 Consolidated sedimentary rock

For the purposes of the landscape classification, all sedimentary bedrock units within the PAE of the Clarence-Moreton bioregion were grouped into a single main category 'consolidated sedimentary rock' (Figure 10).

However, there are distinctive hydraulic differences between these rocks, as described in more detail in companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016). These differences are related to the variable composition of the different rocks, where some units are generally composed of coarser-grained rocks such as sandstone (e.g. the Woogaroo Subgroup, which in some areas is dominated by coarse-grained and well-sorted quartz sand), whereas other units (e.g. Walloon Coal Measures) are dominated by fine-grained material such as mudstone, shale, coal and siltstone, with only minor sandstone. These differences were taken into consideration when developing the numerical groundwater flow model as discussed in other companion products for the Clarence-Moreton bioregion: product 1.1 (Rassam et al., 2014); product 1.2 (Raiber et al., 2014); product 1.5 (McJannet et al., 2015); and product 2.1-2.2 (Raiber et al., 2016).

As a result of their variable composition, and as a broad generalisation, the sedimentary bedrock units in the Clarence-Moreton bioregion can be differentiated into aquifers and aquitards (aquitards are typically described as a 'seal' in petroleum systems studies). Given the spatial and vertical heterogeneity of these units, they can sometimes form an aquifer in a particular part of the bioregion (e.g. at the margin of the Clarence-Moreton Basin where the rocks tend to be composed of coarse-grained materials), but can also act as an aquitard elsewhere (e.g. further away from the basin margin and/or at greater depth where the permeability is typically lower). The spatial (horizontal and vertical) relationships and relative thicknesses of inferred aquifers and aquitards in the Richmond river basin are shown in Figure 8 and Figure 24.

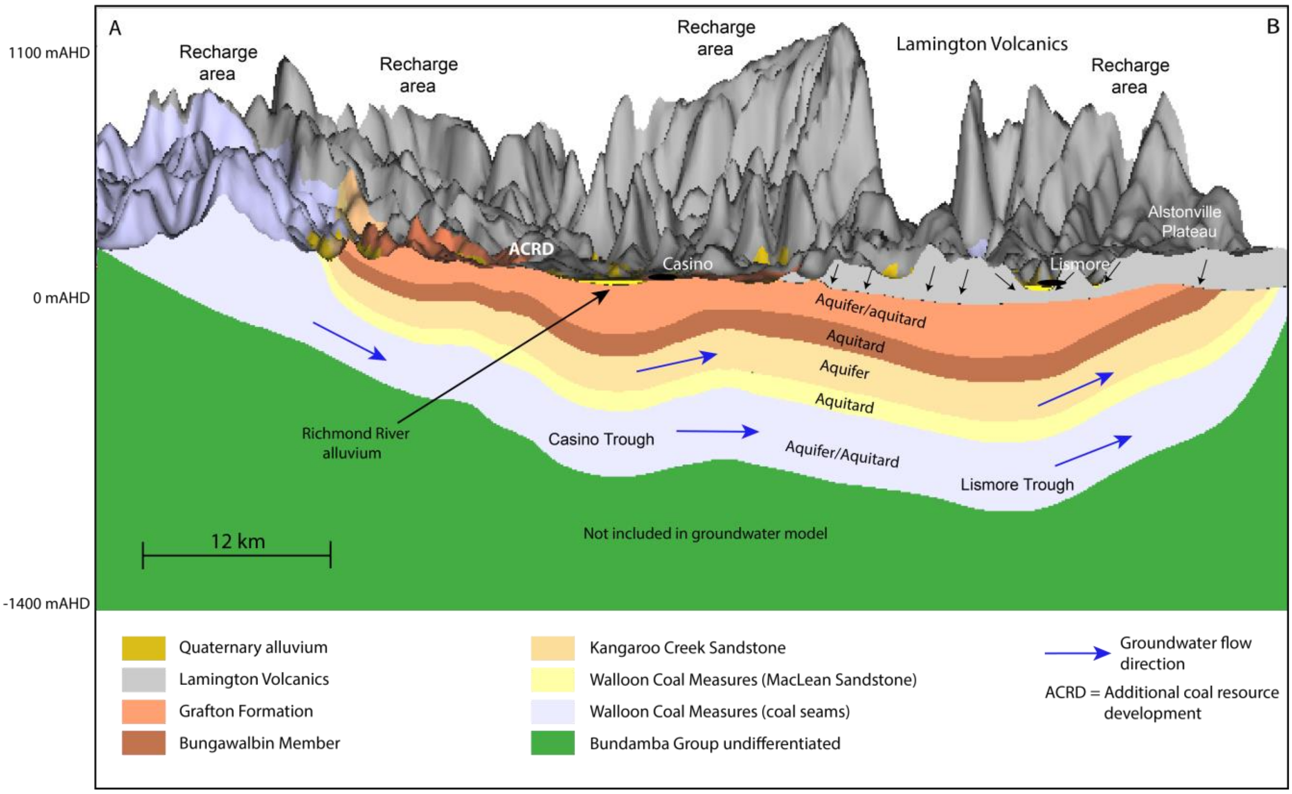


Figure 24 Cross-section through unfaulted three-dimensional geological model of Richmond river basin, highlighting aquifer geometry, relative thicknesses of aquifers and aquitards

The orientation of this cross-section corresponds to line A–B in Figure 8.
Data: Bioregional Assessment Programme (Dataset 5)

2.3.2.2.7.1 Aquifers

In the Clarence-Moreton bioregion, the alluvium and the volcanic rocks are the major aquifers used for groundwater extraction. In addition, three sedimentary bedrock units are classed as aquifers, namely the Kangaroo Creek Sandstone (the lower member of the Orara Formation), the Piora Member (lower member of Grafton Formation) and the Woogaroo Subgroup. The Kangaroo Creek Sandstone and the Woogaroo Subgroup are the two that are currently utilised, or have the most future potential for groundwater extraction. Current groundwater usage in the Richmond river basin is estimated at approximately 11,618 ML/year based on entitlements (McJannet et al., 2015). More than 85% of these allocations are from the alluvial and volcanic aquifers (Figure 25).

The Woogaroo Subgroup, which is the deepest unit in the Clarence-Moreton Basin (Figure 26), contains the freshest groundwater of all sedimentary bedrock units (McJannet et al., 2015), with potentially high yields. It is extensively used for groundwater extraction in Queensland near the northern margin of the sedimentary basin in the Lockyer Valley (Figure 7), where the unit occurs at shallow depths (McJannet et al., 2015). In contrast, the Woogaroo Subgroup is not extensively used for groundwater extraction in the NSW part of the Clarence-Moreton bioregion due to its considerable depth (typically at least 1500 m below ground surface) and limited surface outcrop areas. Recharge takes place in the western part of the Woogaroo Subgroup in NSW whereas groundwater discharge mostly occurs towards the eastern side. However, the areal extent of recharge areas of the Woogaroo Subgroup in NSW is limited to narrow bands or small isolated areas compared to that of the Lockyer Valley. Due to the limited data availability for the Woogaroo Subgroup in the Clarence-Moreton bioregion in NSW in terms of both groundwater levels and water quality, it is not currently possible to assess the potential implications of the limited recharge area on groundwater flow and quality within this unit.

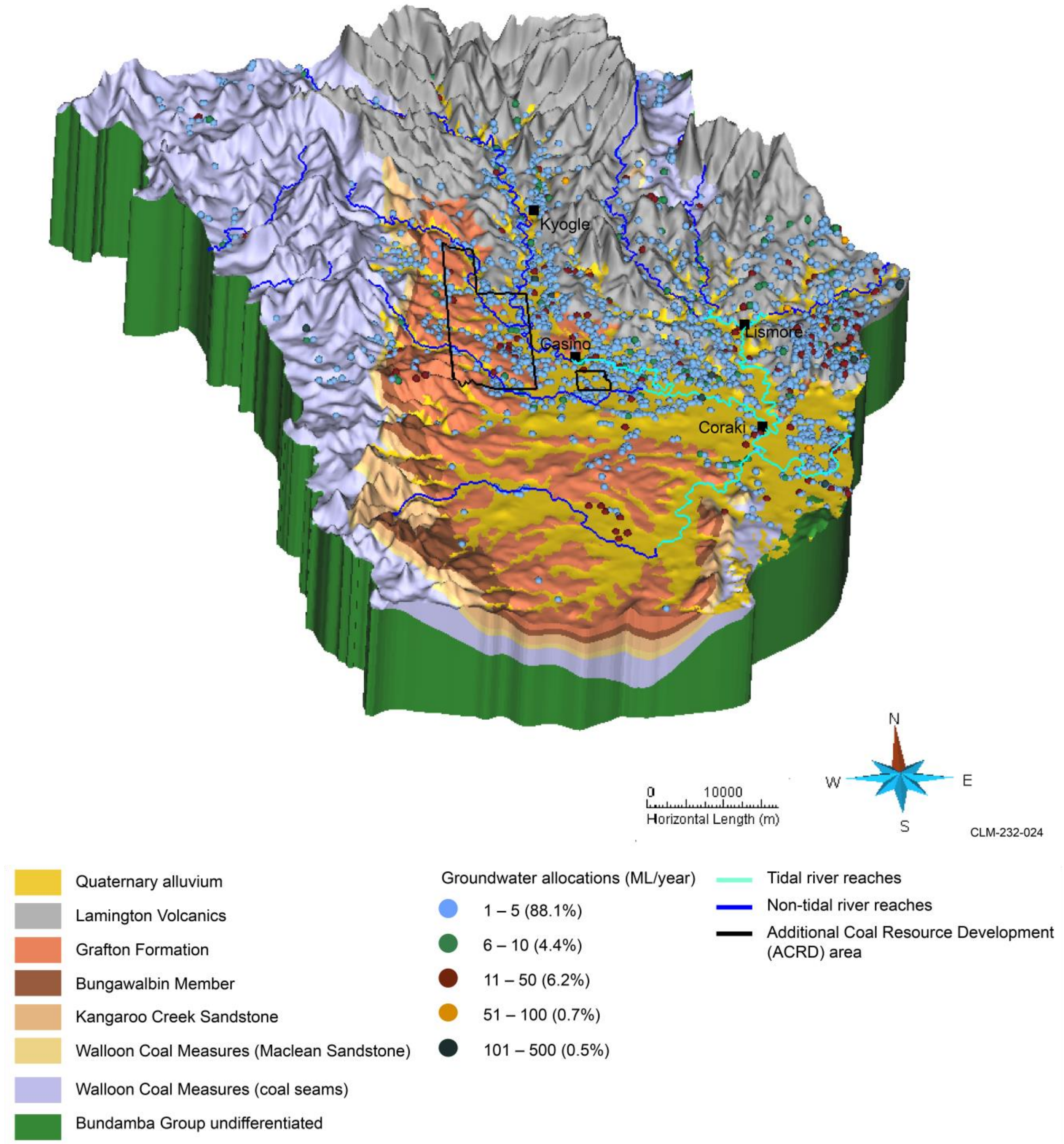


Figure 25 Current groundwater allocations in the Richmond river basin (based on McJannet et al., 2015)

Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5, Dataset 10); Bureau of Meteorology (Dataset 9)

The Woogaroo Subgroup is vertically separated from the major coal-bearing unit (the Walloon Coal Measures) through the overlying Koukandowie Formation and Gatton Sandstone, which in most areas have a combined thickness of approximately 1000 m or more. The potential for groundwater extraction from the Woogaroo Subgroup in the Richmond river basin is limited by the very considerable depth and lack of understanding of bore yields and water quality.

The Kangaroo Creek Sandstone Member as defined by Doig and Stanmore (2012) is composed of quartzose sandstone and conglomerate. The median thickness of the Kangaroo Creek Sandstone as derived from the three-dimensional geological model is 175 m and its maximum thickness is

370 m. The groundwater salinity of the Kangaroo Creek Sandstone is typically low (Parsons Brinckerhoff, 2011; McJannet et al., 2015), but this assessment is based on limited data from the eastern part of the basin. Yields are mostly low (less than 1 L/second), except where bores intercept zones of enhanced permeability (McKibbin and New South Wales Department of Land and Water Conservation, 1995; Parsons Brinckerhoff, 2011). Doig and Stanmore (2012) indicated that the Kangaroo Creek Sandstone has poor aquifer properties (i.e. low yields) below a depth of 150 m. Recharge to the Kangaroo Creek Sandstone, which has in the past been explored as a conventional gas reservoir (Raiber et al., 2014), is likely to occur at its outcrop areas in the western part of the Clarence-Moreton bioregion in NSW. Although poorly constrained by current monitoring data, the aquifer architecture and the three-dimensional geological model suggest that groundwater flows from the highly-elevated western areas towards the east. In the stratigraphic sequence of the Clarence-Moreton Basin, it is located above the Walloon Coal Measures, and is vertically separated from the Richmond Seam (the shallowest coal seam of the Walloon Coal Measures) by the Maclean Sandstone (Figure 24), which is considered to have a low permeability.

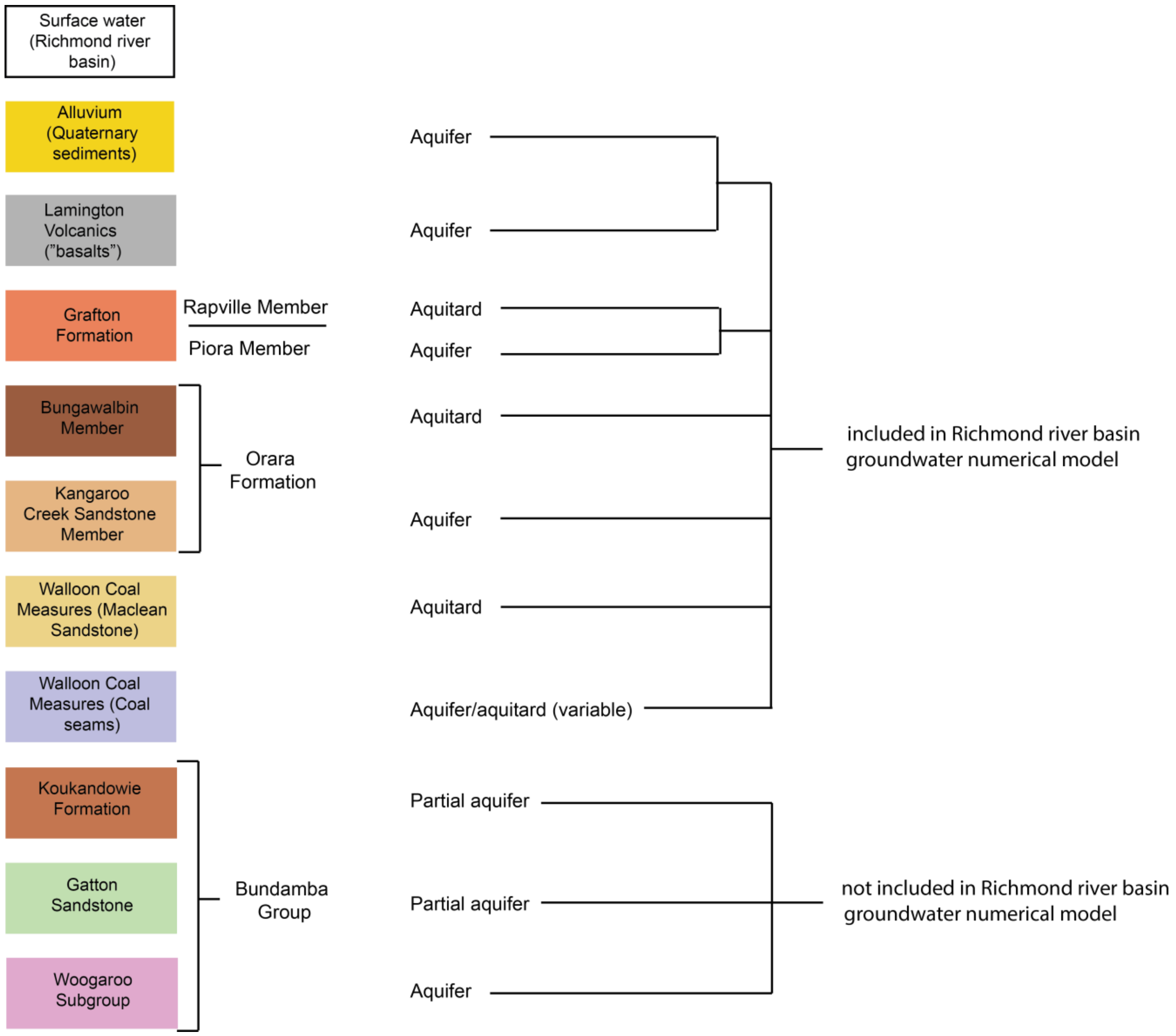


Figure 26 Simplified stratigraphy and generalised hydraulic characteristics of the major stratigraphic units in the Clarence-Moreton bioregion

The lower-most units (Koukandowie Formation and below) are not included in the Richmond river basin groundwater model as they are not currently utilised for groundwater extraction due to their considerable depth, their inferred low yields and the high salinity of groundwater contained within Koukandowie Formation and the Gatton Sandstone (McJannet et al., 2015). Colours correspond to the colours of the three-dimensional geological models.

According to the three-dimensional geological model of the Clarence-Moreton Basin, the Grafton Formation (as defined by Doig and Stanmore (2012)) has a median thickness of approximately 150 m and a maximum thickness of approximately 500 m. It consists of an upper and a lower member (Rapville and Piora members, respectively) with very different hydraulic characteristics. The Piora Member, the lower member of the Grafton Formation, is composed of medium- to coarse-grained quartzose sandstone with an extensive clay matrix (Doig and Stanmore, 2012). While sometimes described as an aquifer, its reported low bore yields of about 0.3 L/second suggest that it is more likely an aquitard. The Rapville Member, the upper member of the Grafton Formation, is composed of interbedded sandstone, siltstone and mudstone, and is considered to be an aquitard or aquiclude (Doig and Stanmore, 2012). Overall, despite its considerable thickness and extensive surface outcrop area, few groundwater bores are screened within, and source water from, the Grafton Formation in the Richmond river basin (Figure 25). The lack of groundwater extraction from this unit may be due to the easier access from alluvial or volcanic groundwater resources. However, it probably also indicates that the Grafton Formation is likely to have low yields and/or poor groundwater quality, and represents a low permeability aquifer (Piora Member) or aquitard (Rapville Member) with limited potential for groundwater extraction.

2.3.2.2.7.2 Aquitards

Several units considered to be aquitards exist within the sedimentary bedrock sequence of the Clarence-Moreton bioregion (Figure 26).

The two stratigraphic units underlying the Walloon Coal Measures (the stratigraphic unit that contains the major coal resources) are the Koukandowie Formation and the Gatton Sandstone (both part of the Bundamba Group in Figure 26). It is poorly documented whether those two units act as aquifers or aquitards throughout the Clarence-Moreton bioregion. However, the assessment of water quality in companion product 1.5 for the Clarence-Moreton bioregion (McJannet et al., 2015) has shown that the Koukandowie Formation and the Gatton Sandstone have the highest groundwater salinity in the bioregion, with a median electrical conductivity of 4750 and 5000 µS/cm, respectively. In the linked Surat Basin (part of the Northern Inland Catchments Bioregional Assessment), the Evergreen Formation (the equivalent to the Gatton Sandstone) is commonly described as an aquitard. Recent sedimentological analyses and a geochemical baseline assessment of the Hutton Sandstone (the equivalent of the Koukandowie Formation) in the north-eastern Surat Basin have suggested that groundwater flow is restricted to a relatively small fraction of the unit’s total thickness (Guiton et al., 2015; Suckow et al., 2015). These analogues from the Surat Basin together with the mostly poor-quality groundwater observed in the Koukandowie Formation and Gatton Sandstone in the Clarence-Moreton bioregion (McJannet et al., 2015) suggest that those two units probably have low yields and represent low-permeability partial aquifers or aquitards. However, additional hydraulic and physical and chemical property data for these formations are required for a more reliable assessment of their hydraulic characteristics. These types of data are not currently available to inform the BAs.

At the regional scale, the Walloon Coal Measures are typically considered as an aquitard in the Clarence-Moreton and the linked Surat basins. However, due to their spatially variable composition, their hydraulic character is also likely to vary considerably. Towards the basin margin, the Walloon Coal Measures consist of coarser-grained sedimentary material due to the proximity to the original sediment source area. For example, near the margins of the Warrill Creek Syncline in the Bremer river basin (Figure 11) artesian flow occurs from groundwater bores screened in the Walloon Coal Measures. Towards the centre of the geological basin, fine-grained rocks such as mudstone, siltstone, fine-grained sandstone and shale inter-bedded with coal predominate. Groundwater recharge to the Walloon Coal Measures occurs in the western part of the Richmond river basin in NSW, where the Walloon Coal Measures outcrop over large areas. There are few groundwater bores screened in the Walloon Coal Measures in this outcrop area, and consequently, few groundwater chloride measurements were available to estimate recharge rates using chloride mass balance, hence, the recharge assessment was based mostly on data from Queensland (Raiber et al., 2016). The limited number of measurements in NSW combined with the large number of chloride measurements in the Clarence-Moreton bioregion in Queensland suggests that recharge rates to the Walloon Coal Measures are small (less than 10 mm/year corresponding to less than 1% of annual average rainfall; Figure 12). The lack of groundwater bores screened in this unit throughout the Clarence-Moreton bioregion and particularly in the Richmond river basin is an additional indication that the Walloon Coal Measures likely have low yields and/or poor groundwater quality.

The Maclean Sandstone forms the upper part of the Walloon Coal Measures in the Richmond river basin (Figure 10). It is composed of silty and lithic, coarse- to fine-grained feldspathic sandstone (Doig and Stanmore, 2012). It has a median thickness of 87 m based on estimates from the three-dimensional geological model, and is described by Doig and Stanmore (2012) as an effective low-permeability top seal (aquitard) that extends over much of the basin and limits the vertical leakage of gas from the coal seams to the surface. Although somewhat counter-intuitive that a stratigraphic unit described as sandstone is considered an aquitard, it is important to note that the type-section where the Maclean Sandstone was first described is located at the basin margin near the sediment source area, where units generally consist of coarser-grained material than in the centre of a sedimentary basin. Furthermore, when the Maclean Sandstone was first described by Flint et al. (1976), only limited down-hole petrophysical data existed in the Clarence-Moreton Basin. As more petrophysical data became available from exploration drilling, the understanding of the sedimentological composition and hydraulic character of different units has evolved, as also observed in the neighbouring Surat Basin. These newly acquired data show that the contact between the Maclean Sandstone and the overlying Kangaroo Creek Sandstone is marked by a distinct decrease in the rate of penetration (the drilling rate describing how many metres are drilled per minute) and a higher density displayed by the Maclean Sandstone in down-hole geophysical profiles.

According to the three-dimensional geological model, the Bungawalbin Member has a median thickness of about 94 m. It is composed of mudstone and carbonaceous mudstone interbedded with fine-grained sandstone (Doig and Stanmore, 2012). Doig and Stanmore (2012) have suggested that it is an aquitard that prevents vertical leakage of groundwater.

The Rapville Member (the upper member of the Grafton Formation) is discussed as part of the Grafton Formation.

2.3.2.3 Surface water

As part of the Assessment, an analysis was carried out to assess streamflow in the Richmond river basin (McJannet et al., 2015). Major streams within the Richmond river basin, their median daily flow volumes (based on flow duration curves), their spatial relationships to the potential CSG development area and tidal river reaches are shown on Figure 27. Findings of the streamflow analysis included:

- The main tributary of the Richmond river basin has a tidal influence just downstream of the Casino gauging station (river course distance of 114 km from the ocean), whereas the Wilsons River tributary is tidal at Lismore (river course distance of 115 km from the ocean) and further upstream (Figure 27). Due to this tidal influence, the flow of the Richmond River downstream of Casino is less likely to be influenced by extractions or discharge associated with potential CSG developments.

- The Richmond River at Casino is perennial and has a long-term median flow of 320 ML/day.
- The south-west part of the Richmond river basin has relatively low median daily flows, with Shannon Brook (28 ML/day) and Myrtle Creek (9 ML/day) both near-permanent, flowing on average 93% and 94% of the time, respectively. The potential CSG development area underlies part of the catchment of Shannon Brook.

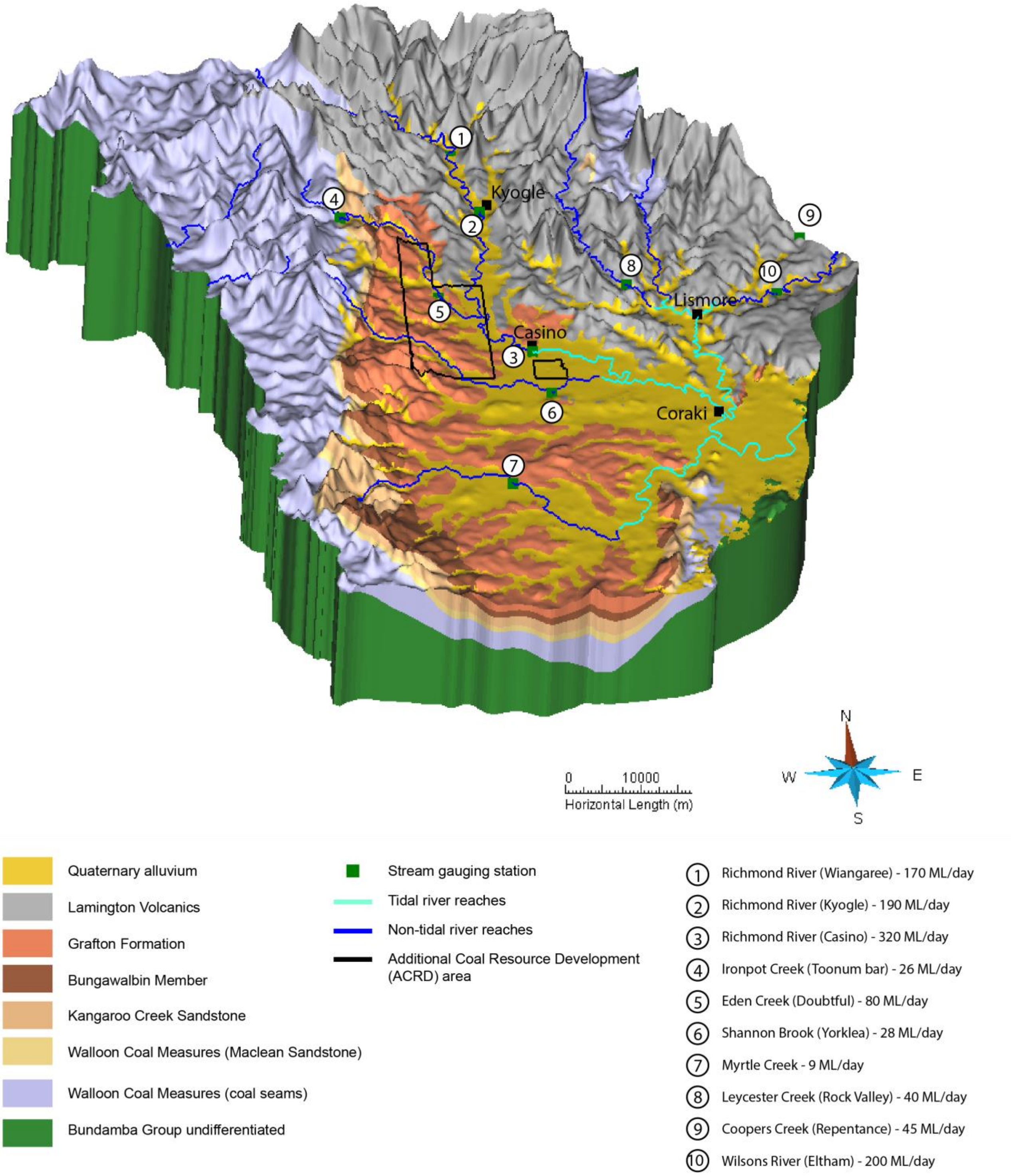


Figure 27 Major streams in the Richmond river basin and tidal river reaches; median daily streamflow rates (in ML/day) at gauging sites are also shown

Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5, Dataset 11)

Most of the gauged streams are perennial, with the exception of Shannon Brook and Myrtle Creek, which are located in the southern part of the basin. Those two near-permanent streams have median flows that are much lower than their counterparts in the northern part of the basin.

The boundary of the surface water PAE, which takes into account locations of all current and future CSG developments, provides the extent to which effects of any possible future development can potentially occur.

Current surface water license allocations in the Richmond river basin are 99,881 ML/year (McJannet et al., 2015). These allocations are concentrated along the main river valleys of the Richmond River and major tributaries such as Eden Creek, as well as in the Wilsons River basin and the Alstonville Plateau in the east of the Richmond river basin (Figure 28).

2.3.2.3.1.1 Location of catchment boundaries and inflow to and outflow from the Richmond river basin

Any outflows from the potential CSG development areas are contained within the Richmond river basin. The surface water analysis for the Clarence-Moreton bioregion is restricted to the Richmond river basin, as this is the only river basin with an Additional Coal Resource Development. However, the underlying groundwater model extends further west into the upper Clarence river basin to capture the wider recharge area of the Walloon Coal Measures, which extend beyond the surface catchment boundary.

The rainfall-runoff model (AWRA-L) has been chosen to model the surface water system. Further information on surface water modelling in the Clarence-Moreton bioregion is available in companion product 2.6.1 (Gilfedder et al., 2016).

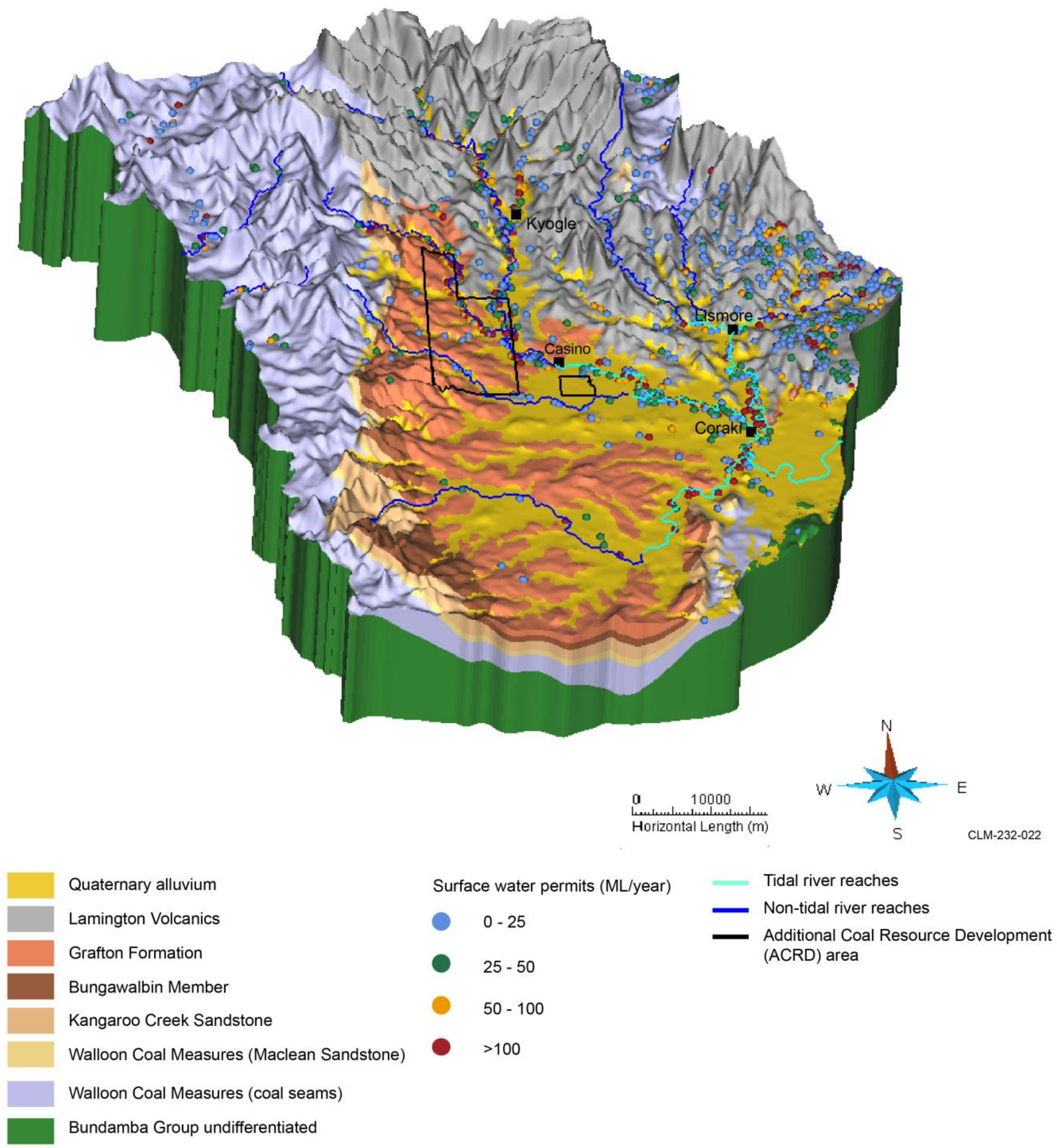


Figure 28 Current surface water permits in the Richmond river basin (based on McJannet et al., 2015)

Data: Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5, Dataset 12)

2.3.2.4 Hydraulic connection between aquifers and surface water and groundwater

2.3.2.4.1 Aquifer interaction

As shown in previous sections, there is a high degree of hydraulic connection between the alluvial and volcanic aquifers in the Clarence-Moreton bioregion with the greatest level of interaction in the headwaters of the alluvial systems, decreasing down-gradient.

The hydraulic relationships between different sedimentary bedrock units, sedimentary bedrock and alluvial aquifers and between sedimentary bedrock and volcanic bedrock are much more difficult to determine than the interaction between shallow aquifers. This is due to the complexity of the Clarence-Moreton Basin aquifer/aquitard system and the lack of groundwater observation bore data for the sedimentary bedrock units. The current conceptual model for the Main Range Volcanics in Queensland (Figure 23) assumes that there is only limited vertical connectivity across the interface between the basalts and the underlying sedimentary bedrock due to the presence of weathering horizons with very low hydraulic conductivities. Some downward percolation of groundwater probably occurs across the interface of the basalt and the underlying sedimentary bedrock, as supported by hydrochemical data in the Logan-Albert river basin within the Clarence-Moreton bioregion (Duvert et al., 2015). The lack of groundwater observation bore data in the Richmond river basin means that hydraulic head gradients between the volcanic and sedimentary bedrock units are poorly constrained. However, the elevated topography of the basalts and the substantially higher recharge rates suggest that there is more likely to be a downward hydraulic gradient from the basalts to the underlying sedimentary bedrock in most areas. Despite some evidence for hydraulic connectivity across this interface (Duvert et al., 2015), the role of downward percolation from the basalts to the underlying sedimentary bedrock is thought to be small in most areas as a result of the presence of thick weathering profiles developed on the sedimentary bedrock prior to eruption of the volcanics that limit vertical leakage across this interface due to their low hydraulic conductivities (Figure 23).

The lack of nested bore sites within the Clarence-Moreton bioregion that enable different sedimentary bedrock stratigraphic units to be simultaneously monitored significantly limits the understanding of inter-aquifer connectivity as it is currently based primarily on inferred petrophysical characteristics of different stratigraphic units and on aquifer geometry. Most sedimentary bedrock units in the Clarence-Moreton bioregion are considered as partial aquifers, aquitards or leaky aquitards (Section 2.3.2.2.7; Figure 26). If an aquitard is an ideal regional seal, then it should limit or prevent the vertical hydraulic connection between the overlying and underlying stratigraphic units. In the case of the Walloon Coal Measures of the central part of the Richmond river basin, Doig and Stanmore (2012) suggested that high gas saturation levels are an indicator that there is an effective seal in place in the central part of the Richmond river basin near the West Casino Gas Project that prevents or limits vertical gas leakage from the Walloon Coal Measures. This seal is assumed to be the Maclean Sandstone, which is between the coal seams of the Walloon Coal Measures and the Kangaroo Creek Sandstone Member. In the West Casino Gas Project area west and south of Casino (Raiber et al., 2015), the Walloon Coal Measures are approximately 300 to 600 m below ground surface, and in addition to the Maclean Sandstone, there are two other stratigraphic units that are considered as aquitards (Bungawalbin Member and Rapville Member) separating the coal seams of the Walloon Coal Measures and the shallow alluvial and volcanic aquifers. Although aquitards are spatially and stratigraphically continuous throughout the West Casino Gas Project area west and south of Casino, their thickness and composition can vary. Furthermore, their role as regional seals may be compromised by the presence of geological structures (i.e. faults, which can act either as conduits or barriers to groundwater flow) or regional differences in rock composition. There are several major geological structures within the Richmond river basin (e.g. East Richmond and Coraki faults; Figure 8) where fault displacement is known to occur. High groundwater salinities in the alluvium near Coraki

(Figure 18) and the similarity between the course of Myrtle Creek and the orientation of Coraki Fault could be an indication that this fault acts as a conduit for upwards discharge of deep groundwater to shallow aquifers or to the surface. However, further work throughout the Richmond river basin (e.g. use of remote sensing to determine which major faults have a surface expression, environmental tracer sampling and determination of shale gouge ratios and juxtaposition values of aquifers and aquitards) and supporting data are required to assess the role of faults on the groundwater flow system. There are currently no field data (e.g. groundwater level measurements from multi-level monitoring bores) available to assess the role of faulting on groundwater systems in the Clarence-Moreton bioregion.

The hydraulic connection between the sedimentary bedrock and the alluvial aquifers is thought to be much less pronounced compared to that between the volcanic and alluvial aquifers, due mostly to the low permeability of the sedimentary bedrock (Section 2.3.2.2.7). However, the degree of hydraulic connectivity is variable both spatially and temporally. For example, increasing groundwater salinity during droughts in parts of the Lockyer Valley alluvial aquifers is linked to leakage from the underlying sedimentary bedrock (Gatton Sandstone), which contains more-saline water (McJannet et al., 2015; Raiber et al., 2015). In the central Richmond river basin east and south of Casino, elevated groundwater salinity in some groundwater bores screened in the alluvial aquifer suggests some degree of hydraulic connectivity between the sedimentary bedrock and the shallow alluvial aquifers (McJannet et al., 2015; Raiber et al., 2015). However, the recharge assessment (Figure 12) has shown that recharge rates in the alluvial aquifer in these areas are lower than elsewhere within the catchment due to the presence of thick clay-rich floodplain sediments, and the elevated groundwater salinities could therefore also be the result of enhanced levels of evapotranspiration.

In the eastern part of the Clarence-Moreton bioregion where different sedimentary bedrock stratigraphic units thin and pinch out at the basin margin or subcrop underneath the alluvial aquifers (Figure 24), upwelling of groundwater from the sedimentary bedrock into the shallow alluvial aquifers is likely. Although the flow directions in the sedimentary bedrock of the Richmond river basin are poorly constrained by monitoring data, an example from the Bremer river basin (which is well supported by monitoring data) shows how groundwater in the sedimentary bedrock units flows from the ranges towards the lowest point of the catchment, where it is likely to discharge into the Bremer River west of Ipswich (Raiber et al., 2015). The analogue example of the Bremer river basin suggests that groundwater discharges from the sedimentary bedrock to the alluvium at the down-gradient end of the Richmond river basin. However, while there are some elevated salinities in the alluvium that may indicate upward discharge of more-saline sedimentary bedrock groundwater, overall, most alluvial groundwaters in areas where the alluvium overlies the down-gradient end of the sedimentary bedrock are fresh (Figure 18). This suggests that upwards leakage from the sedimentary bedrock may be overwhelmed by other sources of recharge to the alluvium, such as river recharge or diffuse rainfall recharge through soils, which become increasingly sandy near the coast.

2.3.2.4.2 Surface water – groundwater interactions

Throughout the Richmond river basin and other areas within the Clarence-Moreton bioregion, there is very strong evidence for interaction between groundwater and surface water. The estimation of groundwater recharge rates and streamflow volumes highlights that the geological unit with the main influence on the hydrological cycle in the Richmond river basin is the Lamington Volcanics. The basalts are recharged during rainfall events and water is stored and transmitted through vesicles and fracture zones. Some of the recharged water in the high energy upper or mid-reaches of the river system drains with very short lag times (near instantaneous to days) to the alluvium or directly to surface water or springs where no alluvium is developed following short flow paths. However, even after extended periods of no rainfall (and thus, no recharge), groundwater continues to drain from the basalts following longer flow paths. This continuous baseflow from the basalts generates the high median flow observed in the upper and mid-reaches of the Richmond river basin, and sustains the permanency of streams even during prolonged periods of no rainfall (Figure 27).

In the mid and lower reaches of the Richmond river basin and other catchments within the Clarence-Moreton bioregion, the hydraulic gradient between alluvial aquifers and streams can reverse during different climatic periods (Atkins et al., 2016). An example from the Lockyer Valley (Figure 20) shows how the deeply incised Laidley Creek changes from a disconnected creek at the climax of a prolonged drought in 2007 to a losing stream (where the stream recharges the underlying alluvial aquifer) in 2009 following the break of the drought and into a gaining stream in 2013 (where baseflow from the alluvia to the streams occurs). This complex temporal pattern of surface water – groundwater interaction, likely to be similar in mid-reaches of other streams in the Clarence-Moreton bioregion, highlights the challenges in defining whether river reaches are gaining or losing, and the need for long-term time-series groundwater-monitoring data. However, unlike Laidley Creek in this mid-reach location in the Lockyer Valley, digital elevation models suggest that the Richmond River and smaller streams in the Richmond river basin are not deeply incised into the alluvial aquifer. Furthermore, lithological logs from groundwater bores show that the alluvium in the mid to lower reaches of the Richmond river basin consists of thick clay-rich sediments at the top of the sequence. Streams have probably not fully penetrated these clay-rich sediments and therefore there may only be limited hydraulic connection with the more permeable sands and gravel at the base of the alluvial sequence. Consequently, surface water recharge to the alluvial aquifer may be limited, and there are likely to be considerable lag times between rainfall and recharge to the alluvial aquifer. Examples from the Clarence-Moreton bioregion in Queensland indicate large time lags between rainfall and groundwater level response (e.g. Figure 22).

The assessment of median streamflow rates (Section 2.3.2.2) shows that smaller streams such as Shannon Brook and Myrtle Creek in the central or southern part of the Richmond river basin have much smaller flow rates than the Richmond River and other streams draining the volcanics (Figure 27). There is likely to be a baseflow contribution from underlying aquifers to these streams, but unlike many of the streams that drain the Lamington Volcanics, these smaller streams that drain the sedimentary bedrock units rather than the Lamington Volcanics are not permanent.

One key aspect of surface water hydrology in the Richmond river basin is that the lower reaches of many streams show tidal influence. For example, the Richmond River is tidal to almost Casino. Elevated groundwater salinities were observed in shallow bores near Coraki (Atkins et al., 2015; Raiber et al., 2015), but it is currently not clear whether this is due to leakage from tidal rivers, slow infiltration promoting high rates of evapotranspiration prior to recharge or upwards discharge of more-saline sedimentary bedrock groundwater. The origin of this more-saline groundwater could likely be determined using additional hydrochemical data (major and minor ions) and selected environmental isotopes.

2.3.2.5 Water balance

The current surface water and groundwater water usage in the Richmond river basin is shown in companion product 1.5 for the Clarence-Moreton bioregion (McJannet et al., 2015). The total storage volume of two main surface water reservoirs and several small dams and weirs in the Richmond river basin is around 25 GL. The current surface water licences permit a maximum water extraction of 99,881 ML/year from the Richmond river basin. It is estimated that 11,618.5 ML of groundwater is allowed to be used annually from 2,505 bores based on the current water allocation data within the groundwater model domain (Figure 10 and companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016b)). Of the estimated water usage, 49.5% and 42% are allocated for irrigation and domestic/stock bores, respectively.

A water balance assessment was conducted in companion product 2.5 for the Clarence-Moreton bioregion (Cui et al., 2016a) using the outputs from the surface water and groundwater models that are reported in companion products 2.6.1 and 2.6.2 for the Clarence-Moreton bioregion (Gilfedder et al., 2016; Cui et al., 2016b, respectively). The water balance components were derived from 30 models constrained by historical observations in water levels, a CSG water production forecast and a baseflow estimate at the river stage gauging station near Casino (Figure 27). The water balances are reported for three 30-year periods (2013 to 2042, 2043 to 2072 and 2073 to 2102) for both the baseline coal resource development (baseline) and the CRDP. The surface water balance was calculated at four nodes. An additional reduction of 321 ML/year in groundwater storage occurs due to the West Casino Gas Project from 2013 to 2042. However, the overall groundwater balance impact of the West Casino Gas Project over the entire model domain is very small based on the current groundwater model conceptualisation. Groundwater storage exhibits a future decline even without the impacts of the West Casino Gas Project, although the mean annual reduction is well below 0.5% of the corresponding mean annual recharge for all the three reporting periods.

2.3.2.6 Conceptual uncertainties of geology and hydrogeology

2.3.2.6.1 Three-dimensional geological model uncertainty

Three-dimensional geological models are created from datasets, such as drill-hole and geophysical data, which sample the subsurface at a limited number of locations, and with variable quality resolution. These data constraints mean that all geological models contain some degree of inherent uncertainty (e.g. Wellmann et al., 2010; Raiber et al., 2012). Furthermore, there is commonly a high degree of randomness as to where these subsurface data are gathered from, as many petroleum, mineral or groundwater resource exploration programs focus on small areas where a dense network of bores or wells is drilled. Consequently, and based on the available data, different three-dimensional geological model realisations can be developed from the same input data. In general, uncertainties in three-dimensional geological models are typically related to (e.g. Mann, 1993; Davis, 2002; Raiber et al., 2012):

- data density
- data quality
- geological complexity
- geological interpretations and conceptual uncertainties.

Some simplifications are always needed in three-dimensional geological models. In the Clarence-Moreton bioregion, such simplifications mean, for example, that stratigraphic units that only occur locally or have poorly understood relationships to other units (e.g. Woodenbong Beds), are not identified as separate model units. In addition, no differentiation was made in the Clarence-Moreton three-dimensional geological model between different types of Quaternary sediments (e.g. alluvial sediments, coastal sands or shallow marine sediments) in the coastal regions of the Richmond and Clarence river basins. These differences cannot be resolved at the regional scale of the models developed for this BA, and would require small-scale models that specifically focus on these areas.

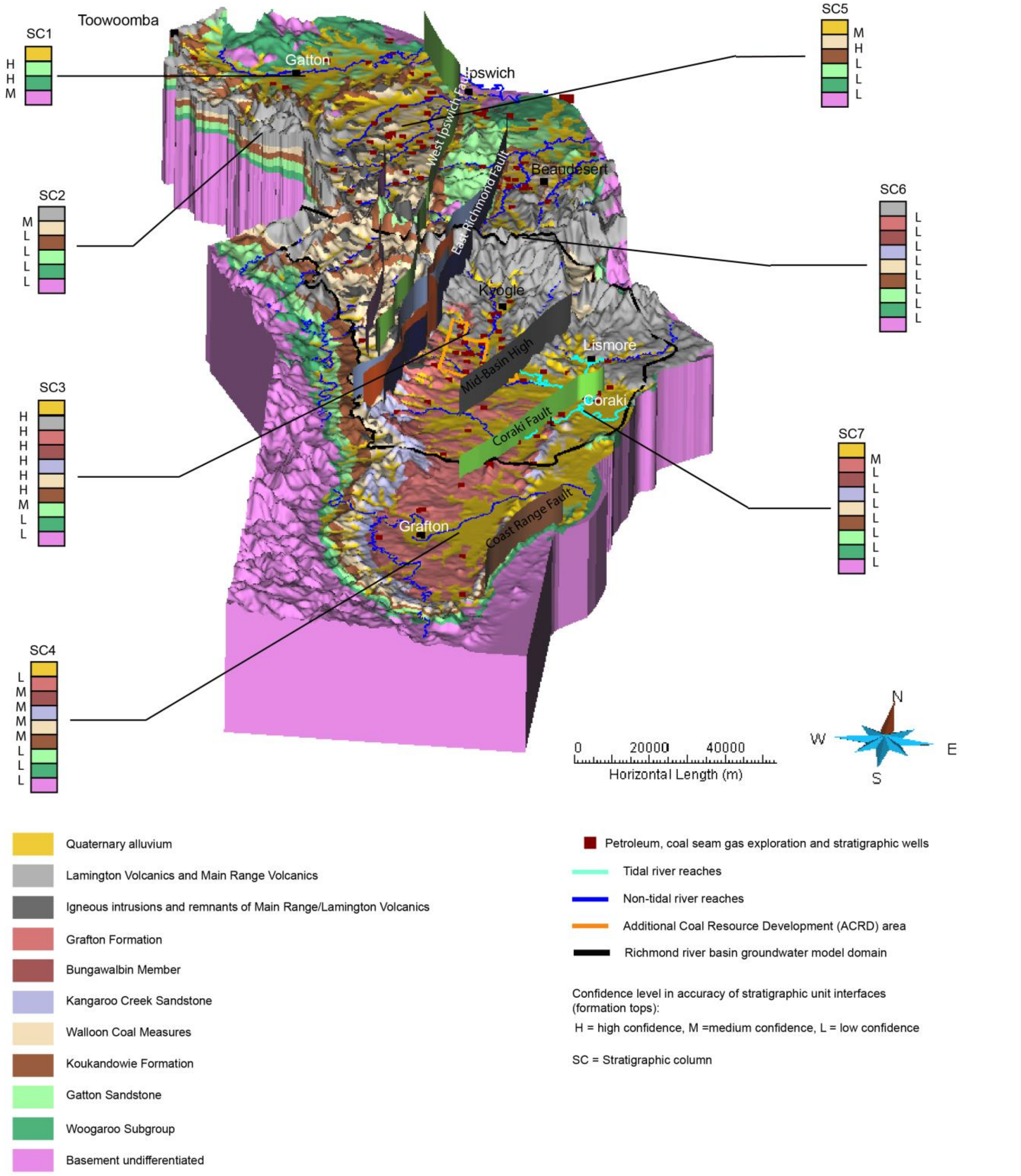


Figure 29 Qualitative assessment of confidence levels in stratigraphic unit interfaces of the three-dimensional geological model

Selected stratigraphic sections (SS) are shown to give examples on variations of geological uncertainty across the Clarence-Moreton bioregion. Selected major faults and other structural elements are projected as vertical surfaces on the three-dimensional geological model.
Data: Bioregional Assessment Programme (Dataset 1, Dataset 2, Dataset 3, Dataset 4); Australian Geological Survey Organisation (Dataset 13)

In this section, the spatial distribution of uncertainties of the three-dimensional geological model of the Clarence-Moreton bioregion, which was related to data density, data quality, geological complexity and geological uncertainties, is explained using multiple stratigraphic columns

(Figure 29). These stratigraphic columns show the distribution of the stratigraphic units in various parts of the Clarence-Moreton bioregion together with a qualitative assessment of the confidence in the accuracy of layer boundaries varying from high, medium or low. This qualitative assessment is based on the availability of different data sources (e.g. groundwater bores, exploration wells or seismic data; Raiber et al., 2016) and how they characterise the geometry of different geological layer boundaries (which define the contact between geological formations). In high confidence areas, the three-dimensional geological model is likely to predict the depth where different stratigraphic units are intersected (i.e. formation tops) with a relatively high degree of accuracy. Conversely, where the confidence level is low, the discrepancy between the predicted and actual depth of formation top intersections observed at a new well that would be drilled at the same location could potentially be very high. Stratigraphic columns are described below:

- Stratigraphic column SC1: at this location in the Lockyer Valley, the density of groundwater bores in the alluvium and deeper aquifers is very high. As a result, the accuracy of the layer boundaries between the alluvium and the underlying Gatton Sandstone, and between the Gatton Sandstone and the underlying Woogaroo Subgroup, is classified as high. As there are fewer groundwater bores or exploration wells that intersect the interface between the Woogaroo Subgroup and the underlying basement, the confidence level in this boundary is classified as medium. Overall, the aquifer geometry in this area is well understood, and additional data from future groundwater bores or exploration wells are unlikely to result in significant changes to the three-dimensional geological model.
- Stratigraphic column SC2: in this area within the headwaters of the Bremer river basin and at the crest of the Great Dividing Range, there are some groundwater bores that intersect the interface between the Main Range Volcanics and the Walloon Coal Measures, but there are no groundwater bores or exploration or stratigraphic wells that intersect any of the deeper units. Consequently, the confidence level in layer boundaries is classified as low, and multiple three-dimensional geological model realisations are possible which all honour the available data. The different model realisations could also translate into very different conceptual hydrogeological models (e.g. with regards to the location of groundwater divide). However, as this area is remote from the Richmond river basin and the West Casino Gas Project area and is not hydraulic connected (Figure 13), this does not have any influence on the predictions of the Richmond river basin groundwater model.
- Stratigraphic column SC3: this area in the Richmond river basin, which forms part of the West Casino Gas Project area, is part of the Casino Trough that has considerable structural complexity. The East Richmond Fault, one of the major faults where stratigraphic units are displaced by several hundred metres (e.g. Ingram et al., 1996), is located to the west of this area. The fault-bound mid-basin high is located to the east of this area. However, there are many CSG and petroleum exploration wells with high quality stratigraphic data, as well as many seismic reflection lines (companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016)) in this area. Consequently, and despite the structural complexity, the confidence in the current aquifer geometry and the reliability of the identified layer interfaces in the area of the West Casino Gas Project are both high. A three-dimensional geological model realisation that represents fault displacement of stratigraphic units will further help to more accurately represent aquifer geometry. However, additional

stratigraphic data from new wells would unlikely result in any fundamental changes to the current conceptual model.

- Stratigraphic column SC4: there is considerable structural complexity in this area with a relatively good coverage of seismic lines (companion product 2.1-2.2 of the Clarence-Moreton bioregion (Raiber et al., 2016)). However, there are very few exploration wells, and hence only limited well control of the seismic data, which may lead to uncertainties in seismic travel time to depth conversions. As outlined in companion product 2.1-2.2 of the Clarence-Moreton bioregion (Raiber et al., 2016), there are very few groundwater bores in this area, and hence there is low confidence in the modelled depth of the interface between the alluvium and the sedimentary bedrock, as well as the interface depths between different sedimentary bedrock units. Additional data that may arise from future wells would considerably improve understanding of aquifer geometry and could result in fundamentally different model realisations. Due to the predominantly west-to-east direction of groundwater flow and the considerable distance from the West Casino Gas Project, this low confidence is unlikely to influence predictions of the Richmond river basin groundwater model.
- Stratigraphic column SC5: this area, which is part of the Warrill Creek Syncline in the Bremer river basin, has a very good coverage of CSG exploration wells (Figure 29 and companion product 2.1-2.2 (observations analysis, statistical analysis and interpolation) of the Clarence-Moreton Bioregional Assessment (Raiber et al., 2016)). Most of these wells intersect the Walloon Coal Measures and Koukandowie Formation interface, but are not deep enough to intersect the contact between the Koukandowie Formation and the Gatton Sandstone. Consequently, the interfaces between the Walloon Coal Measures and the Koukandowie Formation are well understood, but there is limited knowledge on deeper stratigraphic unit boundaries. Additional deep wells would substantially increase the level of confidence.
- Stratigraphic column SC6: this location close to the border between Queensland and NSW represents the area within the Clarence-Moreton bioregion where the three-dimensional geological model has the lowest level of confidence. As a result of the large thickness of the Lamington Volcanics and the high relief topographic surface at the boundary between the Richmond River and the Logan-Albert river basins, there are no stratigraphic wells, exploration wells or groundwater bores that are deep enough to intersect the different sedimentary bedrock units underneath the Lamington Volcanics. There are basement highs to the east (Mount Warning) and west (Mount Barny). Elsewhere within the Clarence-Moreton Basin, the thickest sequences of basalts occur in areas where basement highs are present. However, based on the available evidence, it is not possible to determine whether the Casino Trough in NSW and the depositional centre near Beaudesert are hydraulically linked, or if there is a basement high separating them (Figure 13 and Figure 29). Due to limited data in this area, the three-dimensional geological model contains significant qualitative and subjective interpretations, and fundamentally different model realisations are possible. Hence, a single new deep well in this area would substantially increase the confidence in identifying aquifer geometry and layer boundary locations. However, there is a much higher level of confidence in the reliability of the layer boundaries and particularly the intersection between the Lamington Volcanics and the underlying sedimentary bedrock to

the south (towards Kyogle and the West Casino Gas Project area) and the south-east (towards Lismore and the Alstonville Plateau).

- Stratigraphic column SC7: there is a relatively good coverage of exploration wells and groundwater bores in this area (Figure 29 and companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016)). However, considerable structural complexity exists, which includes juxtaposition (vertical displacement) of aquifers and aquitards of potentially several hundred metres along the Coraki Fault (Figure 29). Furthermore, this area is located close to the margin of the Clarence-Moreton Basin, where layers dip steeply. Consequently, despite the existence of multiple exploration wells and seismic data in this area, the confidence in the identified layer boundaries at this location has been classified as low. Additional data would increase confidence in the three-dimensional geological model predictions and shed further light on how faults may influence groundwater flow.

Although outside of the scope of this BA, the understanding of conceptual geological uncertainties can be refined further in a more quantitative way. For example, formation top intersections from selected wells can be omitted when building the three-dimensional geological model, and the goodness-of-fit between the predicted formation tops and the actual formation top known from the well can be compared (Raiber et al., 2012). Different approaches of characterising and quantifying uncertainty in three-dimensional geological models have been proposed, for example, by Wellmann and Regenauer-Lieb (2012) and Lindsay et al. (2012).

Unlike groundwater models which are commonly developed to simulate transient groundwater behaviour, most three-dimensional geological models are atemporal. However, such models should not be considered as a static final product. Instead, they should be part of a dynamic learning process in which the three-dimensional geological model is used as a guide to target future optimal sampling locations (i.e. locations most in need of new input data such as new wells or seismic data). In this way, any newly acquired data can be input back into the model, thereby leading to improved three-dimensional geological model realisations.

2.3.2.6.2 Conceptual hydrogeological model uncertainty – what is known and unknown

The conceptual hydrogeological model provides the basic understanding of how hydrogeological system components and processes operate and interact (Bredehoeft, 2005). In this product, multiple lines of evidence were used to develop a conceptual understanding of how key system components in geology, hydrogeology and surface water interact in different parts of the Clarence-Moreton bioregion (with a focus on the Richmond river basin). In this section, an overview is provided to identify parts of the conceptual hydrogeological model that are well understood, and highlight areas of major conceptual uncertainty.

Some of the geological uncertainties at selected locations within the Clarence-Moreton bioregion (Figure 29) impact the conceptual hydrogeological model and ultimately contribute to the uncertainty of the groundwater model, which is described in companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016b). As indicated, multiple three-dimensional geological model realisations are possible based on currently available data for the Clarence-Moreton bioregion. This conceptual geological uncertainty can lead to an ‘element of surprise’ in the hydrogeological conceptual model (Bredehoeft, 2005). This applies especially to the area near the crest of the Lamington Volcanics at the northern margin of the Richmond river basin of the groundwater model domain (stratigraphic column 6 in Figure 29). In this area, the uncertainty is very high due to a lack of groundwater bores and exploration wells, attributed to the steep topographic relief and the considerable thickness of the basalts (inferred basalt thickness of up to approximately 850 m). However, as shown in Figure 29, the confidence in the three-dimensional geological model within the Clarence-Moreton bioregion is highest in the area of the West Casino Gas Project due to extensive coverage of exploration wells and seismic data. This means that although there are many geological uncertainties across the entire Clarence-Moreton bioregion, including poor stratigraphic characterisation in some regions, the confidence level in aquifer geometry and the presence and continuity of aquitards is much greater in the West Casino Gas Project area. Consequently, the central part of the groundwater numerical modelling domain coincides with the highest level of three-dimensional geological model reliability in the Clarence-Moreton bioregion.

Where rocks of contrasting hydraulic properties (e.g. aquifers and aquitards) are juxtaposed, faults can form barriers and/or preferential pathways for groundwater flow, which can lead to compartmentalisation of the regional groundwater flow systems (Raiber et al., 2015). The locations and orientation of major faults in the Richmond river basin are well known (e.g. Ingram and Robinson, 1996; Rassam et al., 2014; Raiber et al., 2016), and unlike elsewhere in the Clarence-Moreton bioregion, it is unlikely that there are any major regional fault systems where significant fault displacements occur that have not yet been identified. Well log and seismic data suggest that there is some degree of juxtaposition of aquifers and aquitards along major faults in the Richmond river basin, especially at the Coraki Fault and at the East Richmond Fault (Figure 29). Furthermore, there is evidence from the orientation of streams and groundwater chemistry data that the Coraki Fault may act as a partial groundwater flow path to the surface. Within available time and resources, no faulted three-dimensional geological model could be developed as part of the Clarence-Moreton Bioregional Assessment (Raiber et al., 2016). This limitation will be addressed 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’)). Another part of this strategic project is to use remote-sensing data to confirm whether there is any surface expression of the major faults. Environmental tracer sampling will be conducted at locations where discharge of deep groundwater to the surface is inferred based on the currently available evidence. However, the lack of deep and nested groundwater observation bores means that although this additional work will help to considerably reduce uncertainty, it will not be possible to remove all conceptual uncertainties on the hydraulic role of faults. Ultimately, to further reduce this uncertainty, nested groundwater monitoring bore sites are required.

Apart from the geological uncertainty, a major source of uncertainty in the conceptual hydrogeological models that can directly translate to uncertainties in the groundwater model is the rate and spatial variability of groundwater recharge. An evaluation of recharge was carried out as part of this BA (Figure 12). This recharge assessment is associated with uncertainties related to the spatial heterogeneity of geological materials, climatic variability and the scarcity of climatic and hydrogeological data, as highlighted in companion product 2.1-2.2 for the Clarence-Moreton bioregion (Raiber et al., 2016) and in many scientific publications (e.g. Scanlon et al., 2002). However, despite these uncertainties, the role of the Lamington Volcanics as the major recharge area within the Richmond river basin, where recharge rates are at least an order of magnitude higher than recharge rates to the sedimentary bedrock, is well understood. Furthermore, it is supported by multiple lines of evidence discussed earlier in this section, such as groundwater chemistry data, stream flow rates and general understanding of the link between the alluvial aquifers and the Lamington Volcanics.

It is also well understood that the Lamington Volcanics are simultaneously a major discharge area (Brodie and Green, 2002), where a large proportion of the initial recharge discharges into the stream locally with short lag times and following short flow paths. Only a small proportion of this recharge percolates to deeper aquifers. Hence, there are many springs feeding streams and generating most of the stream flow in the Richmond river basin (Figure 27). This is also documented by multiple lines of evidence, such as water chemistry data, stream flow rates and the association of springs and other groundwater-dependent ecosystems (GDEs) with this feature. Furthermore, the critical hydrological significance of the volcanics as the source for much of the current surface water and groundwater extraction in the Richmond river basin is also underpinned by analogues from other catchments within the Clarence-Moreton bioregion (e.g. Lockyer Valley or Bremer river basin) where more data are available.

A further source of uncertainty in the conceptual hydrogeological model relates to the connection between aquifers and aquitards. Hydraulic connection between aquifers can be controlled to varying degrees by geological structures (discussed above), aquifer composition, aquifer geometry and internal aquifer architecture (e.g. Raiber et al., 2015). In the context of aquifer connectivity in the Richmond river basin, the main uncertainty is related to the lack of petrophysical data of aquitards. In the West Casino Gas Project area, stratigraphic data from the dense network of CSG exploration wells indicate that the aquitards are laterally continuous. If inferred aquitards such as the Maclean Sandstone and the Bungawalbin Member are an ideal regional seal, then they should limit or prevent the vertical hydraulic connection between the overlying and underlying stratigraphic units (i.e. between the Walloon Coal Measures and shallower aquifers) within the West Casino Gas Project area. The high gas saturation levels described by Doig and Stanmore (2012) confirm that there is an effective seal in place in the central part of the Richmond river basin near the West Casino Gas Project. However, even if there are effective aquitards present that limit propagation of impacts associated with the depressurisation of the Walloon Coal Measures to shallower aquifers or the surface within the West Casino Gas Project area, there can still be connectivity elsewhere. For example, where the sedimentary bedrock units thin and pinch out at the surface or where they subcrop underneath the alluvium at the down-gradient end of long regional flow paths at the eastern margin of the Clarence-Moreton bioregion in the Richmond river basin, there is likely to be upwards discharge of deep groundwater to shallow aquifers or to the surface. Without data from nested groundwater monitoring bores, there is no direct evidence to determine to what extent vertical groundwater fluxes between different hydrostratigraphic units occur within the Richmond river basin. However, auxiliary evidence from hydrochemical data (i.e. the freshness of most alluvial groundwaters at the eastern boundary of the Clarence-Moreton Basin) within the Richmond river basin and other catchments within the Clarence-Moreton bioregion (Section 2.3.2.2.4) suggests that discharge from sedimentary bedrock is not the major source of water for alluvial aquifers. In most areas, this sedimentary bedrock discharge component is likely to be overwhelmed by other sources such as the contribution from the Lamington Volcanics or surface water recharge during 'normal' (i.e. non-drought) climatic periods, but may become more important in some areas during droughts.

2.3.2.7 Gaps

There are currently no nested (multi-level) groundwater observation bore sites in the Richmond river basin and other areas within the Clarence-Moreton bioregion where alluvium, volcanic and sedimentary bedrock aquifers are monitored simultaneously. This means that much of the current understanding of vertical head gradients is based on multiple lines of evidence from hydrochemistry data, interpolation from widely-spaced monitoring bore networks, analogues from other parts of the Clarence-Moreton bioregion where more data exist, or general understanding of the regional geology and recharge processes. In addition, although there are some monitoring time-series data for the alluvial aquifer, the number of observations is relatively small (less than 60 observation bores in the Richmond river basin). There are also only a limited number of observation bores in subcatchments of the Richmond river basin such as the Shannon Brook or Eden Creek catchments, which both flow through the area where CSG development may occur. In order to better understand whether inferred aquitards such as the Maclean Sandstone, Bungawalbin Member and Grafton Formation (or part of the Grafton Formation) form regional seals that hydraulically separate the Walloon Coal Measures from shallower aquifers and thus limit or prevent the influence of CSG activities on shallow water resources, more petrophysical data from these aquitards are required. More work is also needed to determine the impact of tidal-dominated river reaches on groundwater salinity.

Faults were not included in the current version of the three-dimensional geological model and consequently no fault-seal analysis (e.g. determination of shale gouge ratios and juxtaposition values, which assess the vertical offset distances between different layers) could be conducted. Alluvial and coastal sediments were not separated in the three-dimensional geological model; separation of these sediments requires development of a smaller-scale high-resolution three-dimensional geological model of the coastal areas, which was beyond the scope of the Assessment.

Overall, this chapter highlights that the limited amount of actual geological field data in the Clarence-Moreton bioregion, such as wells and seismic lines, introduces considerable uncertainty in the three-dimensional geological model. It is important to note that even after integrating multiple data sources, multiple conceptual hydrogeological models honouring the available data are possible in data-scarce areas with complex geology such as the Richmond river basin. This can influence predictions or assessments based on a given conceptual hydrogeological model.

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Dataset 8 Bioregional Assessment Programme (2016) Multivariate statistics of groundwater chemistry in Richmond and Clarence river basins. Bioregional Assessment Derived Dataset. Viewed 25 February 2016, http://data.bioregionalassessments.gov.au/dataset/4ba1dc55-9898-4077-8d8f-120b6e7fd773.

Dataset 9 Bureau of Meteorology (2014) NSW Office of Water – National Groundwater Information System. Bioregional Assessment Source Dataset. Viewed 23 March 2014, https://data.bioregionalassessments.gov.au/dataset/7ab9820e-1e43-4600-8875-a0834345fb6d.

Dataset 10 Bioregional Assessment Programme (2014) NSW Office of Water_GW licence extract linked to spatial locations_CLM_v3_13032014. Bioregional Assessment Derived Dataset. Viewed 23 March 2014, https://data.bioregionalassessments.gov.au/dataset/4b0e74ed-2fad-4608-a743-92163e13c30d.

Dataset 11 NSW Office of Water (2015) Richmond Catchment flow duration curves. Bioregional Assessment Derived Dataset. Viewed 03 September 2015, http://data.bioregionalassessments.gov.au/dataset/e9aefb8f-b088-411f-81da-944d9fdc0a6b.

Dataset 12 NSW Office of Water (2013) Surface Water Offtakes processed for Clarence Moreton v3 12032014. Bioregional Assessment Source Dataset. Viewed 10 April 2015, https://data.bioregionalassessments.gov.au/dataset/715a405b-dc50-46ca-9704-1f698e5b66fc.

Dataset 13 Australian Geological Survey Organisation (2014) Geological faults in the Clarence-Morton bioregion. Bioregional Assessment Source Dataset. Viewed 25 February 2016, http://data.bioregionalassessments.gov.au/dataset/29e4b885-d84f-405e-bcc5-983ccab461f6.

2.3.3 Ecosystems

Summary

A landscape classification was developed to categorise the nature of water dependency among the diverse range of assets, based on key landscape properties related to patterns in geology, terrain, hydrology and vegetation (both natural and modified ecosystems). The process of devising and implementing a landscape classification for the Clarence-Moreton preliminary assessment extent (PAE) mainly involved combining existing classes within datasets associated with aquatic and groundwater-dependent ecosystems, vegetation and land use mapping. Where appropriate, the approach outlined in this product was built on and integrated existing classification systems. Classifiers or attributes are described on which landscape features were categorised and their corresponding rule sets for spatial data initially represented as polygons (e.g. wetlands), lines (stream network) and points (e.g. springs). The majority of the PAE (60.3%) is a modified landscape with by far the largest landscape class being ‘Dryland agriculture’ (57.5%). Natural vegetation landscape classes cover 37.8% of the PAE, with ‘Woodland’ being the most prevalent of these (23.3%), then ‘Open forest’ (8.0%) and ‘Rainforest’ (5.2%). Aspects of water dependency for each landscape class are discussed.

2.3.3.1 Landscape classification

2.3.3.1.1 Methodology

The Clarence-Moreton bioregion is one of the most biologically diverse regions in Australia. It includes the ‘Macleay–McPherson Overlap’, an area where a combination of climate and geography have resulted in the co-occurrence of both temperate and tropical species and a substantial number of regionally endemic species (Burbidge, 1960). The Great Dividing Range runs along the length of the bioregion, providing steep escarpments and fertile valleys and floodplains as rivers start in the mountains and meander across the valleys to discharge at the coast.

The Clarence-Moreton bioregion contains diverse assets that span ecological, sociocultural and economic values (see companion product 1.3 for the Clarence-Moreton bioregion (Murray et al., 2015)). A landscape classification system was developed to categorise the nature of water dependency among this diverse range of assets, based on key landscape properties associated with geology, geomorphology, hydrology and vegetation (both natural and modified ecosystems). Thus, the primary objective of the landscape classification is to present a conceptualisation of the main biophysical and human systems at the surface and describe their hydrological connectivity in relation to how they utilise surrounding water sources. Assets can then be assessed and grouped based on functional criteria depending on their association with a particular landscape class (i.e. landscape classes to which they belong). The term ‘landscape class’ used in this context, represents landscape features classified in a systematic manner and assembled into groups that are indicative of their hydrological connectivity to key groundwater and surface water flow systems. The following section describes the methodology and datasets used to arrive at the landscape classification for ecosystems within the PAE of the Clarence-Moreton bioregion.

There are many different classification and landscape class methodologies which have been developed to provide consistent and functionally relevant representations of ecosystems (e.g. the Australian National Aquatic Ecosystem (ANAE) Classification Framework (AETG, 2012)). Currently, only the Queensland section of the Clarence-Moreton bioregion has a framework in place. Where appropriate, the approach outlined in this product has built on, and integrated these existing classification systems to incorporate the whole bioregion. The process of devising and implementing a landscape classification for the PAE of the Clarence-Moreton bioregion predominantly involved using geology as a basis combined with terrain, hydrology and vegetation. The landscape classification was derived from existing data layers consisting of polygons (e.g. vegetation, terrestrial/surface groundwater-dependent ecosystems (GDEs) or wetlands), lines (stream network) and points (springs, waterholes and waterfalls), thus producing a polygon dataset output.

2.3.3.1.1.1 Classification of landscape features (represented by polygon base data)

The approach taken was formulated in close collaboration with several experts from the Wetland*Info* team (2013) within the Queensland Government who had extensive experience with the landscapes of the Clarence-Moreton bioregion PAE and had input into developing similar classification systems such as the ANAE (Aquatic Ecosystems Task Group, 2012). Landscape classes were derived from spatial analysis using geographic information system (GIS) software. The input datasets and rule sets used to analyse the polygon layers for this component of the classification are given in Table 3.

Geology is the most important characteristic in landscape development in the Clarence-Moreton bioregion. The surface geology of the bioregion can be classified into four regional types: (i) fractured igneous rock (Section 2.3.2.2.6), (ii) consolidated sedimentary rock (Section 2.3.2.2.7), (iii) unconsolidated sediments – alluvium (Section 2.3.2.2.4) and (iv) unconsolidated sediments – estuarine (Section 2.3.2.2.5).

The fractured rock occurs in the steep escarpment mainly along the Queensland–NSW border within the bioregion. The consolidated sedimentary rock covers the rest of the bioregion except where it is covered by the alluvium associated with hydrological features and floodplains or the estuarine sediments along the coast. The broad geological classification divides the PAE according to Queensland's pre-clearing remnant vegetation (Queensland Herbarium, Department of Science, Information Technology, Innovation and the Arts, Dataset 1) with the associated landzone classes and NSW Mitchell landscapes (NSW Office of Environment and Heritage, Dataset 2). Both datasets were reclassified by a geologist to conform to the four identified geology types.

Terrain exerts a strong influence on morphology, flow patterns and associated biota. The slope thresholds from the ANAE for the Murray–Darling Basin, based on the Stein Index (Brooks et al., 2014), were used to determine the four terrain types: (i) lowland, (ii) low energy upland, (iii) high energy upland and (iv) transitional environments.

Hydrological features (other than landscape classes 'Waterfalls', 'Springs and waterholes') were classified into landscape classes according to their geology type, position in the terrain and whether they were a moving or still body of water as well as their permanency. The 'Waterfalls' and 'Springs and waterholes' landscape classes were classified as such, regardless of terrain or geology characteristics.

Modified landscapes are mostly cleared of natural vegetation and are used for agricultural or other anthropogenic purposes. These were classified into three modified landscape types: (i) dryland agriculture or (ii) irrigated agriculture (based on the most recent land use data (BRS, 2009; DSITIA, 2014)); and (iii) urban.

Natural vegetation areas were delineated into seven vegetation types ('Major Vegetation Group' according to NVIS4 (Dataset 5)), based on structure (especially height and cover), growth form and floristic composition (vascular plant species) in the dominant stratum of each vegetation type (Department of the Environment and Water Resources, 2007). Delineation was also made between wet and dry sclerophyll forest.

Landscape classes defined for modified and urban landscapes and natural vegetation areas were determined independent of terrain and geology characteristics.

All landscape classes within the natural vegetation areas and modified landscapes contain groundwater-dependent ecosystems (GDEs). GDEs access groundwater on a permanent or intermittent basis (DSITIA, 2015). They occur within the main landscape classes, where groundwater is close enough to the surface to be accessible. Mapped GDEs for the CLM were obtained from both states (Bioregional Assessment Programme, Dataset 6, Dataset 7). These datasets were derived using the GDE mapping assessment guidelines suggested in the national GDE toolbox (Richardson et al., 2011a, 2011b). Mapping of GDEs has underlying assumptions built on expert knowledge and data where possible. The south-east Queensland mapping has a confidence rating for accuracy of the GDE location and the precent area covered (Wetland*Info*, 2012). Therefore, we considered the GDE mapping as indicative only, with confidence that a GDE occurs in that location but the boundary line between GDE and non-GDE areas may be subjective. Further checking will always improve the accuracy of the GDE maps.

Groundwater dependency was determined by the spatial intersection of GDE polygons in the water-dependent asset register with the vegetation landscape classes, thus resulting in an associated GDE landscape sub-class for each modified landscape and vegetation landscape class.

Derivation of landscape classes was essentially a process of joining different input datasets to create an output polygon dataset representing all landscape classes. Decisions were made at different points during the process about simplification of data (e.g. merging of small splinter polygons into larger neighbouring classes), prioritisation of landscape classes when there was overlap of two or more classes, and improvement of data. Improvement of data (e.g. to code missing areas or re-code existing attributes) relied on the use of supplementary contextual data – maps, satellite imagery, reports or other 'contextual' datasets. Improvement was necessary particularly when defining the polygon water regime classes, where features and/or attributes within Dataset 4 (Bioregional Assessment Programme, Dataset 4) did not adequately cover all relevant aquatic features. The decision about how to proceed in these instances was based on an understanding of the quality of the input data (spatial accuracy, spatial resolution, attribute accuracy, currency) combined with an understanding both of the requirements of the output land classification for subsequent receptor analysis and of the Clarence-Moreton PAE landscape.

Table 3 Classification rule sets used for the polygon layers in the Clarence-Moreton bioregion

Each query discretises the listed dataset into the relevant classification type.

Landscape classification driver	Type	Relevant dataset citation	Dataset (field)[a]	GIS query[a, b, c]
Geology	Fractured rock	Dataset 1 Dataset 2	Qld_RE_13 (LANDZONE) NSW_Mitchell_Landscapes_v3 (Lscape_Nam)	If LANDZONE = (8 – Cenozoic igneous rock OR 11 – Metamorphic Rock) OR Lscape_Nam = (Baryulgil ultramafics OR Flat top basalts OR Lamington volcanic slopes OR Mount Warning plugs OR Nimbin ridges OR Woodenbong syenite plugs); 'Geology' = 'Fractured rock'
	Consolidated sedimentary rock	Dataset 1 Dataset 2	Qld_RE_13 (LANDZONE) NSW_Mitchell_Landscapes_v3 (Lscape_Nam)	If LANDZONE = 9-10 – Fine and coarse grained sedimentary rock OR Lscape_Nam = (Clarence-Manning basin margin OR Clarence foothills OR Grafton-Whipone basin OR Mount Warning exhumed slopes OR Nymboidea great escarpment OR Nymboidea meta-sediments OR Richmond range OR Summervale range); 'Geology' = 'Consolidated sedimentary rock'
	Alluvium	Dataset 1 Dataset 2	Qld_RE_13 (LANDZONE) NSW_Mitchell_Landscapes_v3 (Lscape_Nam)	If LANDZONE = (3 – Recent Quaternary alluvial system OR 5 – Tertiary early Quaternary loamy & sandy plains and plateaus) OR Lscape_Nam = (Byron-Tweed alluvial plains OR Clarence-Richmond alluvial plains OR Manning-Macleay coastal alluvial OR Upper Clarence channels & floodplains; 'Geology' = 'Alluvium'
	Estuarine	Dataset 1 Dataset 2	Qld_RE_13 (LANDZONE) NSW_Mitchell_Landscapes_v3 (Lscape_Nam)	If LANDZONE = 1 – Deposits subject to periodic tidal inundation OR Lscape_Nam = (Ballina coastal ramp OR Brooms Head-Kempsey coastal ramp OR Clarence-Richmond barriers and beaches OR Estuary/water added OR Manning-Macleay barriers and beaches); 'Geology' = 'Estuarine'

Landscape classification driver	Type	Relevant dataset citation	Dataset (field)[a]	GIS query[a, b, c]
Terrain	Lowland	Dataset 3	Stein Index Classification for Streams National 20150513 (Value)	If ‘Value’ = 1 (mrVBF* > 3); ‘Terrain’ = ‘Lowland’
	Transitional	Dataset 3	Stein Index Classification for Streams National 20150513 (Value)	If ‘Value’ = 2 (mrVBF* >=2.5 AND mrVBF<=3); ‘Terrain’ = ‘Transitional’
	Low energy upland	Dataset 3	Stein Index Classification for Streams National 20150513 (Value)	If ‘Value’ = 3 (mrVBF* <2.5 AND mrRTF >2.5); ‘Terrain’ = ‘Low energy upland’
	High energy upland	Dataset 3	Stein Index Classification for Streams National 20150513 (Value)	If ‘Value’ = 4 (mrVBF* < 2.5 AND mrRTF <= 2.5); ‘Terrain’ = ‘High energy upland’
Water regime	Floodplain	Dataset 4	CLM_geofab_waterbody_wetlandinfo (FLOODPLAIN, WETCLASS)	If ‘FLOODPLAIN = ‘F’ AND NOT (‘WETCLASS’ = ‘L’ OR ‘E’ OR P’) with contextual information; ‘Water regime’ = ‘Floodplain’
	Floodplain lake	Dataset 4	CLM_geofab_waterbody_wetlandinfo (FLOODPLAIN, WETCLASS, SrcFCName)	If (‘FLOODPLAIN = ‘F’ AND ‘WETCLASS’ = ‘L’) OR (‘SrcFCName’ = ‘Lakes’ with visual inspection using Dataset 2 to recode some of these features to ‘floodplain lake’) with contextual information; ‘Water regime’ = ‘Floodplain lake’
	Artificial reservoir	Dataset 4	CLM_geofab_waterbody_wetlandinfo (HYDROMOD_L, SrcFCName)	If (‘HYDROMOD_L’ = ‘artificial wetlands – dams, ringtanks’ OR ‘modified – dams or weirs’) OR “SrcFCName” = ‘Reservoirs’ with contextual information; ‘Water regime’ = ‘Artificial reservoir’
	Non-floodplain lake	Dataset 4	CLM_geofab_waterbody_wetlandinfo (WETCLASS, FLOODPLAIN, SrcFCName)	If [‘WETCLASS’ = ‘L’ AND NOT (‘FLOODPLAIN’ = ‘F’)] OR (‘SrcFCName’ = ‘Lakes’ with visual inspection using Dataset 2 to recode some of these features to ‘Non-floodplain lake’) with contextual information; ‘Water regime’ = ‘Non-floodplain lake’
	Floodplain swamp	Dataset 4	CLM_geofab_waterbody_wetlandinfo (FLOODPLAIN, WETCLASS, HAB_L)	If ‘FLOODPLAIN’ = ‘F’ AND (WETCLASS = ‘E’ OR ‘P’) AND ‘HAB_L’ = ‘Coastal/ Sub-coastal floodplain tree swamps (Melaleuca and Eucalypt)’ with contextual information; ‘Water regime’ = ‘ Floodplain swamp’
	Non-floodplain swamp	Dataset 4	CLM_geofab_waterbody_wetlandinfo (FLOODPLAIN, SrcFType, HAB_L)	If ‘FLOODPLAIN’ = NOT ‘F’ AND (SrcFType = ‘swamp’) AND ‘HAB_L’ = ‘Coastal/ Sub-coastal non-floodplain grass, sedge and herb swamps’ with contextual information; ‘Water regime’ = ‘Non-floodplain swamp’

Landscape classification driver	Type	Relevant dataset citation	Dataset (field)[a]	GIS query[a, b, c]
Vegetation	Rainforest	Dataset 5	NVIS4_1 (MVG_NAME)	If 'MVG_NAME' = 'Rainforests and Vine Thickets'; 'Vegetation' = 'Rainforest'
	Open forest (wet sclerophyll forest)	Dataset 5	NVIS4_1 (MVG_NAME)	If 'MVG_NAME' = 'Eucalypt Tall Open Forests'; 'Vegetation' = 'Open forest (wet sclerophyll forest)'
	Woodland (dry sclerophyll forest)	Dataset 5	NVIS4_1 (MVG_NAME)	If 'MVG_NAME' = 'Eucalypt Open Forests/Eucalypt Low Open Forests/Eucalypt Woodlands/Acacia Forests and woodlands/Callitris Forests and woodlands'; 'Vegetation' = 'Woodland (dry sclerophyll forest)'
	Shrubland	Dataset 5	NVIS4_1 (MVG_NAME)	If 'MVG_NAME' = 'Acacia Shrublands/Other Shrublands/ Heathlands/Chenopod Shrublands/Samphire Shrublands and Forblands'; 'Vegetation' = 'Shrubland'
	Grassland	Dataset 5	NVIS4_1 (MVG_NAME)	If 'MVG_NAME' = 'Tussock grasslands/Other Grasslands/Herblands/Sedgelands and Rushlands'; 'Vegetation' = 'Grassland'
	Mangrove	Dataset 5	NVIS4_1 (MVG_NAME)	If 'MVG_NAME' = 'Mangroves'; 'Vegetation' = 'Mangrove'
	Groundwater-dependent ecosystems	Dataset 6	Southeast Queensland GDE surface areas (GDE_TYPE) Southeast Queensland GDE terrestrial areas (GDE_TYPE)	If 'GDE_TYPE' = 'SURFACE EXPRESSION' OR 'GDE_TYPE' = 'TERRESTRIAL G'; 'GDE' = 'SURFACE EXPRESSION' OR 'TERRESTRIAL G'
		Dataset 7	NSW Northern Rivers GDE (Type)	If 'Type' = 'Terrestrial' OR 'Type' = 'Wetland'; 'GDE' = 'Terrestrial' OR 'Wetland' ELSE NULL
Modified landscape	Dryland agriculture	Dataset 8	Basin Scale Land Use of Australia - 2014 (Primary_v7)	If 'Primary_V7' = 'Production from dryland agriculture and plantations'; 'Vegetation' = 'Dryland agriculture'
	Irrigated agriculture	Dataset 8	Basin Scale Land Use of Australia - 2014 (Primary_v7)	If 'Primary_V7' = 'Production from irrigated agriculture and plantations'; 'Irrigated agriculture' = 'Production from irrigated agriculture and plantations'
	Urban	Dataset 9	GEODATA TOPO 250k Series 3 – BuiltUpAreas (FEATURETYPE)	If 'FEATURETYPE' = 'Built Up Area' AND visual analysis of more recent data indicates urban areas; 'Urban'= 'Urban'
Other	Other			If NOT any other class

[a]GIS = geographic information system
[b]Punctuation and typography used as in the dataset
[c]Terms refer to attribute column headings and attributes within the relevant GIS dataset(s)
mrVBF* = multi-resolution valley bottom flatness; mrRTF = multi-resolution ridge top flatness ; GDE = groundwater-dependent ecosystem

2.3.3.1.1.2 Classification of watercourses (represented by line-based data)

The approach to classifying watercourses in the PAE broadly focused on whether or not they were streams or rivers. The watercourses were primarily based on the Bureau of Meteorology's Geofabric cartographic mapping of river channels derived from 1:250,000 topographic maps (Bureau of Meteorology, Dataset 10). The Geofabric is a purpose-built geographic information system (GIS) that maps Australian rivers and streams and identifies their hydrologic connections. Detailed descriptions of the Geofabric can be found in the Geofabric product guide (Bureau of Meteorology, 2012). The water regime of the Geofabric watercourses was defined according to their hierarchy – either as 'river' (hierarchy 'major') or 'stream' (hierarchy 'minor'). The major hierarchy relates to large in-channel bodies of moving water, including large anabranching systems that are mostly perennial. Minor hierarchy streams are smaller in-channel bodies of moving water, including creeks, and are tributaries or distributaries of a river. They can be ephemeral in nature (Brooks et al., 2014).

Rivers were further classed as 'tidal river' with upstream tidal limits based on information derived from relevant published reports (Department of Natural Resources, 2006; Middelmann et al., 2000; Gold Coast City Council (n.d.); Anorov, 2004).

The Geofabric watercourse mapping is a line dataset. As part of the process to derive the output landscape classes, all Geofabric watercourses were buffered by 0.5 m on either side of the watercourse (i.e. a total of 1 m). This did not adequately represent the true extent of some watercourses – particularly estuaries and wide rivers. Accordingly, the estuary watercourses were broadened to reflect their real extent as defined in Dataset 5 (Department of the Environment, Dataset 5), where NVIS4_1 dataset classes were 'sea and estuaries' and 'inland aquatic – freshwater, salt lakes, lagoons' and where these waterbodies were not already captured in the aquatic classes defined in Table 3.

The differentiation between freshwater streams and rivers served, in part, to acknowledge the hierarchical differences in geomorphological and ecological processes within main channel depositional zones as opposed to smaller tributary systems. These rivers and streams were further differentiated from estuarine watercourses, to reflect major functional differences in hydrological processes and ecological functions (Table 4).

Table 4 Classification rule sets used for the line layers in the Clarence-Moreton bioregion

Classification	Hydrological type	Relevant dataset citation	Dataset (field)[a]	Query[a]
Water regime	Stream	Dataset 10	SH_Cartography_GDB (Hierarchy)	If 'Hierarchy' = Minor; 'Water regime' = 'Stream'
	River	Dataset 10 Dataset 5	SH_Cartography_GDB (Hierarchy) NVIS4_1 (MVG_NAME)	If 'Hierarchy' = Major AND 'MVG_NAME' = ('sea and estuaries' OR 'inland aquatic – freshwater, salt lakes, lagoons') AND NOT another aquatic waterbody class; 'Water regime' = 'River'
	Tidal river	Dataset10 Dataset 5	SH_Cartography_GDB (Hierarchy) NVIS4_1 (MVG_NAME)	If 'Hierarchy' = Major AND 'MVG_NAME' = ('sea and estuaries' OR 'inland aquatic – freshwater, salt lakes, lagoons') AND NOT another aquatic waterbody class AND 'tidal' according to published information; 'Water regime' = 'Tidal river'

[a]Punctuation and typography used as in the dataset

2.3.3.1.1.3 Classification of springs, waterholes and waterfalls (represented by point-based data)

In the absence of adequate spatial datasets defining the location of springs, waterholes and waterfalls, these were classified based on their occurrence in the water-dependent asset register (see companion product 1.3 for the Clarence-Morton bioregion (Murray et al., 2015)) (Table 5). Processing of all points included buffering to 0.5 m (1 m diameter).

Table 5 Classification rule sets used for the point layer in the Clarence-Moreton bioregion

Classification	Types	Relevant dataset citation	Dataset (field)[a]	Query[a]
Water regime	Springs and waterholes; Waterfalls	Dataset 11	Asset register (Group, Class)	If 'Group' = 'Ecological' AND 'Class' = ('Marsh, sedgeland, bog, spring or soak' OR 'Waterhole, pool, rockpool or billabong')

[a]Punctuation and typography used as in the dataset

2.3.3.1.1.4 Distribution of landscape classes

Thirty-five landscape classes were defined for the PAE of the Clarence-Moreton bioregion (Table 6 and Table 7). For the water regime classes (other than 'Springs and waterholes; waterfalls'), these landscape classes are a function of the four geological types and the four terrain types defined in Table 3, resulting in 24 landscape classes. The importance of geology as the main landscape-forming driver is discussed in the geology section (see Section 2.3.2.2) and Section 2.3.3.1.1. Most of the PAE (60.4%) is a modified landscape with by far the largest landscape class being 'Dryland agriculture' (57.5%) (Table 6). Natural vegetation landscape classes and associated GDEs cover 37.8% of the PAE, with 'Woodland' being the largest of these (23.3%), followed by 'Open forest' (8.0%) and 'Rainforest' (5.2%) (Figure 30 and Figure 31). Meaningful comparisons between total areas of hydrological landscape derived from line and point input datasets ('Stream', 'River', 'Tidal river', 'Waterfalls', and 'Springs and waterholes' landscape classes) cannot be made, as their mapped area is not a true representation of their actual size (a feature of the processing methodology, as outlined in the previous section). However, Table 7 provides length attributes for the landscape classes based on linear features (rivers, streams).

Table 6 Area and percentage representation of landscape classes across the preliminary assessment extent (PAE) of the Clarence-Moreton bioregion – non-river and non-stream landscape classes only

Landscape class number	Landscape class name	Total land area (ha)	Percentage of PAE (%)
1	All geology, all terrain, artificial reservoir	1,938.7	0.1%
2	Alluvium, all terrain, non-floodplain swamp	9,907.7	0.4%
5	Alluvium, low energy upland or transitional, floodplain	30.5	0.0%
6	Alluvium, low energy upland or transitional, floodplain lake	246.4	0.0%
9	Alluvium, lowland or transitional, floodplain swamp	5,480.0	0.2%
10	Alluvium, lowland, floodplain lake	1,011.6	0.0%
11	Alluvium, lowland, non-floodplain lake	46.8	0.0%
16	Consolidated sedimentary, lowland or transitional, non-floodplain swamp	295.6	0.0%
18	Estuarine, all terrain, non-floodplain swamp	3,467.1	0.2%
21	Estuarine, lowland, floodplain lake	4,715.0	0.2%
25	Waterfalls	0.0	0.0%[a]
26	Springs and waterholes	0.1	0.0%[a]
27	Dryland agriculture	1,206,645.6	54.7%
27a	Dryland agriculture GDE	47,566.7	2.2%
28	Grassland	4,504.5	0.2%
28a	Grassland GDE	6,585.2	0.3%
29	Irrigated agriculture	34,545.0	1.6%
29a	Irrigated agriculture GDE	1,245.8	0.1%
30	Mangrove	239.3	0.0%
30a	Mangrove GDE	132.9	0.0%
31	Open forest	163,369.4	7.4%
31a	Open forest GDE	10,784.6	0.5%
32	Rainforest	106,447.0	4.8%
32a	Rainforest GDE	7,745.0	0.4%
33	Shrubland	11,373.8	0.5%
33a	Shrubland GDE	4,438.9	0.2%
34	Woodland	420,792.8	19.1%
34a	Woodland GDE	88,477.6	4.0%
35	Urban	25,354.3	1.2%
	Other (sand, bare rock, unknown)	37,094.5	1.7%
	TOTAL	22,044,82	100%

GDE = groundwater-dependent ecosystem
[a]Total land area of 'Waterfalls' and 'Springs and waterholes' landscape classes is distorted because of the buffer (0.5 m radius) applied to all of these point features which does not represent true size.

Table 7 Length of stream network represented by stream and river landscape classes across the preliminary assessment extent (PAE) of the Clarence-Moreton bioregion

Landscape class number	Landscape class name	Total length (km)	Percentage of total length (%)
3	Alluvium, all terrain, tidal river	209.7	0.9%
4	Alluvium, high energy upland, stream or river	1,404.0	6.2%
7	Alluvium, low energy upland or transitional, river	418.5	1.8%
8	Alluvium, low energy upland or transitional, stream	2,655.7	11.7%
12	Alluvium, lowland, river	496.2	2.2%
13	Alluvium, lowland, stream	2,056.7	9.1%
14	Consolidated sedimentary, high energy upland or low energy upland or transitional, river	340.2	1.5%
15	Consolidated sedimentary, high energy upland or low energy upland or transitional, stream	9,556.9	42.2%
17	Consolidated sedimentary, lowland, stream	139.5	0.6%
19	Estuarine, all terrain, stream	675.8	3.0%
20	Estuarine, all terrain, tidal river	220.9	1.0%
22	Fractured rock, high energy upland, river	73.1	0.3%
23	Fractured rock, high energy upland, stream	4,065.4	18.0%
24	Fractured rock, lowland or transitional, stream	334.5	1.5%
	TOTAL	22,647.6	100%

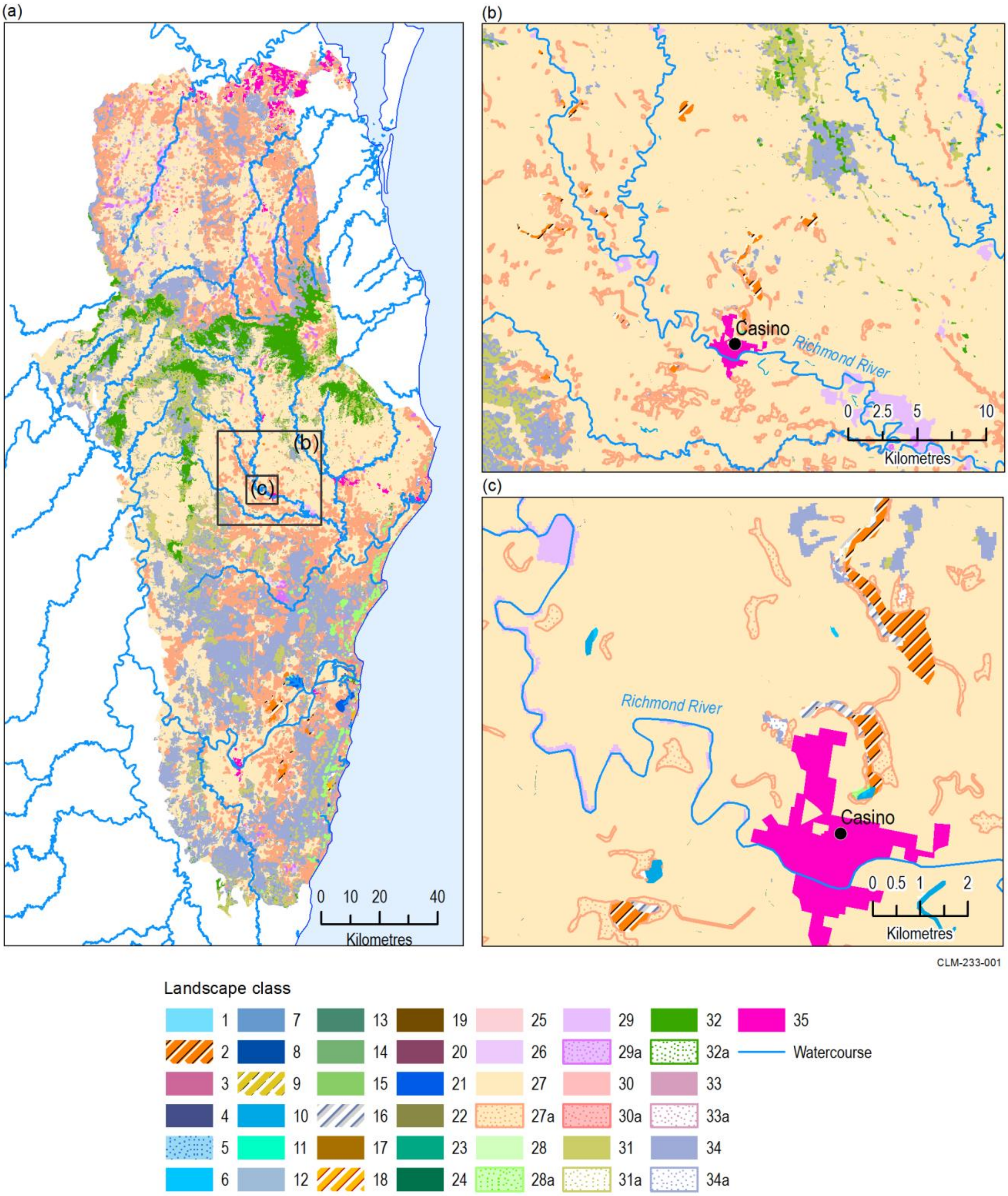

Figure 30 Distribution of all landscape classes in the preliminary assessment extent (PAE) of the Clarence-Moreton bioregion

(a) the PAE in the Clarence-Moreton bioregion, (b) area surrounding Casino, NSW in the Richmond river basin, and (c) zoomed in area adjacent to Casino, NSW, within the PAE
Names of landscape classes are listed beside the corresponding landscape class number in Table 6 and Table 7.
Data: Bioregional Assessment Programme (Dataset 13)

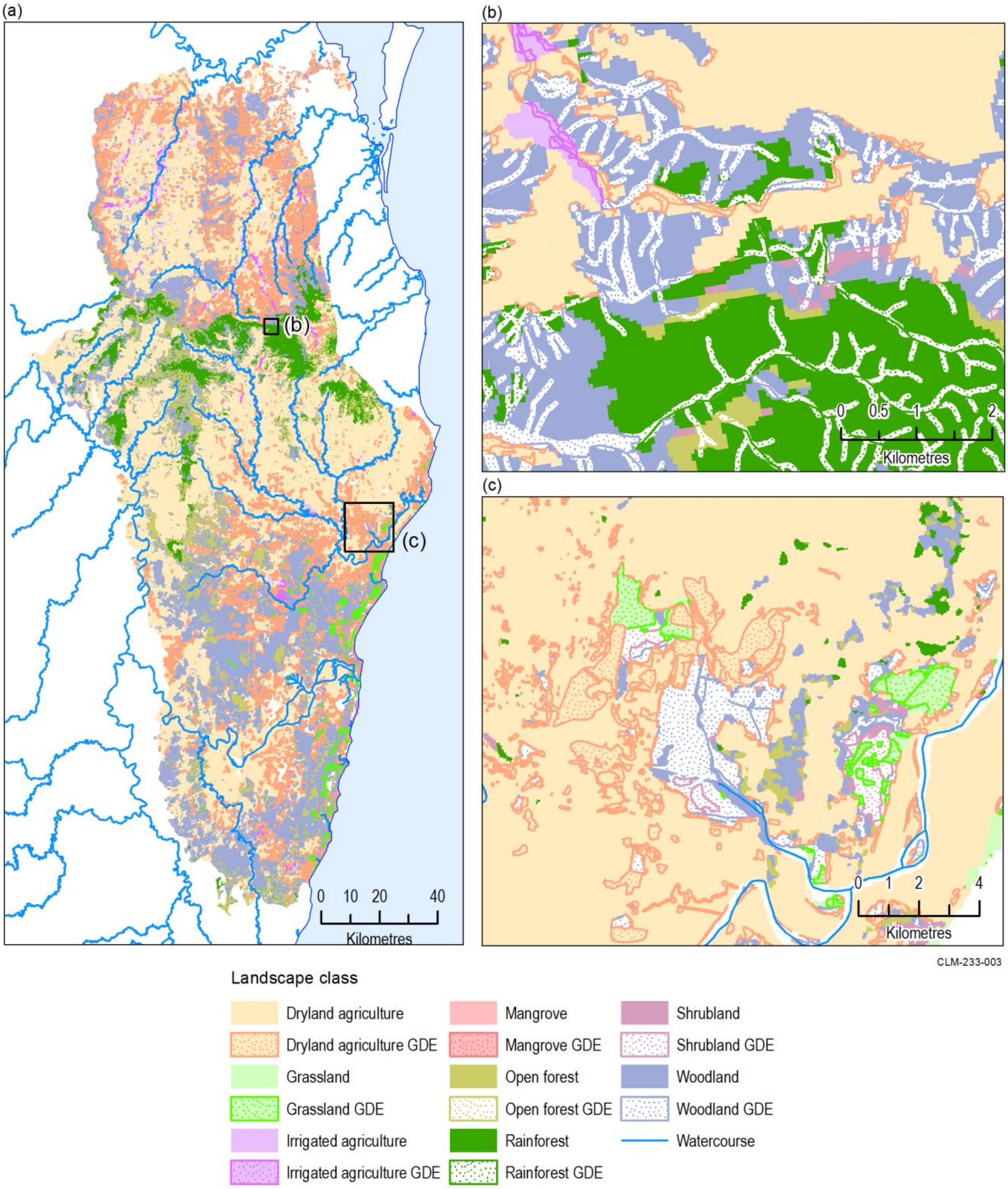

Figure 31 Distribution of vegetation landscape classes in the preliminary assessment extent (PAE) of the Clarence-Moreton bioregion

(a) the PAE in the Clarence-Moreton bioregion, (b) subset of the PAE near of the Border Ranges, on the NSW–Queensland border, and (c) subset of the PAE in the Wardell-Broadwater area, NSW
Data: Bioregional Assessment Programme (Dataset 13)

2.3.3.1.2 Description of landscape classes

The landscape classes were divided chiefly according to geological properties. Detailed information and conceptual models for geology are reported in the geology section (see Section 2.3.2.2).

2.3.3.1.2.1 Fractured igneous rock

Fractured rock (in the Clarence-Moreton bioregion this is mostly extrusive igneous rock such as basalt) is commonly unsaturated and has a high permeability due to its well-developed fracture network. Water infiltrates through the fractures in the recharge zone, and is stored within, and transmitted through, the fractures and primary pore space towards the edge of basalt flows. Here, it discharges back to the surface as springs and provides baseflow to streams (see Section 2.3.1.1 and Section 2.3.1.2 for more detail). Within this category, there were three landscape classes comprising surface water environments (Table 8).

Table 8 Surface water landscape classes within fractured igneous rock in the Clarence-Moreton bioregion

Landscape class number	Landscape class	Definition
22	Fractured rock, high energy upland, river	A steep section (according to the Stein Index) of basin where a major channel crosses igneous rock
23	Fractured rock, high energy upland, stream	A steep section (according to the Stein Index) of basin where a minor tributary crosses igneous rock
24	Fractured rock, lowland or transitional, stream	A flat section (according to the Stein Index) of basin where a minor tributary crosses igneous rock; may occur in the lowland or between upland and lowland areas

2.3.3.1.2.2 Consolidated sedimentary rock

Consolidated sedimentary rock consists of unsaturated to saturated, low to highly permeable rock that stores and transmits groundwater through the pore space of the rock. Groundwater may be transmitted to hydraulically connected aquifers, or discharged at the surface (Section 2.3.2.2). This category resulted in four landscape classes comprising three flowing water and one still water environment (Table 9).

Table 9 Surface water landscape classes within consolidated sedimentary rock in the Clarence-Moreton bioregion

Landscape class number	Landscape class	Definition
14	Consolidated sedimentary, high energy upland or low energy upland or transitional, river	A main channel crossing porous sedimentary rock through flat or steep sections (according to the Stein Index) of basin; exists in upland or between upland and lowland areas
15	Consolidated sedimentary, high energy upland or low energy upland or transitional, stream	Minor tributary crossing porous sedimentary rock through flat or steep sections (according to the Stein Index) of basin; exists in upland or between upland and lowland areas
16	Consolidated sedimentary, lowland or transitional, non-floodplain swamp	A predominantly still water habitat in a flat section (according to the Stein Index) of basin not supplied by overbank flooding or directly from main channel on porous sedimentary rock; occurs in lowland and between upland and lowland areas
17	Consolidated sedimentary, lowland, stream	Minor tributary crossing porous sedimentary rock through the low, flat areas (according to the Stein Index) of a basin

2.3.3.1.2.3 Unconsolidated sediments – alluvium

Alluvium consists of unconsolidated sand, clay and gravel surrounding modern-day water channels as well as paleochannels and floodplains. Alluvium has fluctuating levels of saturation as water fills and discharges from the intergranular pore space between the sediments (Section 2.3.2.2). This category contains 12 landscape classes (Table 10).

Table 10 Surface water landscape classes within alluvium in the Clarence-Moreton bioregion

Landscape class number	Landscape class	Definition
2	Alluvium, all terrain, non-floodplain swamp	A still water, non-open-water dominated habitat not reliant on overbank flooding or water source from a river or tributary
3	Alluvium, all terrain, tidal river	River downstream of the high tide limit and upstream of the river mouth
4	Alluvium, high energy upland, stream or river	A steep section (according to the Stein Index) of basin where a minor tributary or major channel crosses fine-grained sediments
5	Alluvium, low energy upland or transitional, floodplain	A relatively flat section (according to the Stein Index) of basin where a minor tributary or main channel experiences periodic flooding and lateral movement of water overbank crosses fine-grained sediments; may occur in the upland or between upland and lowland areas
6	Alluvium, low energy upland or transitional, floodplain lake	A predominantly still water habitat in a flat section (according to the Stein Index) of basin which is watered from minor tributary or main channels directly or via periodic flooding and lateral movement of water overbank; crossing fine-grained sediments and may occur in the upland or between upland and lowland areas
7	Alluvium, low energy upland or transitional, river	A flat section (according to the Stein Index) of basin where a main channel crosses fine-grained sediments; may occur in the upland or between upland and lowland areas
8	Alluvium, low energy upland or transitional, stream	A flat section (according to the Stein Index) of basin where a minor tributary crosses fine-grained sediments; may occur in the upland or between upland and lowland areas
9	Alluvium, lowland or transitional, floodplain swamp	A predominantly still surface water habitat occurring on a flat section (according to the Stein Index) of basin and sourced by overbank flooding or direct flow from the stream-river network; associated with fine-grained sediments and may occur in between upland and lowland areas or in lowlands
10	Alluvium, lowland, floodplain lake	A predominantly still water and open-water habitat in a flat section (according to the Stein Index) of basin receiving direct water supply from a minor tributary or the main channel and/or may experience periodic flooding and lateral movement of water overbank; occurs on fine-grained sediments and may exist in the upland or between upland and lowland areas
11	Alluvium, lowland, non-floodplain lake	A predominantly still water and open-water habitat in the flat (according to the Stein Index) lower basin and filled by localised rainfall and/or local rainfall rather than directly via surface water from the stream-river network
12	Alluvium, lowland, river	A flat section (according to the Stein Index) of basin where a main channel crosses fine-grained sediments
13	Alluvium, lowland, stream	A flat section (according to the Stein Index) of basin where a minor tributary crosses fine-grained sediments

The hydrological features of the Clarence-Moreton bioregion, allowing water movement and sediment deposits across the river basins, are associated with the erosional flatness index (Gallant and Dowling, 2003). Floodplains occur in flatter valley bottom areas with minimal relief, which is limited in this bioregion to the alluvium within the immediate vicinity of the rivers and streams. Floodplain lakes and swamps (Figure 32(a)) experience periodic inflow from overbank flows from rivers, as well as outflows. They also experience dry periods, where no flow occurs and the water bodies decrease in size. Non-floodplain swamps (Figure 32(b) and Figure 33) are dependent on groundwater. In dry seasons, recharge of groundwater as well as evaporation and plant transpiration can remove water from these swamps, leaving only refuge pools or even lead to them completely drying up. Plant communities have adapted to these conditions; and fauna either have adapted or leave the area until water returns in the wet/dry cycle of these environments (DSITIA, 2015).

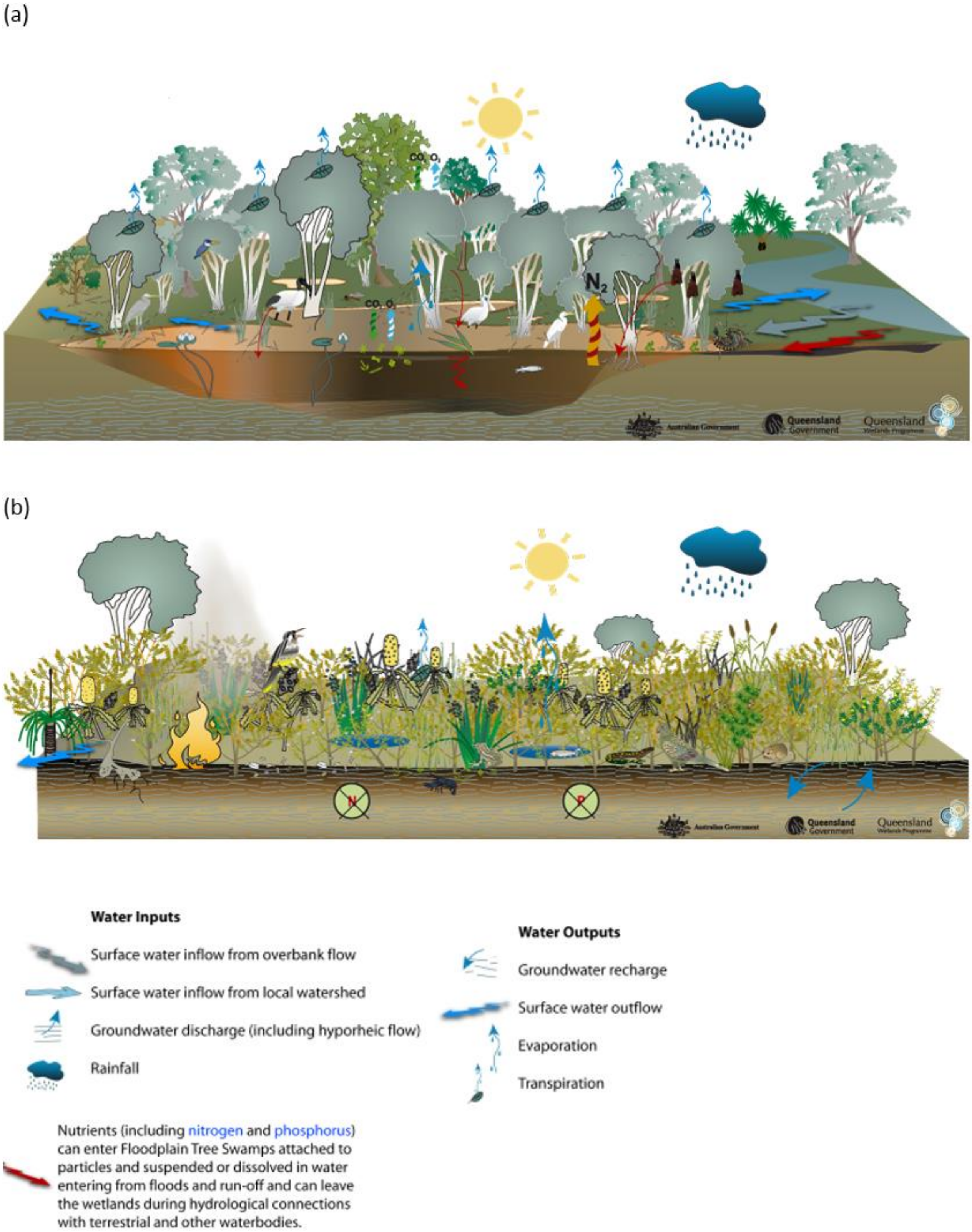

Figure 32 Conceptual models of coastal and subcoastal swamps in the wet season

The first conceptual model (a) depicts a floodplain tree swamp, classified as an 'Alluvium lowland or transitional floodplain swamp', with Melaleuca and Eucalypt species. The second conceptual model (b) depicts a non-floodplain wet heath swamp, classified as an 'Alluvium, all terrain, non-floodplain swamp'.
Data: DSITI (Dataset 12), 'Coastal and subcoastal floodplain tree swamp–Melaleuca spp. and Eucalyptus spp.' and 'Coastal and subcoastal floodplain wet heath swamp', © The State of Queensland (Department of Science, Information Technology and Innovation) 2015

2.3.3.1.2.4 Unconsolidated sediments – estuarine

Estuarine zones represent the interface between freshwater and marine environments. Estuarine sediments consist of unconsolidated sand, clay and gravel, forming saturated estuarine mud flats and coastal swamps in places. Rivers discharge freshwater sediments and nutrients into the estuary and these zones also experience a tidal influence from the sea. This category contains four landscape classes (Table 11).

Table 11 Surface water landscape classes within estuarine zones in the Clarence-Moreton bioregion

Landscape class number	Landscape Class	Definition
18	Estuarine, all terrain, non-floodplain swamp	A predominantly still (but not open) water habitat in a flat section (according to the Stein Index) of the basin downstream of the upper tidal limit and not supplied by overbank flooding or directly from the main channel
19	Estuarine, all terrain, stream	Minor tributary downstream of the upper tidal limit
20	Estuarine, all terrain, tidal river	Main channel downstream of the upper tidal limit down to the river mouth
21	Estuarine, lowland, floodplain lake	A still, open-water habitat downstream of the upper tidal limit, subject to periodic flooding from the estuarine river and streams

Estuarine zones can also be influenced by the presence of accessible groundwater and associated GDEs. Figure 33 shows the estuarine zone interface between the alluvium and marine environments and the movement of groundwater, including terrestrial and surface expression GDEs.

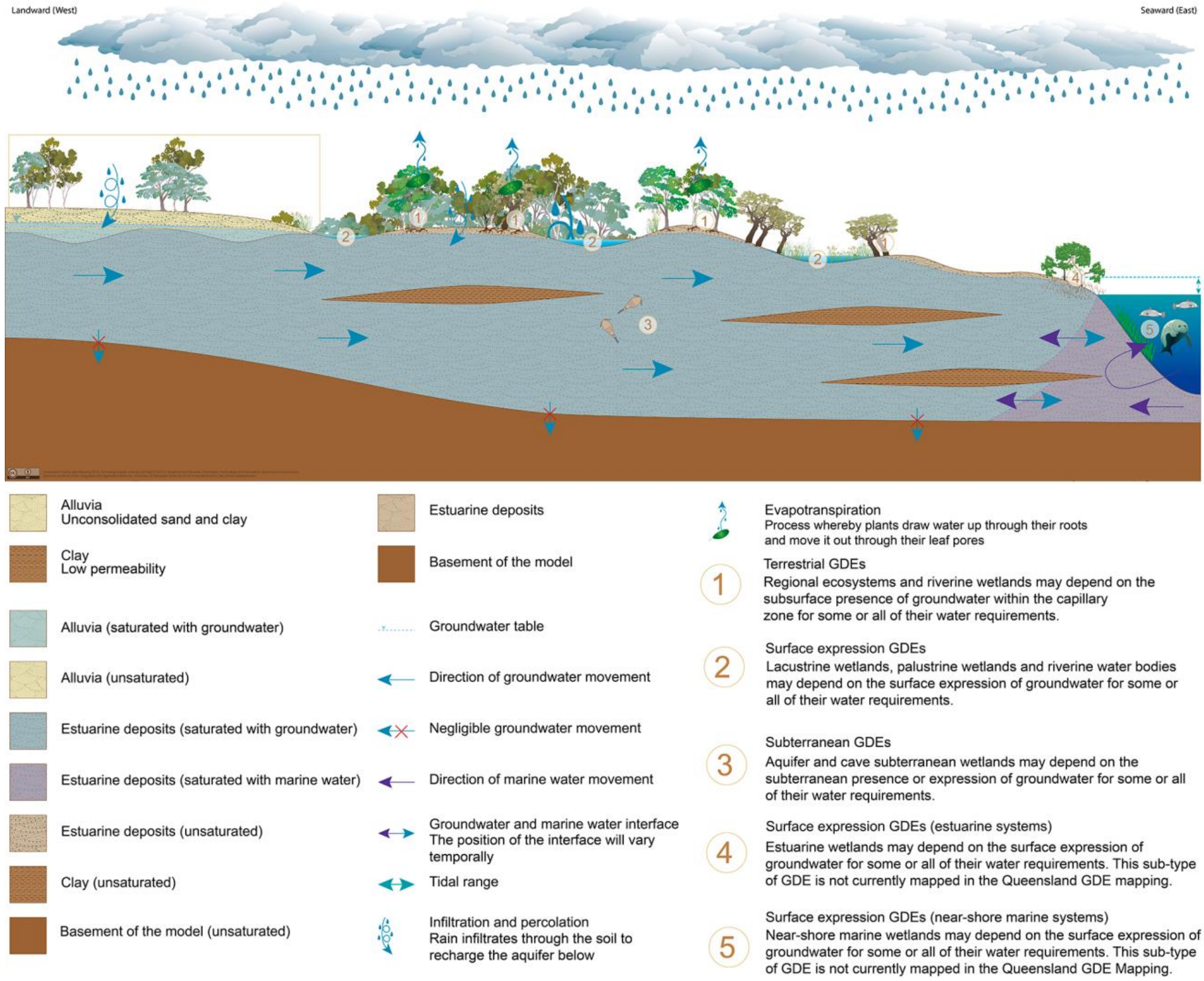

Figure 33 Conceptual model of low-lying coastal swamps with groundwater-dependent ecosystems associated with alluvium and estuarine sediments

GDE = groundwater-dependent ecosystem

Data: DSITI (Dataset 12), 'Low-lying coastal swamps', © The State of Queensland (Department of Science, Information Technology and Innovation) 2015

2.3.3.1.2.5 Other hydrological landscapes (all geology)

Other hydrological data (non-economic) that did not fit into the above classes were classified separately regardless of geology or terrain. This resulted in three other landscape classes (Table 12).

Table 12 Other surface water landscape classes within Clarence-Moreton bioregion

Landscape class number	Landscape class	Definition
1	All geology, all terrain, artificial reservoir	A human-made impoundment of river or stream or a human-made off-channel water storage.
25	Waterfalls	For bioregional assessment purposes in the Clarence-Moreton bioregion, a waterfall is a listed asset where a river or stream spills vertically to a lower point in the landscape (typically by at least a few metres).
26	Springs and waterholes	For bioregional assessment purposes in the Clarence-Moreton bioregion, a spring is a listed asset where groundwater becomes expressed as surface water, and a waterhole is a surface water asset that did not intersect with available GeoFabric surface water layers.

2.3.3.1.2.6 Vegetation ecosystems (including associated groundwater-dependent ecosystem)

Terrestrial vegetation was classified under the main vegetation groups. Cleared land was classified according to its land use. GDEs were present in all vegetation classes and were considered a sub-class of each vegetation class. This resulted in eight landscape classes and eight GDE sub-classes (Table 13).

Table 13 Vegetation landscape classes for natural and modified landscapes, including groundwater dependent ecosystems within each vegetation landscape class in the Clarence-Moreton bioregion

Landscape class number	Landscape class	Definition
27	Dryland agriculture	Farming area extensively cleared of native vegetation and not irrigated
27a	Dryland agriculture GDE	Farming area extensively cleared of native vegetation, not irrigated but where vegetation is reliant on subsurface water
28	Grassland	Area covered by native grasses, sedges, rushes and ferns
28a	Grassland GDE	Area covered by native grasses relying on subsurface water
29	Irrigated agriculture	Farming area extensively cleared of native vegetation and irrigated
29a	Irrigated agriculture GDE	Farming area extensively cleared of native vegetation, irrigated and where production is also reliant on subsurface water
30	Mangrove	Woody shrub forests growing in the intertidal zone on the coast
30a	Mangrove GDE	Woody shrub forests growing in the intertidal zone, and where subsurface water is fundamental to the long-term survival and function of this habitat
31	Open forest	Eucalypt tall open forest with trees over 30 m tall and a dense understory (wet sclerophyll)
31a	Open forest GDE	Eucalypt tall open forest with trees over 30 m tall and a dense understory and where subsurface water is fundamental to the long-term survival and function of this habitat
32	Rainforest	Forests that grow in high rainfall areas
32a	Rainforest GDE	Forests that grow in high rainfall areas and where subsurface water is fundamental to the function of this habitat
33	Shrubland	Landscape dominated by vegetation shorter than trees and with multiple woody stems originating near the ground
33a	Shrubland GDE	Landscape dominated by vegetation shorter than trees and with multiple woody stems originating near the ground, and where subsurface water is fundamental to the long-term survival and function of this habitat
34	Woodland	Eucalypt forest and woodland with trees ranging from 10 to 30 m in height. Trees whose crowns shade less than 30% of the ground allowing for grass or shrub-dominated understorey; associated with drier soils (dry sclerophyll)
34a	Woodland GDE	Subsurface water is fundamental to the long-term survival and function of these areas where trees have crowns shading less than 30% of the ground on drier soils

The unconsolidated sedimentary environments may include unconfined aquifers, where groundwater moves through inter-granular voids between gravel and sand particles (DSITIA, 2015). GDEs are reliant on this groundwater present at least intermittently in these low-lying coastal environments (Figure 33 and Figure 34).

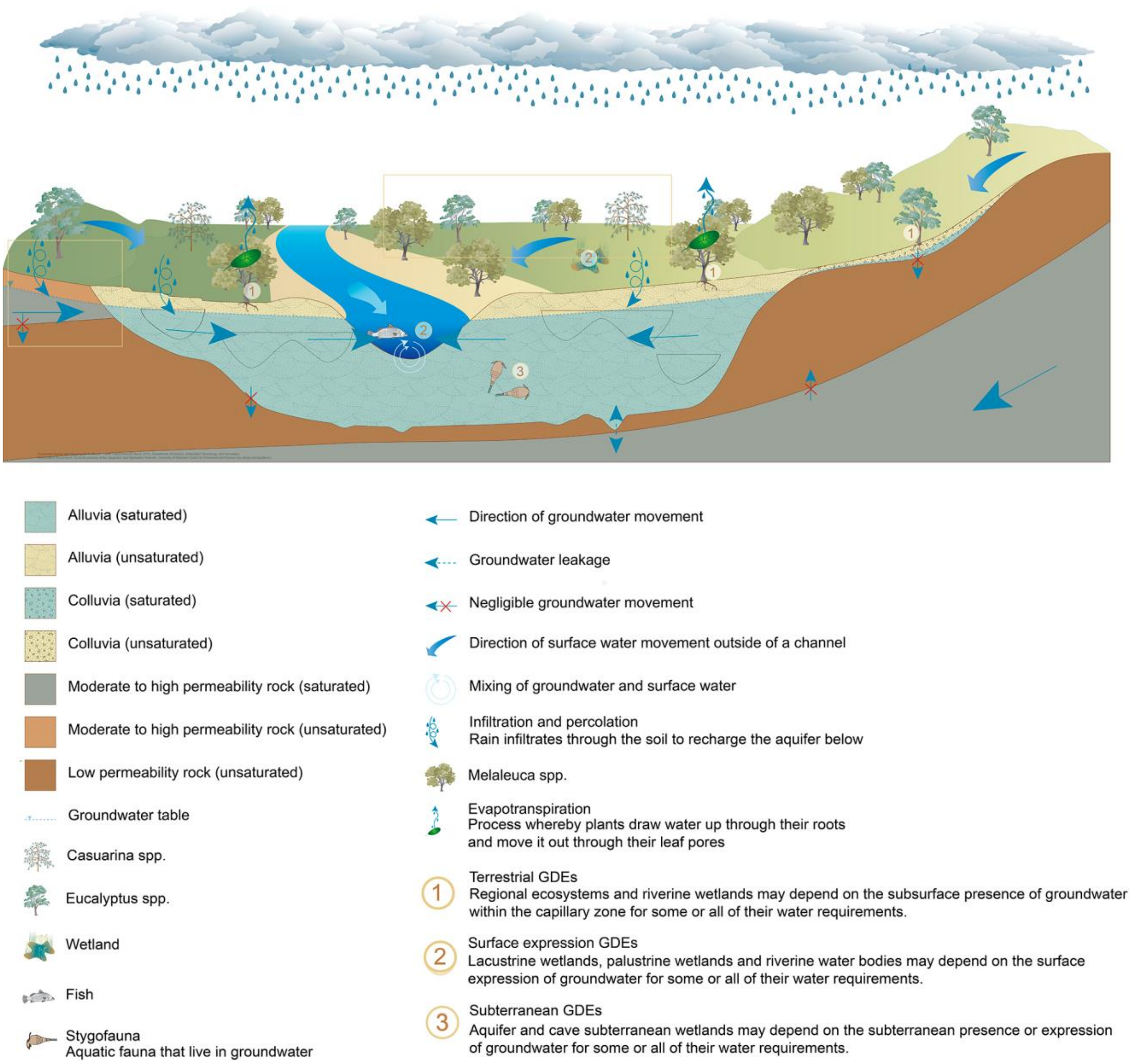

Figure 34 Conceptual model of lowland alluvium with groundwater-dependent ecosystems associated with alluvium sediments

Data: DSITI (Dataset 12), 'Alluvia—lower basin', © The State of Queensland (Department of Science, Information Technology and Innovation) 2015

There were other categories that did not fit into the above landscape classes (Table 14). Urban landscapes, including towns, were given a separate class. Areas that could not be be classified into an appropriate landscape class were placed in an 'other' category. This category is commonly a legacy of the original data layers, where there was insufficient spatial information to classify the area.

Table 14 Other classes that did not fit well into a landscape classification in the Clarence-Moreton bioregion

Landscape class number	Landscape class	Definition
35	Urban	Densely human-populated areas (e.g. cities, towns, suburbs)
	Other (sand, bare rock, unknown)	Small areas of land that cannot be easily accounted for in a large-scale, semi-automated GIS-based landscape classification

2.3.3.1.2.7 Summary of landscape classes in the Clarence-Moreton bioregion

The following summary table (Table 15) lists the individual landscape classes with their associated vegetation communities, threatened communities and species, along with the nature of water dependency. It also provides some examples of associated assets within each landscape class. Note that items listed in the associated vegetation communities, threatened species and communities and the assets do not represent a complete list but are only a subset (refer to companion product 1.3 for the Clarence-Moreton bioregion (Murray et. al., 2015) for a full list).

Table 15 Location, associated communities, threatened species and threatened ecological communities, nature of dependency and water regime for the landscape classes of the Clarence-Moreton bioregion

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
All geology, all terrain, artificial reservoir	1	Widespread in Queensland section of the bioregion; sparsely located in NSW section (Maroon Dam, Queensland; Emigrant Creek Dam, NSW)	*Eucalyptus tereticornis* woodland on Quaternary alluvium *Anguilla reinhardtii, Tandanus tandanus, Macquaria novemaculeata*	Swamp Tea-tree (*Melaleuca irbyana*) Forest of South-east Queensland Threatened Ecological Community White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community	Primarily reliant on surface water	Primarily surface water (regional, seasonal), however groundwater may be periodically important
Alluvium, all terrain, non-floodplain swamp	2	Relatively common and widespread in mid to lower Richmond river basin and the lower Clarence river basin; isolated examples in the upper Clarence river basin	*Melaleuca* spp. and *Eucalyptus* spp. and/or *Lophostemon* spp. and/or *Banksia* spp. and/or *Gahnia sieberiana, Xanthorrhoea* spp., or *Baloskion tetraphyllum, Lepironia articulata* etc.	*Nannoperca oxleyana* Lowland Rainforest of Subtropical Australia Threatened Ecological Community	Reliant on localised rainfall and surface water for inundation; groundwater may or may not be important for inundation	Rainfall and runoff, (localised, temporary) and groundwater (local-regional, intermittent)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Alluvium, all terrain, tidal river	3	The Richmond River downstream of Casino and encompassing major tributaries; also lower Albert and Logan rivers and small parts of the Brisbane River; also at tidal extremity in the Clarence river basin	Top predators include: bullshark *Carcharinus leucas* and dolphin, *Tursiops aduncus*; important recreational and commercial species: *Mugil cephalus, Acanthopagrus australis, Platycephalus fuscus, Girella tricuspidata, Silago ciliata, Argyrosomus hololepidotus, Pomatomus saltatrix,* and prawns (*Penaeus* spp.)	*Casuarina glauca* woodland on margins of marine clay plains Endangered Regional Ecosystem *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem	Surface water discharge via river relative to tidal magnitude determines hydrology and water chemistry (e.g. salinity, sedimentation).	Surface water in the form of main channel discharge
Alluvium, high energy upland, stream or river	4	Widespread and common in the stream network of the bioregion	*Anguilla reinhardtii, Galaxias* spp.	Lowland Rainforest of Subtropical Australia Threatened Ecological Community *Acacia harpophylla* open forest on sedimentary rocks Endangered Regional Ecosystem *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem	Surface water key driver during and following major rainfall events; groundwater of increasing relative contribution during extended low flow periods	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)
Alluvium, low energy upland or transitional, floodplain	5	Canungra Creek river basin within the Albert river basin, Queensland	*Anguilla reinhardtii, Galaxias* spp.		Dependent on overbank flooding during high rainfall events	Surface water (regional, seasonal)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Alluvium, low energy upland or transitional, floodplain lake	6	Primarily in the mid to lower Richmond river basin and the lower Clarence river basin; limited distribution in the mid Albert and Logan river basins	*Anguilla reinhardtii, Retropinna semoni, Hypseleotris compressa, Melanotaenia duboulayi, Rhadinocentrus* sp.		Primarily reliant on overbank flooding or surface water filling distributaries	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)
Alluvium, low energy upland or transitional, river	7	Within the stream network in mid and upper river basins throughout the bioregion	Fish assemblage: *Anguilla reinhardtii, Tandanus tandanus, Retropinna semoni, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata;* crayfish assemblage: *Euastacus* spp.	Lowland Rainforest of Subtropical Australia Threatened Ecological Community *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem *Maccullochella ikei*	Predominantly surface water systems fed by rainfall in uplands with groundwater becoming increasingly important during extended low rainfall periods; *Maccullochella ikei* movement has connections with flow regime	Surface water a mixture of seasonal rainfall and groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Alluvium, low energy upland or transitional, stream	8	Widespread throughout the stream network of the bioregion (except in main channels)	Fish assemblage: *Anguilla reinhardtii, Galaxias* spp., *Tandanus tandanus, Retropinna semoni, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata;* crayfish assemblage: *Euastacus* spp.	Lowland Rainforest of Subtropical Australia Threatened Ecological Community *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem *Eucalyptus racemosa* woodland on remnant Tertiary surfaces Endangered Regional Ecosystem Gallery rainforest (notophyll vine forest) on alluvial plains Endangered Regional Ecosystem *Maccullochella ikei*	Surface and groundwater-dependent systems, the latter being increasingly important during extended low rainfall periods; *Maccullochella ikei* movement has connections with flow regime	Surface water supply from seasonal rainfall and/or groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Alluvium, lowland or transitional, floodplain swamp	9	Widespread in Queensland section of the bioregion	Fish assemblage: *Anguilla reinhardtii, Tandanus tandanus, Retropinna semoni, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata;* crayfish assemblage: *Euastacus* spp.	*Melaleuca irbyana* low open forest on sedimentary rocks Endangered Regional Ecosystem Gallery rainforest (notophyll vine forest) on alluvial plains Endangered Regional Ecosystem *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem *Eucalyptus racemosa* woodland on remnant Tertiary surfaces Endangered Regional Ecosystem	Primarily surface water dependent, intermittent groundwater dependence may occur	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)
Alluvium, lowland, floodplain lake	10	Relatively widespread within the mid to lower Richmond river basin and the lower Clarence river basin; few examples from elsewhere in the bioregion	*Anguilla reinhardtii, Retropinna semoni, Hypseleotris compressa,Myxus petardi, Macquaria novemaculeata, Melanotaenia duboulayi, Rhadinocentrus* sp.	*Nannoperca oxleyana*	Primarily surface water dependent, intermittent groundwater dependence may occur	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Alluvium, lowland, non-floodplain lake	11	Primarily mapped in Bremer, Logan river basins in Queensland section of the bioregion	*Anguilla reinhardtii, Retropinna semoni, Hypseleotris compressa, Melanotaenia duobalayi, Rhadinocentrus* sp.		Localised surface water and groundwater dependent; open water environment, no flow and fine-grained sediments promote macrophyte and phytoplankton productivity; important habitat for waterbirds	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)
Alluvium, lowland, river	12	Major main channel rivers of the bioregion	Fish assemblage: *Anguilla reinhardtii, Tandanus tandanus, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata, Gobiomorphus australis, Myxus petardi*	Lowland Rainforest of Subtropical Australia Threatened Ecological Community *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem *Corymbia intermedia, Eucalyptus tereticornis* open forest on remnant Tertiary surfaces, usually near coast. and in deep red soils Endangered Regional Ecosystem *Maccullochella ikei*	Permanent surface water in main channel as a function of stream order and deep bed scouring contacting groundwater table in places; important refuge for lowland freshwater species/life stages; primary migratory pathway between stream network and estuary during low and high discharge; open-water, sediment deposition and open canopy habitat facilitates in-stream macrophyte and phytoplankton production	Surface water ultimately a mixture of seasonal rainfall and groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Alluvium, lowland, stream	13	Throughout much of the bioregion	Fish assemblage: *Anguilla reinhardtii, Tandanus tandanus, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata, Gobiomorphus australis, Myxus petardi*	Lowland Rainforest of Subtropical Australia Threatened Ecological Community *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem Gallery rainforest (notophyll vine forest) on alluvial plains Endangered Regional Ecosystem *Eucalyptus populnea* woodland on alluvial plains Endangered Regional Ecosystem *Nannoperca oxleyana*	Ephemeral and permanent sections of streams depending on surface and groundwater supply and riparian cover	Surface water supply from seasonal rainfall and/or groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Consolidated sedimentary, high energy upland or low energy upland or transitional, river	14	Throughout much of the bioregion and especially concentrated in upper-mid river basin areas; largely absent from igneous hills and floodplains	Fish assemblage: *Anguilla reinhardtii, Tandanus tandanus, Retropinna semoni, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata;* crayfish assemblage: *Euastacus* spp.	Natural grasslands on basalt and fine-textured alluvial plains of northern New South Wales and southern Queensland Threatened Ecological Community Araucarian microphyll to notophyll vine forest on Cenozoic and Mesozoic sediments Endangered Regional Ecosystem *Mixophyes iteratus* *Euastacus gumar* *Euastacus sulcatus* *Euastacus suttoni* *Euastacus pilosus* *Maccullochella ikei*	Dynamic systems that can shift along a continuum from fast flowing to not flowing as a function of rainfall and groundwater inputs. This dynamic shapes the interactions between several aquatic species including a locally endemic crayfish assemblage. Transitional rivers and boulder-bedrock habitat within pools can serve as key habitat and breeding areas for threatened cod, *Maccullochella ikei.*	Surface water a mixture of seasonal rainfall and groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Consolidated sedimentary, high energy upland or low energy upland or transitional, stream	15	Widespread and common across the bioregion except in the Richmond and Clarence river basin lowlands	Fish assemblage: *Anguilla reinhardtii, Tandanus tandanus, Retropinna semoni, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata;* crayfish assemblage: *Euastacus* spp.	Sub-tropical rainforest GDE Sub-tropical and warm temperate rainforest GDE Richmond Range spotted gum-box GDE *Eucalyptus seeana, Corymbia intermedia, Angophora leiocarpa* woodland on sedimentary rocks Endangered Regional Ecosystem Semi-evergreen vine thicket with *Brachychiton rupestris* on sedimentary rocks Endangered Regional Ecosystem *Melaleuca irbyana* low open forest on sedimentary rocks Endangered Regional Ecosystem *Mixophyes iteratus* *Euastacus gumar* *Euastacus sulcatus* *Euastacus suttoni* *Euastacus pilosus*	Dynamic systems that can shift along a continuum from fast flowing to not flowing to ephemeral streams as a function of rainfall and groundwater inputs; small or large-order streams can remain wetted and even flow due to groundwater. This dynamic shapes the interactions between several aquatic species including a locally endemic crayfish assemblage and including the distribution of the juveniles of large-bodied generalists and smaller-bodied specialist species. Note that hydrology and geology underpin complex relationships including some crayfish species that are in-stream obligates while others are burrowing species nearby but not in the stream.	Surface water supply from seasonal rainfall and/or groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Consolidated sedimentary, lowland or transitional, non-floodplain swamp	16	In mid to lower Richmond and Clarence river basins	Wet heath GDE, paperbark GDE, swamp oak GDE *Anguilla reinhardtii, Retropinna semoni, Hypseleotris compressa, Melanotaenia duboulayi, Rhadinocentrus* sp.	*Nannoperca oxleyana*	Permanence of these wetlands is variable as a function of surface and groundwater supply, localised transpiration rates and water consumption. Shallow margins are important for aquatic and semi-aquatic fauna and flora (e.g. frogs, sedges).	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)
Consolidated sedimentary, lowland, stream	17	Widespread in the bioregion in association with main lowland channels or as part of major tributaries of large rivers	Lowland redgum GDE, paperbark/forest red gum GDE, blackbutt-bloodwood GDE Fish assemblage: *Anguilla reinhardtii, Tandanus tandanus, Retropinna semoni, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata;* crayfish assemblage: *Euastacus* spp.	*Eucalyptus seeana, Corymbia intermedia, Angophora leiocarpa* woodland on sedimentary rocks Endangered Regional Ecosystem *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem *Maccullochella ikei*	Degree of stream permanence highly variable and therefore an important habitat for semi-aquatic fauna and flora (e.g. frogs, sedges)	Surface water supply from seasonal rainfall and/or groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Estuarine, all terrain, non-floodplain swamp	18	Confined to the southern coastline of the NSW section of the bioregion from south of the Richmond River to south of the Clarence River	Broadwater National Park GDE, Bundjalung National Park GDE, heath GDE, freshwater wetland GDE, sedgeland/rushland GDE, swamp mahogany GDE, swamp oak GDE, wet heath GDE *Anguilla reinhardtii*	*Nannoperca oxleyana*	These swamps exist in microclimates subject to coastal rainfall and humidity. Salinity is variable and fauna and flora are structured accordingly. Often water is tannin stained and acidic. Habitat for Wallum specialist freshwater species (e.g. *Nannoperca oxleyana, Tenuibranchiurus*) not associated with or largely absent from large basins.	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)
Estuarine, all terrain, stream	19	Primarily along the NSW coastline of the bioregion with a few streams recognised in the lower Brisbane and Logan river basins	Blackbutt-bloodwood GDE, dry blackbutt GDE, spotted gum GDE *Anguilla reinhardtii, Macquaria novemaculeata, Mugil* spp.	Gallery rainforest (notophyll vine forest) on alluvial plains Endangered Regional Ecosystem *Nannoperca oxleyana*	Streams are supplied by local rainfall and groundwater. Tannin-stained and acidic water in a subset of cases provides habitat for Wallum specialist freshwater species (e.g. *Nannoperca oxleyana, Tenuibranchiurus*) not associated with or largely absent from large basins.	Surface water supply from seasonal rainfall and/or groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Estuarine, all terrain, tidal river	20	Substantial lower river basin areas in the Clarence and Richmond rivers and isolated parts of the Logan and Brisbane rivers overlapping the bioregion	Littoral rainforest GDE, mangrove GDE, paperbark GDE, Swamp Oak GDE Top predators include: bullshark *Carcharinus leucas* and dolphin, *Tursiops aduncus;* important recreational and commercial species: *Mugil cephalus, Acanthopagrus australis, Platycephalus fuscus, Girella tricuspidata, Silago ciliata, Argyrosomus hololepidotus, Pomatomus salatrix*, and prawns (*Penaeus* spp.)	Littoral Rainforest and Coastal Vine Thickets of Eastern Australia Threatened Ecological Community Lowland Rainforest of Subtropical Australia Threatened Ecological Community *Casuarina glauca* woodland on margins of marine clay plains Endangered Regional Ecosystem *Nannoperca oxleyana*	Main channel with hydrology subject to tidal and basin discharge regimes; important area for mangroves and nurseries for early life stages of mobile freshwater and marine fauna	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)
Estuarine, lowland, floodplain lake	21	Lower Clarence river basin, and immediately to the south in the bioregion	Lowland red gum GDE, paperbark GDE, swamp GDE, swamp oak GDE *Anguilla reinhardtii , Macquaria novemaculeata, Mugil* spp.		Subject to overbank flooding in high discharge events and supplied by distributaries and groundwater; largely permanent water systems that function as important nursery areas for mobile marine, freshwater and waterbird assemblages, as a function of still and open-water habitat	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Fractured rock, high energy upland, river	22	Confined to steep high rainfall parts of major river basins on igneous rock (e.g. upper Albert River, Wilsons River, Leycester Creek)	Sub-tropical and warm temperate rainforest GDE, *Lophostemon confertus* open forest on Cenozoic igneous rocks GDE Fish assemblage: *Anguilla reinhardtii*, *Galaxias* spp.; crayfish assemblage: *Euastacus* spp.	Lowland Rainforest of Subtropical Australia Threatened Ecological Community Araucarian microphyll to notophyll vine forest on Cenozoic and Mesozoic sediments Endangered Regional Ecosystem *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem *Euastacus sulcatus* *Euastacus valentulus* *Euastacus mirangudjin*	Permanent water in main channels subject to high flow in association with rainfall; low flows maintained at times via groundwater fed streams; upland refugia for aquatic species; core habitat for adult large-bodied crayfish species (e.g. *Eustacus sulcatus*, *E. valentulus*) and eels (*Anguilla* spp.)	Surface water (regional, seasonal) and groundwater (landscape, seasonal/intermittent)
Fractured rock, high energy upland, stream	23	Widespread in upper Bremer, Logan, Albert, Tweed, Richmond and to a lesser extent Clarence river basins	Sub-tropical & warm temperate rainforest GDE, sub-tropical rainforest GDE, Araucarian complex microphyll vine thicket on Cenozoic igneous rocks GDE Fish assemblage: *Anguilla reinhardtii, Galaxias* spp.; crayfish assemblage: *Euastacus* spp.	Lowland Rainforest of Subtropical Australia Threatened Ecological Community White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community	Permanent and ephemeral streams with flow regimes dictated by combinations of surface and groundwater supply; cool, shaded upland rainforest associated streams that support specialist endemic species of crayfish including highly localised species (e.g. *Euastacus dalagarbe*) and the juveniles of large-bodied generalist species (e.g.	Surface water supply from seasonal rainfall and/or groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
				Corymbia citriodora subsp. variegata open forest on Cenozoic igneous rocks especially trachyte Endangered Regional Ecosystem Semi-evergreen vine thicket with *Brachychiton rupestris* on Cenozoic igneous rocks, usually in southern half of bioregion Endangered Regional Ecosystem Gallery rainforest (notophyll vine forest) on alluvial plains Endangered Regional Ecosystem *Euastacus sulcatus* *Euastacus valentulus* *Euastacus dalagarbe* *Euastacus mirangudjin* *Euastacus girumulayn*	*Euastacus sulcatus, Euastacus valentulus*)	

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Fractured rock, lowland or transitional, stream	24	Mostly in the upper Bremer, upper Albert and upper Richmond river basins; also mid Logan, throughout much of Warrill Creek and all northerly tributaries of the Richmond river basin	Wet heath GDE Fish assemblage: *Anguilla reinhardtii, Tandanus tandanus, Retropinna semoni, Hypseleotris compressa, Mugil cephalus, Macquaria novemaculeata;* crayfish assemblage: *Euastacus* spp.	Lowland Rainforest of Subtropical Australia Threatened Ecological Community *Eucalyptus pilularis* open forest on coastal metamorphics and interbedded volcanics Endangered Regional Ecosystem *Corymbia citriodora subsp. variegata* open forest on Cenozoic igneous rocks especially trachyte Endangered Regional Ecosystem *Maccullochella ikei* *Euastacus sulcatus* *Euastacus valentulus* *Euastacus mirangudjin*	Ephemeral and permanent streams subject to variable discharge as a function of surface and groundwater supply; transitional streams provide habitat or potential habitat for *Maccullochella ikei*	Surface water supply from seasonal rainfall and/or groundwater supply

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Waterfalls	25	Scattered throughout upland areas particularly along the scenic rim; also in the headwaters of the Clarence river basin	On Cenozoic igneous rocks: complex notophyll vine forest GDE, complex microphyll vine thicket GDE, *Eucalyptus saligna* or *E. grandis* tall open forest GDE, montane shrubland GDE, escarpment red gum GDE	Tooloom Falls Area Indigenous site	Periodic or permanent spilling of waterfalls is clearly dependent on surface water and potentially groundwater supply. Migration of certain fauna (e.g. glass eels, freshwater prawns) up or down waterfalls is dependent on flow regime at these barriers.	Surface water supply from seasonal rainfall and/or groundwater supply
Springs and waterholes	26	Alstonville Plateau, Gullyvul Spring, Washpool Spring, Doggies Waterhole, Richmond river basin springs	Lowland red gum GDE, sub-tropical and warm temperate rainforest GDE Spiny crayfish (*Euastacus* spp.)	Stygofauna likely but field validation not achieved (Jon Marshall (DSITIA, Queensland Govt), pers. comm.)	Groundwater expressions at springs; waterholes may have either surface or groundwater supply depending on the location. Aquifer expression via springs is a primary feature of first order streams in the north-east Richmond basin but springs are not mapped.	Springs: groundwater; waterholes: surface water supply from seasonal rainfall and/or groundwater supply
Dryland agriculture	27	Widespread in the bioregion largely with the exception of upland areas of the scenic rim and above the Clarence River floodplain	Bailey’s stringybark, Clarence Lowlands spotted gum, Coast Range bloodwood-mahogany, complex notophyll vine forest on Cenozoic igneous rocks, *Corymbia citriodora, Eucalyptus crebra* open forest on sedimentary rocks, dry heathy	White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community Natural grasslands on basalt and fine-textured alluvial plains of northern New South Wales and southern	Primarily a non-surface-water-dependent landscape class	Rainfall and runoff, (localised, temporary)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
			blackbutt-bloodwood, *Eucalyptus eugenioides, Eucalyptus biturbinata, Eucalyptus melliodora* open forest on Cenozoic igneous rocks, *Eucalyptus moluccana* on sedimentary rocks, Foothill grey gum-ironbark-spotted gum, Northern Ranges dry tallowwood	Queensland Threatened Ecological Community *Eucalyptus seeana, Corymbia intermedia, Angophora leiocarpa* woodland on sedimentary rocks Endangered Regional Ecosystem *Corymbia citriodora subsp. variegata* open forest on Cenozoic igneous rocks especially trachyte Endangered Regional Ecosystem *Eucalyptus racemosa* woodland on remnant Tertiary surfaces Endangered Regional Ecosystem		
Dryland agriculture GDE	27a	Widespread in the bioregion	Bailey's stringybark, Clarence Lowlands spotted gum, Coast Range bloodwood-mahogany, complex notophyll vine forest on Cenozoic igneous rocks *Corymbia citriodora, Eucalyptus crebra* open forest on sedimentary rocks, dry heathy	Lowland Rainforest of Subtropical Australia Threatened Ecological Community White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community	A subset of the dryland agricultural landscape contains remnant GDEs	Rainfall and runoff, (localised, temporary) and groundwater (local-regional, intermittent)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
			blackbutt-bloodwood, *Eucalyptus eugenioides, Eucalyptus biturbinata, Eucalyptus melliodora* open forest on Cenozoic igneous rocks, *Eucalyptus moluccana* on sedimentary rocks, Foothill grey gum-ironbark-spotted gum, heath, inland melaleuca, lowland red gum, paperbark, river oak, sub-tropical and warm temperate rainforest, sedgeland/rushland, swamp mahogany, swamp oak, swamp tea-tree forest and regrowth, wet heath	Natural grasslands on basalt and fine-textured alluvial plains of northern New South Wales and southern Queensland Threatened Ecological Community *Melaleuca irbyana* low open forest on sedimentary rocks Endangered Regional Ecosystem *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem *Acacia harpophylla* open forest on sedimentary rocks Endangered Regional Ecosystem Gallery rainforest (notophyll vine forest) on alluvial plains Endangered Regional Ecosystem		
Grassland	28	Primarily within 10 km along the NSW coastline; also scattered locations further inland in parts of Queensland and NSW in the bioregion	Bailey's stringybark		Primarily a non-surface-water-dependent landscape class	Rainfall (local, seasonal)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Grassland GDE	28a	Primarily within 10 km along the NSW coastline; also scattered locations further inland in parts of Qld and NSW in the CLM Broadwater National Park	Freshwater wetland, heath, lowland red gum, paperbark, sedgeland/rushland, swamp, wet heath		A subset of the dryland agricultural landscape contains remnant GDEs	Rainfall (local, seasonal) and groundwater supply
Irrigated agriculture	29	Throughout the Bremer, Logan and Albert river basins, including the Warrill Creek river basin; along much of the Richmond River; also on the Alstonville plateau and in the Clarence River basin	Lowlands grey box	White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community	Water extracted from surface or groundwater for agriculture	Groundwater or surface water extraction
Irrigated agriculture GDE	29a	Throughout the Bremer, Logan and Albert river basins, including the Warrill Creek river basin; localised parts of the NSW section of the bioregion	Lowland red gum, river oak, wet heath	Lowland Rainforest of Subtropical Australia Threatened Ecological Community *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem	Remnant native habitat and potentially important localised water source for irrigators, mobile native animals and live stock during dry periods	Groundwater
Mangrove	30	Highly localised at the mouths of the Brisbane, Richmond and Clarence rivers, and in a few additional coastal locations in NSW	Mangrove, mangrove shrubland to low closed forest on marine clay plains and estuaries; important nursery habitat and tidal foraging ground for riverine and estuary fish and crustacean assemblages	Lowland Rainforest of Subtropical Australia Threatened Ecological Community	Essentially a marine environment, experiences variable salinity as a function of basin runoff and discharge	Rainfall (local, seasonal)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Mangrove GDE	30a	Highly localised at the mouths of the Brisbane, Richmond and Clarence rivers, and in a few additional coastal locations in NSW; differences in Mangrove and Mangrove GDE distribution occur at fine spatial resolution	Mangrove, paperbark, swamp oak		Freshwater expression via groundwater in isolated areas surrounded by otherwise an essentially marine environment; experiences variable salinity as a function of basin runoff and discharge	Rainfall (local, seasonal) and groundwater

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Open forest	31	Widespread in NSW according to available data, except on Richmond and Clarence river floodplains; also concentrated in Queensland along NSW–Queensland border, and upper Bremer river basin	Araucarian complex microphyll vine forest on Cenozoic igneous rocks, Bailey’s stringybark, blackbutt-bloodwood/apple (inland), Clarence Lowlands spotted gum, Coast Range bloodwood-mahogany, coastal grey box-forest red gum, coastal sands blackbutt, complex notophyll vine forest, *Corymbia citriodora, Eucalyptus crebra* open forest on sedimentary rocks, *Eucalyptus dunnii* tall open forest on Cenozoic igneous rocks, *Eucalyptus grandis* or *Eucalyptus saligna* tall open forest on most multiple geologies, spotted gum - ironbark-grey box communities	White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community Natural grasslands on basalt and fine-textured alluvial plains of northern New South Wales and southern Queensland Threatened Ecological Community Araucarian microphyll to notophyll vine forest on Cenozoic and Mesozoic sediments Endangered Regional Ecosystem	Primarily a non-surface-water-dependent landscape class	Rainfall (local, seasonal)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Open forest GDE	31a	Primarily south of the Richmond River to the southern limit of the bioregion. Also heavily concentrated in Queensland along the NSW–Queensland border	blackbutt-bloodwood/apple Clarence Lowlands spotted gum, Coast Range bloodwood-mahogany, coastal sands blackbutt, *Eucalyptus tereticornis* woodland to open forest on alluvial plains, forest red gum, lowland red gum, paperbark, swamp mahogany, swamp oak	White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community Araucarian microphyll to notophyll vine forest on Cenozoic and Mesozoic sediments Endangered Regional Ecosystem	Potentially important localised water source for mobile native animals and live stock during dry periods	Rainfall (local, seasonal) and groundwater

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Rainforest	32	Much of the scenic Rim including the upper Logan, Albert, Tweed, Richmond and Clarence river basins; also parts of Warrill Creek (Queensland) and Orara River Valley (NSW)	Araucarian complex microphyll and notophyll vine forest or *Eucalyptus saligna* or *E. grandis* tall open forest on Cenozoic igneous rocks, Northern Ranges dry tallowwood	Littoral Rainforest and Coastal Vine Thickets of Eastern Australia Threatened Ecological Community Lowland Rainforest of Subtropical Australia Threatened Ecological Community Araucarian microphyll to notophyll vine forest on Cenozoic and Mesozoic sediments Endangered Regional Ecosystem Semi-evergreen vine thicket with *Brachychiton rupestris* on multiple geologies Endangered Regional Ecosystems	Primarily a non-surface-water-dependent landscape class	Rainfall (local, seasonal)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Rainforest GDE	32a	Essentially all of the rainforest mapped in the Queensland section of the bioregion; contrasting the sparse and scattered subset of localities for rainforest in the NSW section	Littoral rainforest	White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community Lowland Rainforest of Subtropical Australia Threatened Ecological Community Littoral Rainforest and Coastal Vine Thickets of Eastern Australia Threatened Ecological Community Araucarian microphyll to notophyll vine forest on Cenozoic and Mesozoic sediments Endangered Regional Ecosystem Gallery rainforest (notophyll vine forest) on alluvial plains Endangered Regional Ecosystem		Rainfall (local, seasonal) and groundwater

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Shrubland	33	Primarily along the near coast of the NSW section of the bioregion; and in the upper river basins of the Queensland section of the bioregion in river basins from the Bremer to the Tweed; sparsely distributed elsewhere in the bioregion	Coastal complex, Bailey's stringybark	Lowland Rainforest of Subtropical Australia Threatened Ecological Community White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community *Corymbia citriodora subsp. variegata* open forest on Cenozoic igneous rocks especially trachyte Endangered Regional Ecosystem	Primarily a non-surface-water-dependent landscape class	Rainfall (local, seasonal)
Shrubland GDE	33a	Primarily along the near coast of the NSW section of the bioregion; and in the upper river basins of the Queensland section of the bioregion in river basins from the Bremer to the Albert	Heath, paperbark, sedgeland/rushland, swamp mahogany, swamp oak, wallum heath, wet heath	White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community		Rainfall (local, seasonal) and groundwater

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Woodland	34	Widespread in the bioregion; absent from certain parts of the lower Richmond and Clarence river basins	Bailey's stringybark, spotted gum communities, Coast Range bloodwood-mahogany, *Corymbia citriodora, Eucalyptus crebra* open forest on sedimentary rocks, dry blackbutt, spotted gum, blackbutt-bloodwood, red gum, *Eucalyptus crebra* woodland, *Eucalyptus eugenioides*, *Eucalyptus biturbinata*, *Eucalyptus melliodora* open forest or *Eucalyptus moluccana* on sedimentary rocks, grey gum-ironbark-spotted gum, scribbly gum, ironbark/bloodwood communities, *Lophostemon confertus* open forest on Cenozoic igneous rocks, northern open grassy blackbutt, dry tallowwood, rough-barked apples, needlebark stringybark, spotted gum-ironbark/grey gum, stringybark-bloodwood	Swamp tea-tree forest of South-east Queensland threatened ecological community; *Marsdenia coronata* (Vulnerable under Nature Conservation Act, Queensland) Lowland Rainforest of Subtropical Australia Threatened Ecological Community White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community Natural grasslands on basalt and fine-textured alluvial plains of northern New South Wales and southern Queensland Threatened Ecological Community Araucarian microphyll to notophyll vine forest on Cenozoic and Mesozoic sediments Endangered Regional Ecosystem	Primarily a non-surface-water-dependent landscape class	Rainfall (local, seasonal)

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
				Corymbia citriodora subsp. variegata open forest on Cenozoic igneous rocks especially trachyte Endangered Regional Ecosystem *Eucalyptus racemosa* woodland on remnant Tertiary surfaces Endangered Regional Ecosystem *Eucalyptus seeana, Corymbia intermedia, Angophora leiocarpa* woodland on sedimentary rocks Endangered Regional Ecosystem		
Woodland GDE	34a	Widespread in Queensland section of the bioregion; in the lowlands between the Richmond and Clarence river and along the coastally south of Lennox Heads	Baileys stringybark, spotted gum, coastal range bloodwood-mahogany, coastal swamp box, blackbutt-bloodwood, grey gum-ironbark-spotted gum, grey gum-grey ironbark-white mahogany/(forest red gum), heath, scribbly gum, melaleuca, ironbark/bloodwood communities, lowland red gum and grey box,	Swamp tea-tree forest of South-east Queensland threatened ecological community; *Marsdenia coronata* (Vulnerable under Nature Conservation Act, Queensland) White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community	Surface and/or groundwater-dependent systems embedded within non-surface-water-dependent landscapes	Rainfall (local, seasonal) and groundwater

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
			northern open grassy blackbutt, paperbark, swamp mahogany, swamp oak, wet heath	*Acacia harpophylla* open forest on sedimentary rocks Endangered Regional Ecosystem Araucarian microphyll to notophyll vine forest on Cenozoic and Mesozoic sediments Endangered Regional Ecosystem *Corymbia citriodora subsp. variegata* open forest on Cenozoic igneous rocks especially trachyte Endangered Regional Ecosystem *Eucalyptus seeana, Corymbia intermedia, Angophora leiocarpa* woodland on sedimentary rocks Endangered Regional Ecosystem *Eucalyptus tereticornis* woodland on Quaternary alluvium Endangered Regional Ecosystem *Melaleuca irbyana* low open forest on sedimentary rocks Endangered Regional Ecosystem		

Landscape class	Landscape class number	Location (and associated assets)	Associated communities	Threatened ecological communities, endangered regional ecosystems, threatened aquatic species	Nature of dependency	Water sources and water regime (spatial[a], temporal[b])
Urban	35	Much of lower Brisbane river basin (e.g. Brisbane, Ipswich) including the lower Bremer represent heavily urbanised areas; smaller urban settings include townships of Grafton, Casino, and Ballina in the NSW section of the bioregion		Lowland Rainforest of Subtropical Australia Threatened Ecological Community Littoral Rainforest and Coastal Vine Thickets of Eastern Australia Threatened Ecological Community	Densely populated human areas rely on water extraction primarily from reservoirs and potentially from groundwater supply.	Heavily modified hydrology dependent largely contingent on large-scale water storage and/or direct surface water extraction
Other (sand, bare rock, unknown)		Sparsely distributed in the bioregion, and associated with the edge of the bioregion as a function of the interface between river basins (i.e. bare rock on pinnacles) and land and ocean (i.e. sand)		White Box-Yellow Box-Blakely's Red Gum Grassy Woodland and Derived Native Grassland Threatened Ecological Community	Primarily a non-surface-water-dependent landscape class	Rainfall (local, seasonal) and unknown

[a]Spatial scale refers to the flow system and its predominant pattern at local (100 to 104 m^2), landscape (104 to 108 m^2) or regional (108 to 1010 m^2) scales in last column.
[b]Temporal scale of the water regime refers to the timing and frequency of the reliance on a particular water source in last column.
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 11)

2.3.3.2 Gaps

Accessing spatial data across the Clarence-Moreton bioregion is problematic as the source, resolution and consistency of the spatial data vary significantly across the Queensland–NSW state border. The landscape classification was also hindered by the level of availability of spatial data across the two states. The resolution of the available data was more tailored for regional mapping but was problematic for dendritic narrow stream networks and other hydrological features, such as waterfalls and waterholes and springs. It was also noticed that some landscape classes were incompletely mapped. Regionally comprehensive data representing systematically mapped springs and waterfalls and floodplains were also lacking for the Queensland and NSW sections of the Clarence-Moreton bioregion.

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2.3.4 Baseline and coal resource development pathway

Summary

Based on available data and information relating to coal mining and exploration and appraisal for coal seam gas (CSG) in the Clarence-Moreton bioregion, the Assessment team determined that (as of mid-2015) there is one existing baseline coal mine (Jeebropilly Mine, west of Ipswich) and one CSG development that could potentially progress to future commercial production.

This CSG development is located in the Richmond river basin near Casino, NSW. The focus on this area is due to the combination of highly gas-saturated coal seams that also have a relatively high permeability. These are located along the western side of the Casino Trough at depths as shallow as 250 m. In December 2015 Metgasco Ltd (Metgasco) decided to discontinue their proposed development of the West Casino Gas Project. However, as per the coal resource development pathway (CRDP) methodology (Section 2.3.1.1), once the CRDP is determined, it is not changed for bioregional assessment (BA) purposes. This means that the West Casino Gas Project continues to form the basis for the groundwater modelling as an additional coal resource development (ACRD).

The three-dimensional geological model and conceptual assessment of hydrogeological pathways in the Clarence-Moreton bioregion suggest that there is no hydraulic connection between the Bremer river basin (where the Jeebropilly Mine is located) and the Richmond river basin. This lack of hydraulic connection led the Assessment team to focus only on modelling potential impacts for the West Casino Gas Project, and not include the Jeebropilly Mine in the groundwater model development.

2.3.4.1 Developing the coal resource development pathway

The coal resource development pathway (CRDP) is informed by companion product 1.2 for the Clarence-Moreton bioregion (Raiber et al., 2014) and based on the judgment of the Assessment team. The Assessment team used all publicly available evidence and followed the approach outlined in companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014) to evaluate the potential for each coal resource development to proceed to future commercial production. The CRDP is based on information available as of July 2015 and was finalised after feedback provided at two CRDP workshops held in December 2014 in Brisbane and Sydney. Representatives from the Commonwealth Office of Water Science, state government departments and agencies and industry attended the workshop.

In BAs, the CRDP includes all baseline coal resource development (baseline) plus any additional coal resource development (ACRD) continuing into the future. Baseline is defined as a future that includes all coal mines and CSG fields that are commercially producing as of December 2012. The CRDP is defined as all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations that are expected to begin commercial production after December 2012. Groundwater modelling for the Clarence-Moreton bioregion is described in more detail in companion product 2.6.2 (Cui et al., 2016).

A detailed overview of the existing coal or CSG exploration programmes in the Clarence-Moreton bioregion is given in the companion product 1.2 for the Clarence-Moreton bioregion (Raiber et al., 2014).

Some of the key points of product 1.2 include:

- There is currently only one operational coal mine in the Clarence-Moreton bioregion (Jeebropilly Mine, west of Ipswich); coal production at the Jeebropilly Mine will continue until 2017, followed by rehabilitation and closure.
- There are several coal mines west of Ipswich that have been closed recently, and which are currently undergoing revegetation and rehabilitation. In particular, the New Oakleigh Coal Mine closed in 2013 after many decades of operation. As commercial coal production had effectively ceased by December 2012, and the main focus of operations in 2013 was rehabilitation and revegetation as per their mine closure plan, the New Oakleigh Coal Mine was not included in the baseline for the Clarence-Moreton Bioregional Assessment.
- There has been no previous commercial CSG development within the Clarence-Moreton bioregion.
- There are several conventional gas exploration programmes within the Clarence-Moreton bioregion (out of scope for BAs).
- There are multiple CSG exploration programmes in the Clarence-Moreton bioregion. Two companies have conducted pilot testing in Queensland (Arrow Energy Pty Ltd) and NSW (Metgasco). After consideration of the current stage of exploration or appraisal and discussion with the relevant CSG companies, it was decided that the only potential CSG development that may proceed to a production stage within the foreseeable future in the Clarence-Moreton bioregion is Metgasco’s potential development near Casino in the Richmond river basin of NSW.

A recent decision by Metgasco (16 December 2015) to sell back their petroleum exploration licenses (PELs) and petroleum production license application (PPLA) to the NSW Government effectively means that future development of any CSG resources in the Clarence-Moreton bioregion is highly uncertain. However, it is important to state that, as per the companion submethodology M04 (as listed in Table 1) for developing a CRDP (Lewis, 2014), once the CRDP is determined, it is not changed for BA purposes, even in cases such as this where Metgasco have now discontinued their operations in the Clarence-Moreton bioregion.

As highlighted above, there are no existing CSG developments within the Clarence-Moreton bioregion. The only operating coal mine within the Clarence-Moreton bioregion (Jeebropilly Mine) is located more than 120 km away from the potential CSG development area near Casino. This coal mine is included in the baseline. The three-dimensional geological model of the Clarence-Moreton bioregion confirms that there is no hydraulic connection between the Bremer river basin (where the only operating coal mine is located) and the Richmond river basin, as there are multiple regional-scale basement highs (e.g. Mt. Barney basement high and South Moreton Anticline; Figure 35) that separate the hydrostratigraphic units in these depositional centres (Section 2.3.2.2.3). This lack of hydraulic connection between the Bremer and Richmond river basins led the Assessment team to focus only on modelling impacts for the West Casino Gas Project, and not include the Jeebropilly Mine in the groundwater model development.

2.3.4.1.1 West Casino Gas Project

Metgasco has carried out an exploration programme covering an area of about 4550 km^2, which included drilling of wells to evaluate both conventional (out of scope for BAs) and unconventional gas resources and assessing various drilling techniques in the Walloon Coal Measures and other stratigraphic units in NSW in PEL 13, PEL 16 and PEL 426 (Table 16; companion product 1.2 for the Clarence-Moreton bioregion (Raiber et al., 2014)). Most of the exploration programme carried out by Metgasco has focused on the upper Richmond Seam, which is the shallowest coal seam of the Walloon Coal Measures in areas where the thickest accumulation of Walloon Coal Measures has been observed in the Casino Trough, west of Casino. The focus on this area is attributable to the combination of highly gas-saturated coal seams, which also have a relatively high permeability, ensuring gas flow without significant early water production compared to other CSG operations (Raiber et al., 2014). CSG extraction from the Walloon Coal Measures in the Casino Trough was initially expected from depths of approximately 500 to 700 m (Metgasco, 2007), but exploration along the western side of the Casino Trough has revealed that high levels of gas saturation occur at depths as shallow as 250 m.

The Metgasco project near Casino is the only ACRD defined in the CRDP for the Clarence-Moreton bioregion.

2.3.4.1.2 Timeline of developments

2.3.4.1.2.1 West Casino Gas Project

If CSG development in the Richmond river basin proceeds, it will initially likely focus on the Richmond Seam (shallowest and thickest coal seam) in the most prospective exploration areas west and north-west and south of Casino. At a later stage, CSG from deeper coal seams in this area may also be developed. As described in companion product 1.2 for the Clarence-Moreton bioregion (Raiber et al., 2014), in 2012, Metgasco commenced plans to apply for a petroleum assessment lease (PAL), which would have allowed the development of up to five wells, and for a larger petroleum production lease (PPL) north-west of Casino (Table 16). However, the work on this ‘West Casino Gas Project’ was put on hold due to the uncertainties related to CSG development in the Richmond river basin.

In 2013, Metgasco commissioned Parsons Brinkerhoff to conduct a groundwater modelling study to evaluate potential impacts of depressurisation of the Walloon Coal Measures in the area west of Casino. Due to uncertainties with regards to the potential development of CSG resources in the Richmond river basin, it is presently not possible to specify potential well locations. The assumptions underpinning the groundwater model developed as part of the BA for the Clarence-Moreton bioregion are therefore based on a report by Parsons Brinkerhoff (2013), which outlines some assumptions on a base-case development concept for the potential West Casino Gas Project, and shows the hypothetical locations of wells within this potential CSG development area.

Some of these assumptions are:

- The potential gasfield will have a 20-year project life.
- The potential gasfield will consist of 90 wells located within the PPL, with at least 1 km between adjoining wells.
- Development would occur in different stages over a 19-year time period.
- Each wellhead will source two lateral wells within the Richmond Seam of the Walloon Coal Measures.

In its report to Metgasco, Parsons Brinkerhoff (2013) noted that the final development concept may differ, for example, with regards to the staging of the wells and the orientation of the lateral wells. The extent of the potential gas development area west of Casino assumed by Parsons Brinkerhoff (2013) for the development of the groundwater model is shown in Figure 35. Due to the uncertainty associated with potential CSG development in the Richmond river basin, it is difficult to predict timelines of future development. For the purpose of developing the groundwater model for the Clarence-Moreton bioregion, it was assumed that development would commence in 2018.

As outlined in companion product 1.2 for the Clarence-Moreton bioregion (Raiber et al., 2014), discussions with Metgasco suggested that the area west of Casino has been identified as the most prospective exploration area.

However, in addition, as of July 2015, there is a pending PPLA, PPLA 9, south of Casino (Figure 35). PPLA 9 is partly located within the 2 km residential exclusion zone (Figure 35). No further details are known about the staging or number of wells of this potential development. However, due to the focus of potential development on the gas resources west of Casino, it was assumed that PPLA 9 would only be a small development with up to five wells. As for the area west of Casino, in the absence of more specific knowledge, it was assumed that the development would commence in 2018; hypothetical well locations close to the existing exploration wells were chosen for the purpose of groundwater modeling for the bioregional assessment.

As stated previously, in December 2015 Metgasco decided to discontinue its proposed development of the West Casino Gas Project. However, as per the companion submethodology (as listed in Table 1) for developing a CRDP (Lewis, 2014), once the CRDP is determined, it is not changed for BA purposes. This means that the timeline described will continue to form the basis for the groundwater modelling.

Table 16 Existing operations and proposed developments in the baseline coal resource development and coal resource development pathway for the Clarence-Moreton bioregion as of 01 July 2015

The primary activity in bioregional assessments (BAs) is the comparison of two potential futures: (i) the *baseline coal resource development (baseline)*, a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012; and (ii) *the coal resource development pathway (CRDP)*, a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012. The difference in results between CRDP and baseline is the change that is primarily reported in a BA. This change is due to the additional coal resource development (ACRD) – all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin production after December 2012.

Name of existing operation or proposed development	Coal mine or coal seam gas operation	Company	Included in baseline?	Included in coal resource development pathway (CRDP)?	Start of mining operations or estimated project start	Projected mine life or estimated project life	Tenement(s)	Total coal resources (Mt)[b] (for coal mining)or 2P[c] gas reserves (for CSG) (PJ)	Comments
West Casino Gas Project	CSG	Metgasco Pty Ltd	No	Yes - model	Unknown, assumed to be 2018 for the purpose of groundwater modelling	20 years	PEL13, 16 and PPLA 9	338[a]	As of mid-2015, planning in advanced stage; commissioning of a modelling study in preparation for EIS (Parsons Brinckerhoff, 2013); as of mid-2015, existing application for a petroleum production license (PPLA 9). In September 2014, Metgasco has announced that its gas reserves and resources have been downgraded from those reported in 2013, with all reserves moved to the resource category (Metgasco, 2014). On the 16 Dec 2015, Metgasco has decided to sell back their petroleum exploration licenses (PELs) and petroleum production license application (PPLA) to the NSW Government.

Name of existing operation or proposed development	Coal mine or coal seam gas operation	Company	Included in baseline?	Included in coal resource development pathway (CRDP)?	Start of mining operations or estimated project start	Projected mine life or estimated project life	Tenement(s)	Total coal resources (Mt)[b] (for coal mining)or 2P[c] gas reserves (for CSG) (PJ)	Comments
Jeebropilly Mine	Coal mine	New Hope Group	Yes – not modelled	Yes	1982	Over 25 years (mining operations will cease in 2017 followed by rehabilitation and closure)	NA	131[b]	The assessment of geology and hydrogeology (Section 2.3.2 of this product) showed that there is no hydraulic connection between the Richmond river basin and the Bremer river basin (where the Jeebropilly Mine is located). This lack of hydraulic connection led the Assessment team to focus only on modelling potential impacts in the ACRD (West Casino Gas project), and not include the Jeebropilly Mine in the groundwater model development.

[a]This number corresponds to the total 2P gas reserves reported by Metgasco. However, in September 2014, Metgasco announced that it has reclassified its gas reserves as resources (Metgasco, 2014).
[b]Indicates the different resource classes that may combine to form the total resource tonnage – typically these are reported in accordance with the Joint Ore Reserves Committee (JORC) Code. For example, the different JORC resource classes of measured, indicated and inferred resources could be shown (or whichever combination of resource classes is applicable for each project).
[c]proved plus probable reserves
NA indicates that data are not available to the authors
PEL = petroleum exploration lease, PPLA = petroleum production license application

Figure 35 Maximum extent of the additional coal resource development (ACRD) in the Richmond river basin

The extent of the coal resource developments in the coal resource development pathway (CRDP) is the union of the extents in the baseline and in the additional coal resource development (ACRD).
Data: NSW Department of Trade and Investment, Minerals Resources, Petroleum Geoscience (Dataset 1); Bioregional Assessment Programme (Dataset 2, Dataset 3 and Dataset 4)

2.3.4.2 Water management for coal resource developments

2.3.4.2.1 Coal seam gas developments

As no environmental impact statement has been submitted yet, there is a high degree of uncertainty with regard to water management strategies in relation to potential CSG development in the Richmond river basin. A water management plan for Metgasco's 2012 to 2014 exploration programme (Metgasco, 2012) outlines, among other aspects, produced water volumes, water treatment and water monitoring (discussed in detail in companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016)). However, this water management plan only relates to the exploration stage and does not indicate a preferred water management option for any future potential production operations.

2.3.4.2.2 Coal mines

As outlined in Section 2.3.4.1 and in Raiber et al. (2014), there are unlikely to be any new coal mine developments within the Clarence-Moreton bioregion in the foreseeable future, and the only currently operating coal mine within the Clarence-Moreton bioregion in Queensland will not have any impact on the hydrology and hydrogeology of the Richmond river basin as these groundwater flow systems are separated by basement highs.

2.3.4.3 Gaps

The most significant gap relates to the management of water for CSG activities, mainly due to the fact that they are still in the exploration phase. Hence, there is no firm knowledge regarding water requirements and production. There continues to exist considerable uncertainty on the exact locations and number of wells of potential future CSG development areas within the Richmond river basin.

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2.3.5 Conceptual modelling of causal pathways

Summary

In this section, the main causal pathways that describe the interaction between various coal seam gas (CSG) activities and water-dependent assets are described for the Richmond river basin, building on the conceptual understanding of geology, hydrogeology and surface hydrology presented in Section 2.3.2 of this product and the assessment of ecosystems and landscape classes presented in Section 2.3.3.

The coal resource development pathway (CRDP) includes one existing baseline coal mine (Jeebropilly Mine) and one CSG operation (Metgasco's West Casino Gas Project).

As the assessment of geology and hydrogeology (Section 2.3.2 of this product) confirmed that there is no hydraulic connection between the Richmond river basin and the Bremer river basin (where the Jeebropilly Mine is located), only hazards and causal pathways associated with CSG operations were thus addressed in this section. The hazard analysis was used to systematically identify activities that occur as part of CSG activities in the Clarence-Moreton bioregion and which may initiate *hazards*, defined as events, or chains of events, that might result in an *effect* (a change in the quality and/or quantity of surface water or groundwater). A large number of hazards were identified, some of which were beyond the scope of bioregional assessments (BAs), such as accidents. Others are adequately addressed by site-based risk management processes and regulation. Hazards associated with CSG operations deemed to be within the scope of the Clarence-Moreton Bioregional Assessment were grouped into four main causal pathway groups: (i) 'Subsurface depressurisation and dewatering' (ii) 'Subsurface physical flow paths', (iii) 'Surface water drainage', and (iv) 'Operational water management'.

Knowledge of the spatial context of the surface water and groundwater systems of the Richmond river basin enabled the development of four major conceptual models of causal pathways.

The 'Subsurface depressurisation and dewatering' causal pathway group includes coal mine and CSG operations that intentionally dewater and depressurise subsurface hydrostratigraphic units (such as coal seams and aquifers) to permit coal resource extraction. Dewatering applies to coal mines and, given that no coal mines are being modelled in the baseline or CRDP, it will not be discussed further in relation to the Clarence-Moreton bioregion. Subsurface depressurisation associated with CSG development has the potential to directly affect the regional groundwater system at the point, local or regional scales; in addition, it can indirectly affect surface water – groundwater interactions in aquifer outcrop areas. In the Richmond river basin, there are several aquitards such as the Maclean Sandstone and Bungawalbin Member which can potentially prevent wider impacts of depressurisation on overlying aquifers. However, if these aquitards were compromised by faults, the pressure change can be transmitted much quicker with potential impacts extending to the uppermost aquifers. For the 'Subsurface physical flow paths' causal pathway group, subsurface physical flow paths can be affected by hydraulic fracturing and compromised well integrity. The extent

of these changes is likely to be minor and limited to the vicinity (<1 km) of the compromised well or the location where hydraulic fracturing occurs. ‘Surface water drainage’ is the causal pathway group which was most commonly identified for CSG operations during the hazards assessment of the Clarence-Moreton bioregion. Subsidence, diverting site drain lines, rainwater and runoff diversion, levee bunds and creek crossings can change, or disrupt, surface water drainage. Effects on surface water direction, volume and quality can have medium-term (5 to 10 years) to long-term (10 to 100 years) cumulative effects on watercourses within and downstream of tenements. For the ‘Operational water management’ causal pathway group, operational water management can have a cumulative effect on surface water catchments and stream networks, surface water – groundwater interactions and groundwater conditions.

The linkages between the four potential causal pathway groups and the landscape classifications identified in the Clarence-Moreton bioregion are explained. They are underpinned by knowledge of the geology, hydrogeology and surface water – groundwater interactions in the Richmond river basin and are presented in Section 2.3.5.3.1. Five examples that demonstrate the rationale of those linkages are provided.

Finally, a synthesis section summarises how all chapters of this product link together, and how the conceptual model framework presented in this product will inform subsequent companion products of the Clarence-Moreton Bioregional Assessment.

2.3.5.1 Methodology

Conceptual models of causal pathways are a specific type of conceptual model that characterises the *causal pathways*, the logical chains of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets.

These conceptual models bring together the existing understanding and conceptual models of the key system components, processes and interactions for the geology, hydrogeology, surface water, and surface ecosystems, and consider the most plausible and important impacts and their spatial and temporal context. The conceptual modelling draws heavily on information from companion products from Component 1: Contextual information, which is summarised in Section 2.3.2, Section 2.3.3 and Section 2.3.4.

The causal pathways underpin the construction of groundwater and surface water models, and frame the assessment of the impacts on and risks to water and water-dependent assets. The approach taken in the Clarence-Moreton bioregion has leveraged existing state-based resources and knowledge of geological, surface water and groundwater conceptual models. A considerable amount of additional work was carried out as part of the Clarence-Moreton Bioregional Assessment (the Assessment) on the conceptual understanding of key systems components (described in Section 2.3.2). The Assessment team summarised the key system components, processes and interactions for the geology, hydrogeology and surface water of the bioregion at the ‘Conceptual modelling of causal pathways’ workshop held in Sydney in June 2015. The focus of the workshop was to improve the landscape classification (described in Section 2.3.3) and description of the conceptual model of causal pathways. Discussion with representatives from

NSW and Australian government agencies and industry at the workshop focused on knowledge gaps and uncertainties identified by the Assessment team.

In a BA, the identification and definition of causal pathways are supported by a formal hazard analysis, known as Impact Modes and Effects Analysis (IMEA) as outlined in companion submethodology M11 (Ford et al., 2016) and illustrated in Figure 5 (Section 2.3.1). IMEA is a variant of the established hazard analysis tool, Failure Modes and Effects Analysis (FMEA). The causal pathways are based on the outcomes of this hazard analysis and current understanding of the way ecosystems and landscape classes in the Clarence-Moreton bioregion work and interact. The IMEA rigorously and systematically identifies potential *hazards*, defined as events, or chains of events, that might result in an *effect* (change in the quality and/or quantity of surface water or groundwater). Only hazards identified through the IMEA process are considered further in the BA. Additionally, the IMEA considers all the possible ways in which activities may lead to effects or impacts, before assessing the severity, likelihood and detectability of such impacts under current controls through structured scoring.

Key to an IMEA is identifying *activities*, planned events associated with a CSG operation or coal mine. Activities are grouped into *components*, which are grouped into *life-cycle stages*. It is important to assign activities to their appropriate life-cycle stage because the scale and duration of similar activities can be different for each life-cycle stage, which is reflected in the scores for severity and/or likelihood of the impacts resulting from these activities.

Activities for CSG operations are separated into five life-cycle stages and four components:

- life-cycle stages: (i) exploration and appraisal, (ii) construction, (iii) production, (iv) decommissioning, and (v) work-over
- components: (i) wells, (ii) processing facilities, (iii) pipelines, and (iv) roads and infrastructure.

Activities for open-cut coal mines are separated into five life-cycle stages and three components:

- life-cycle stages: (i) exploration and appraisal, (ii) development, (iii) production, (iv) closure, and (v) rehabilitation
- components: (i) open pit, (ii) surface facilities, and (iii) infrastructure.

An *impact cause* is an activity (or aspect of an activity) that initiates a hazardous chain of events. An activity can have undesirable effects (such as water and gas extraction that unintentionally reduces groundwater pressure to unacceptable levels) or desirable effects (such as reinjection of co-produced water to restore groundwater pressure in a heavily utilised aquifer).

An *impact mode* (column 4 in Table 17) is the manner in which a hazardous chain of events could result in an effect. There might be multiple impact modes for each activity or chain of events. The impact modes may arise through various mechanisms, including anthropogenic activities that are planned and expected to occur as part of operations; unplanned events due to human error or infrastructure failure; or through combination with external factors (e.g. heavy rainfall or floods).

Examples are illustrated in Figure 5 (Section 2.3.1):

- An example for open-cut coal mines (Figure 5(a)) is initiated with the activity 'dewatering down to coal seam for an open-cut mine', which is the impact cause. The impact mode ('intentional dewatering down to coal seam') leads to the effect ('change in groundwater quantity (drawdown)'), which in turn may result in an ecological impact, 'reduced groundwater availability for a groundwater-dependent ecosystem'.
- An example for CSG operations (Figure 5(b)) is initiated with the activity 'corridor or site vegetation removal for CSG operations or coal mine', which is the impact cause. Subsequent events ('rainfall event' and 'soil erosion') then combine to form the impact mode ('soil erosion following heavy rainfall') that leads to multiple effects ('change in surface water quantity and surface water quality') and associated stressors ('surface water flow' and 'total suspended solids (TSS)'). In turn, this may cause an ecological impact, 'change of condition of habitat for a given species'.

Participants in the IMEA workshops were invited to identify all plausible hazards and impact modes on an activity-by-activity basis, together with the potential hydrological effects on groundwater and/or surface water. Each hazard is scored with respect to the severity, likelihood and time to detection. The IMEA elicits an interval (upper and lower score) for each hazard that all workshop participants agree upon:

- The *severity score* describes the magnitude of the impact resulting from a hazard, which is scored so that an increase (or decrease) in score indicates an increase (or decrease) in the magnitude of the impact.
- The *likelihood score* describes the annual probability of a hazard occurring, which is scored so that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the probability of occurrence.
- The *detection score* describes the expected time to discover a hazard, scored in such a way that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the expected time (measured in days) to discover it.

Two overarching hazard ranking scores are calculated:

- *hazard score*, the sum of the severity score and likelihood score
- *hazard priority number*, the sum of severity score, likelihood score, and detection score.

It is important to emphasise that despite the use of severity scores and likelihood scores, the hazard ranking scores do not provide an absolute or even relative measure of risk. IMEA provides a relative rank of hazards. The value of this analysis lies in the systematic and thorough identification of hazards and in their ranking relative to each other. Hazards with higher scores do not imply that the risks associated with those potential hazards are in some way significant or apply equally across the Clarence-Moreton bioregion at all times, only that it is important that these hazards (along with many others) are considered for inclusion in the BA.

There is considerable structure and hierarchy within these lists of IMEA hazards (Bioregional Assessment Programme, Dataset 1) with the finer-level hazards aggregating to successively coarser resolutions. For example, there are a range of activities as part of CSG operations that may require the removal of site vegetation (the impact cause), including the creation of pipeline networks, storage ponds, site processing plants, water treatment plants, ground-based geophysics and the construction of access roads; these may all potentially result in changes to surface water quality from soil erosion following heavy rainfall (impact mode).

The hazards identified by the IMEA represent a conceptual model of the chain of events that begins with an activity and ends with a potential impact on groundwater or surface water; causal pathways include these chains of events and also extend to resulting ecological impacts (see Figure 5). Causal pathways are considered for CSG operations and open-cut coal mines separately, for both the baseline coal resource development (baseline) and the coal resource development pathway (CRDP). A full suite of generic causal pathways for hazards due to coal mines and CSG operations is presented in figures in an appendix in companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016). These figures identify activities, impact causes and impact modes as well as those aspects of surface water and groundwater that might be affected. The causal pathways in the submethodology are generally applicable to all subregions or bioregions; Section 2.3.5 presents specific results for the Clarence-Moreton bioregion.

Hazards are grouped for the Clarence-Moreton bioregion if they have the same causal pathways, even if those hazards occur because of different activities, at different life-cycle stages, or at different intensities. This smaller set of causal pathway groups provides a useful starting point for summarising and representing the causal pathways associated with coal resource development (e.g. through influence diagrams) and focusing on those causal pathways that are in scope for BA.

The spatial footprint for the identified hazards and causal pathways identified is a core focus of the conceptual modelling, and is arrived at on the basis of existing knowledge, scientific logic and preliminary hydrological modelling results. An important aspect of this is using those same sources to identify which landscape classes and assets may be affected by a potential hydrological change that arises from those causal pathways, and (equally importantly) which landscape classes and assets will *not* be affected. Throughout the BA, areas that will not be affected are progressively ruled out in order to focus efforts of the Assessment team and ultimately the impact and risk analysis.

2.3.5.2 Hazard analysis

2.3.5.2.1 Coal seam gas operations

A hazard analysis was conducted for the Clarence-Moreton bioregion based on the proposed CSG operations and associated water management. The assessment of geology and hydrogeology demonstrated that there is no hydraulic connection between the Richmond river basin and the Bremer river basin, where the only existing baseline coal mine (Jeebropilly Mine) is located. Consequently, potential hazards associated with coal mines were not considered in the BA for the Clarence-Moreton subregion. The hazard analysis for the Clarence-Moreton bioregion was completed during a one-day workshop in May 2015 with experts from CSIRO and the Office of Water Science.

A total of 226 CSG-related activities were identified and scored in the Clarence-Moreton bioregion; these are all activities identified during the IMEA (Bioregional Assessment Programme, Dataset 1). However, the results are based on a subset of activities with complete scores. The 30 highest ranking hazardous activities and impact modes based on hazard score and hazard priority number midpoints are shown in Figure 36. In Table 17, the 30 highest ranked potentially hazardous activities are explained in more detail, and grouped according to different criteria as explained herein:

Impact mode: refers to the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There may be multiple impact modes for each activity or chain of events. In order to better understand the impacts of different activities associated with CSG operations on water-dependent assets, those activities were grouped according to different impact modes. ‘Disruption of natural surface water drainage’ was the most frequently identified hazard in the top 30 hazards (9 times), with ‘Soil erosion following heavy rainfall’ being potentially important in this context. Disruption of natural surface drainage was identified as hazardous as it may lead to impacts on the direction, volume or quality of surface water.

Causal pathway: describes the logical chain of events – planned or unplanned– between coal resource development to changes in groundwater or surface water, and then to impacts on water-dependent assets. This category (column 5 in Table 17) further simplifies the groupings from the ‘Impact mode’ category into major causal pathways.

Effects: refers to potentially undesirable changes (impacts) caused by CSG activities on the quality or quantity of a groundwater or surface water resource (column 6 in Table 17). Impacts relating to groundwater manifest themselves as changes to groundwater quality, groundwater pressure or aquifer properties whereas those relating to surface water may affect the flow regime, surface water quality and volume. Out of the 226 potentially hazardous activities, 118 are related to surface water and 47 are related to groundwater with some relating to both. An activity can have undesirable effects such as water and gas extraction that reduces groundwater pressure, or desirable effects such as the reinjection of co-produced water that restores groundwater pressure.

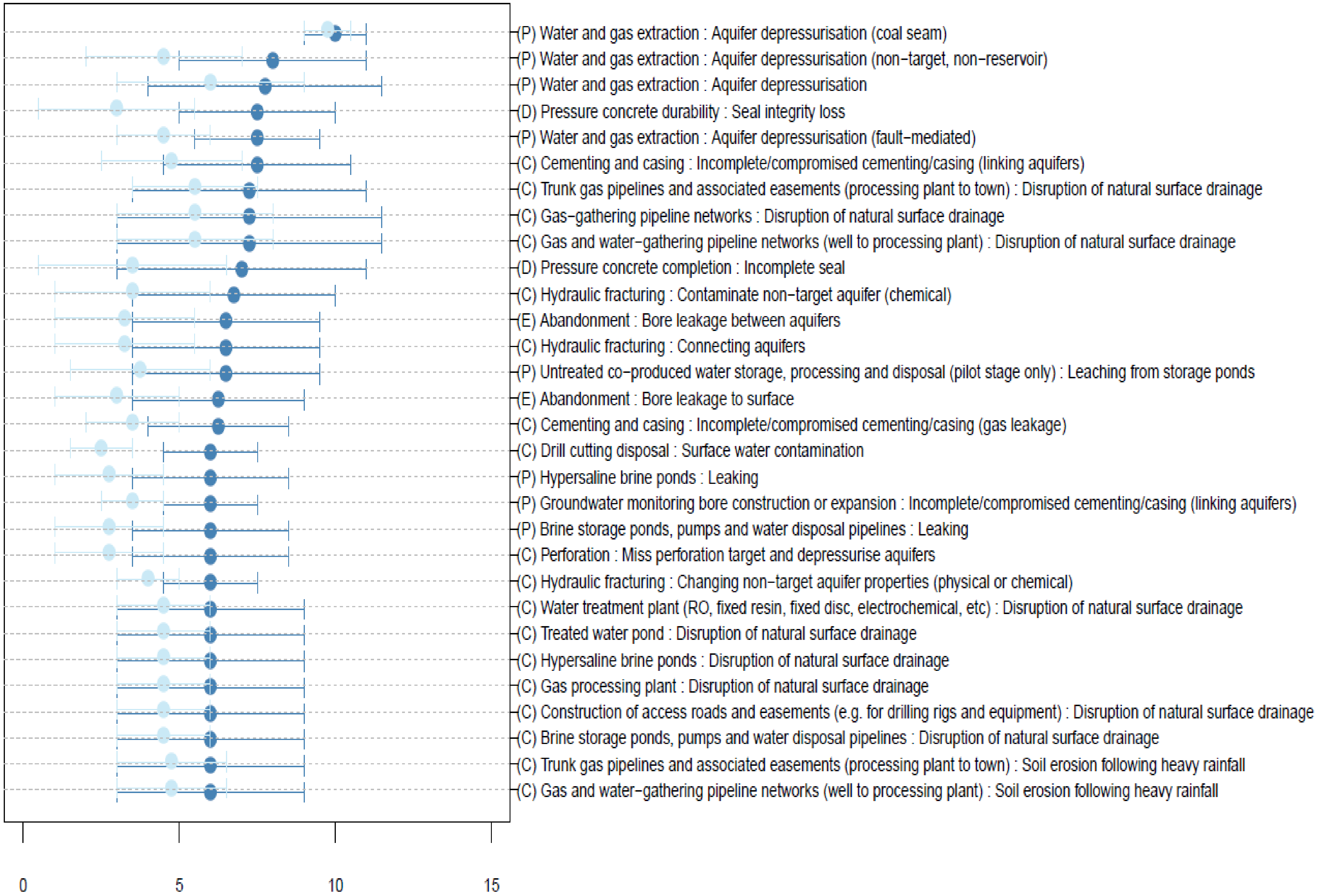

Figure 36 Highest ranked hazards for coal seam gas (CSG) operations ranked by hazard priority number midpoint in the Clarence-Moreton bioregion (based on Ford et al., 2016)

The x-axis shows the hazard priority number and hazard score. The interval between the highest and lowest hazard priority number are shown in dark blue, and the hazard score intervals are shown in light blue. The same hazard may appear multiple times, as it may arise from a number of different life cycles and activities. Life-cycle stages are indicated by (E) for exploration and appraisal, (P) for production, (D) for decommissioning and (C) for construction.

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

Table 17 Top 30 hazardous coal seam gas (CSG) activities and associated impact modes and causal pathways for the Clarence-Moreton bioregion

Lower-ranking hazards that are in scope are also considered in the bioregional assessment. The full list of identified hazards is included in Bioregional Assessment Programme (Dataset 1).
[a]Life-cycle stages are indicated by (C) for construction, (E) for exploration and appraisal, (P) for production, (D) for decommissioning and (W) for work-over.
[b]The activities are listed in order of their ranking (Figure 36)

Component	Life-cycle stage[a]	Activity[b]	Impact mode	Causal pathway	Effect
Wells	P	Water and gas extraction	Aquifer depressurisation (coal seam)	Groundwater extraction causal pathway	GW pressure
Wells	P	Water and gas extraction	Aquifer depressurisation (non-target, non-reservoir)	Groundwater extraction causal pathway	GW pressure
Wells	P	Water and gas extraction	Aquifer depressurisation	Groundwater extraction causal pathway	GW flow (reduction)
Wells	D	Pressure concrete durability	Seal integrity loss	Well integrity causal pathway	GW quality
Wells	C	Cementing and casing	Incomplete/compromised cementing/casing (linking aquifers)	Well integrity causal pathway	GW quality
Wells	P	Water and gas extraction	Aquifer depressurisation (fault-mediated)	Groundwater extraction causal pathway	GW pressure
Processing	C	Gas-gathering pipeline networks	Disruption of natural surface drainage	Surface drainage causal pathway	SW volume, SW quality
Pipelines	C	Trunk gas pipelines and associated easements (processing plant to town)	Disruption of natural surface drainage	Surface drainage causal pathway	SW volume, SW quality, GW quantity
Pipelines	C	Gas and water-gathering pipeline networks (well to processing plant)	Disruption of natural surface drainage	Surface drainage causal pathway	SW volume, SW quality, GW quantity
Wells	D	Pressure concrete completion	Incomplete seal	Well integrity causal pathway	GW quality, GW pressure
Wells	C	Hydraulic fracturing	Contaminate non-target aquifer (chemical)	Hydraulic fracturing causal pathway	GW quality
Wells	P	Untreated co-produced water storage, processing and disposal (pilot stage only)	Leaching from storage ponds	Water management causal pathway	GW quality

Component	Life-cycle stage[a]	Activity[b]	Impact mode	Causal pathway	Effect
Wells	E	Abandonment	Bore leakage between aquifers	Well integrity causal pathway	GW composition, GW quality, GW pressure
Wells	C	Hydraulic fracturing	Connecting aquifers	Hydraulic fracturing causal pathway	GW composition, GW quality, GW pressure
Wells	E	Abandonment	Bore leakage to surface	Well integrity causal pathway	SW quality
Wells	C	Cementing and casing	Incomplete/compromised cementing/casing (gas leakage)	Well integrity causal pathway	GW quality
Wells	W	Waste disposal	Surface water contamination	Water management causal pathway	SW quality
Wells	C	Drill cutting disposal	Surface water contamination	Water management causal pathway	SW quality
Pipelines	C	Trunk gas pipelines and associated easements (processing plant to town)	Soil erosion following heavy rainfall	Water management causal pathway	SW quality
Processing	P	Hypersaline brine ponds	Leaking	Water management causal pathway	SW quality, GW quality
Processing	P	Brine storage ponds, pumps and water disposal pipelines	Leaking	Water management causal pathway	SW quality, GW quality
Wells	C	Perforation	Miss perforation target and depressurise aquifers	Well integrity causal pathway	GW pressure, GW quality
Wells	P	Groundwater monitoring bore construction or expansion	Incomplete/compromised cementing/casing (linking aquifers)	Well integrity causal pathway	GW composition, GW quality
Roads and infrastructure	C	Construction of access roads and easements (e.g. for drilling rigs and equipment)	Disruption of natural surface drainage	Surface drainage causal pathway	SW direction, SW volume, SW quality
Processing	C	Water treatment plant (RO, fixed resin, fixed disc, electrochemical, etc.)	Disruption of natural surface drainage	Surface drainage causal pathway	SW volume, SW quality
Processing	C	Treated water pond	Disruption of natural surface drainage	Surface drainage causal pathway	SW volume, SW quality
Processing	C	Hypersaline brine ponds	Disruption of natural surface drainage	Surface drainage causal pathway	SW volume, SW quality
Processing	C	Gas processing plant	Disruption of natural surface drainage	Surface drainage causal pathway	SW volume, SW quality

Component	Life-cycle stage[a]	Activity[b]	Impact mode	Causal pathway	Effect
Processing	C	Brine storage ponds, pumps and water disposal pipelines	Disruption of natural surface drainage	Surface drainage causal pathway	SW volume, SW quality, GW quantity
Wells	C	Hydraulic fracturing	Changing non-target aquifer properties (physical or chemical)	Hydraulic fracturing causal pathway	Aquifer properties

2.3.5.2.2 Hazard handling and scope

A comprehensive list of hazards has been generated for CSG operations as part of the hazards workshop, as described in Section 2.3.5.2.1. This section describes the scope of subsequent work, which addresses only a subset of the full list of hazards.

The hazards of primary focus from a BA perspective are those that extend beyond the development site and that may have cumulative impacts. This is consistent with the regional focus of BA, and it is where BA will add value beyond site-specific environmental impact statements (EIS). Ultimately, however, BAs need to be able to address all identified hazards by considering the scope, modelling, other literature or narratives, and specifying where science gaps may exist.

BAs are constrained by considering only impacts that can happen via water; thus, hazards such as dust, fire or noise are out of scope and are addressed by site-based risk management unless there is a water-mediated pathway.

Leading practice is assumed and accidents are considered to be covered adequately by site-based risk management procedures and are beyond the scope of BA; for example, the failure of a pipeline is covered by site-based risk management.

Hazards that pertain to the development site and with no off-site impacts are important to acknowledge but will typically be addressed by site-based risk management procedures.

For CSG operations, the following hazards are considered out of scope in the Clarence-Moreton bioregion because they are covered by site-based risk management and regulation and do not have plausible cumulative effects on water in the subregion:

- abandonment practice
- hazards addressed by site management and where no water-mediated pathway exists (e.g. dust, fire or noise)
- containment failure due to construction or design
- disruption of surface drainage network for site-based infrastructure, plant and facilities, roads, creek crossings
- equipment/infrastructure failure (e.g. pipeline failures)
- leaching/leaking from storage ponds and stockpiles
- spillages and disposals (e.g. diesel, mud, cuttings or fluid recovery)
- vegetation clearance and subsequent soil erosion following heavy rainfall.

The hydrological effect of an activity such as 'water and gas extraction' depends on the impact cause and impact mode. For example, 'depressurisation' (impact cause) that causes 'subsidence' (impact mode) may affect 'surface water direction' (hydrological effect) and 'aquitard leaks' (impact cause) that cause 'non-target, non-reservoir aquifer depressurisation' (impact mode) affects 'groundwater pressure' (hydrological effect).

Hydrological effects associated with CSG operations that are considered to be in scope in the Clarence-Moreton bioregion are:

- surface water quality
- surface water direction
- surface water flow
- groundwater quality
- aquifer properties
- groundwater composition
- groundwater flow (reduction)
- groundwater level
- groundwater pressure

In Table 17, various impact modes were identified, many of which shared similar causal pathways. Consequently, four major causal pathway groups that cover the entire top 30 potential hazards associated with CSG operations in the Clarence-Moreton bioregion were identified:

- 'Subsurface depressurisation and dewatering' causal pathway group. The hazard analysis identifies impacts on aquifers associated with depressurisation of the Walloon Coal Measures (the aquifer which hosts the CSG resources) as the highest ranked hazard associated with CSG operations in the Clarence-Moreton bioregion. For example, the hazard analysis identifies the following ways in which aquifers may be impacted: depressurisation of the Walloon Coal Measures (an intended activity conducted to reduce the hydrostatic pressure in the coal seams) and depressurisation of overlying aquifers (non-CSG target and non-reservoir).
- 'Subsurface physical flow paths' causal pathway group. Activities related to well construction and abandonment also rate as high-priority hazards and are identified seven times in the top 30 during different phases of the CSG life cycle (e.g. exploration, construction or production). Examples of potential impact modes associated with well construction and abandonment include the loss of seal integrity due to the sustained pressure on concrete and incomplete cementing and casing, which could potentially link aquifers and aquitards. Hydraulic fracturing is only identified twice in the top-ranking 30 hazards. Potential hazards related to hydraulic fracturing that were identified include the contamination of non-target aquifers as well as a change of their hydraulic properties.
- 'Operational water management' causal pathway group. This causal pathway group includes impact modes that relate to hazards resulting from activities such as the disposal of waste water.

- 'Surface water drainage' causal pathway group. The potential impact modes associated with the construction of infrastructure include activities such as the construction of pipelines, access roads and gas processing plants. These were classified as high-priority hazards.

2.3.5.3 Causal pathways

In the Clarence-Moreton bioregion, the only potential development that has been identified as likely within the time frames considered for the BA is Metgasco's West Casino Gas Project (Raiber et al., 2014). There are no existing CSG developments in the Clarence-Moreton bioregion as outlined in Section 2.3.2. There is no hydraulic connection between the Richmond river basin and the Bremer river basin, where the only baseline coal mine (Jeebropilly Mine) is located. Due to lack of hydraulic connection between the baseline coal mine and the only additional coal resource development (Metgasco's West Casino Gas Project in the Richmond river basin) (Section 2.3.2), it is scientifically justifiable to not model the baseline mine, and instead focus on West Casino Gas Project.

2.3.5.3.1 Coal seam gas operations

Hazards associated with CSG operations that are considered to be in scope for BA in the Clarence-Moreton bioregion are aggregated into four primary causal pathway groups. These four causal pathway groups represent a conceptual model of the chain of events that begins with an activity and ends with a potential impact on a groundwater or surface water dependent asset.

In this section, the four causal pathway groups associated with CSG activities are described to provide bioregion-specific context and show how different components of the hydrological system may be affected by potential CSG activities. The causal pathways are explained using a cross-section based on the three-dimensional geological model (presented in Section 2.3.2) through the area of potential CSG development in the Richmond river basin. The arrows on the diagrams highlight the potential causal pathways. The colours of hydrostratigraphic units correspond to the colours in the three-dimensional geological models and cross-sections of the Richmond river basin (Section 2.3.2).

2.3.5.3.1.1 'Subsurface depressurisation and dewatering' causal pathway group

This group of causal pathways arises when coal mines and coal seam gas (CSG) operations intentionally dewater (in case of coal mines) and depressurise (in case of CSG operations) subsurface hydrostratigraphic units (such as coal seams and aquifers) to permit coal resource extraction. Dewatering applies to coal mines and will not be discussed further here. CSG operations involve groundwater extraction during the appraisal and production stages that aims to depressurise the Walloon Coal Measures to reduce hydrostatic pressure and facilitate gas release. In the Richmond river basin, the top of the Walloon Coal Measures is typically at a depth of about 400 to 700 m below surface. In addition to the intended flow of water within the seams towards the extraction wells, the declining water pressure results in pressure gradients that can potentially perturb the natural flow paths with potential impacts on the quantity and quality of groundwater (due to a change in inter-aquifer connectivity, Figure 37), as well as surface water (due to a change in surface water – groundwater interaction, Figure 37). In addition, water availability from overlying aquifers such as the Kangaroo Creek Sandstone that could lie within the depression cone (resulting from the abstraction) may be compromised (e.g. due to the reduced pressure). Those impacts may occur either on a point, local or regional scale and the presence and temporal variability of impacts is a function of aquifer composition, aquifer diffusivity and the presence or absence of aquitards and geological structures.

There is generally a declining likelihood of impact further away from the extraction well, both in the vertical and horizontal directions. That is, maximal impact is expected proximal to the extraction well in the Maclean Sandstone (upper part of the Walloon Coal Measures), which overlies the coal seams of the Walloon Coal Measures, and minimal impact in the alluvium and the Lamington Volcanics, which occur much farther away from the extraction well (Figure 37). As diffusivity decreases, the response of the groundwater system slows, which means that maximal drawdown takes longer to be attained. The final shape of the depression cone is a function of aquifer transmissivity, with highly transmissive aquifers having steeper cones where the drawdown is more confined near the extraction well.

The role of subsurface architecture and geological structure is important, especially the presence or absence of aquitards and faults, the location of faults relative to the extraction wells, fault displacements, the hydraulic role of faults as either barriers or conduits to flow and the composition and hydraulic properties of any fault-related infill material. For example, the Maclean Sandstone is a regional aquitard that can potentially prevent or limit the wider impacts of groundwater extraction from the Walloon Coal Measures, which may otherwise affect groundwater pressures in the Kangaroo Creek Sandstone. The Bungawalbin Member, also an aquitard, may further reduce or prevent propagation of impacts to shallow aquifers. Consequently, the integrity and continuity of such aquitards is paramount. Where faults or fractures are present, the pressure change can be transmitted much quicker and with potential impacts that may extend to the uppermost alluvial aquifer. However, this depends on the fault zone characteristics and the geometry of the geological compartments defined by the faults or fractures. Furthermore, it may be possible that prolonged depressurisation will reactivate a fault pathway, and thus create a pathway that was not active prior to the aquifer depressurisation.

If the extraction impacts extend all the way up to the alluvial aquifer, they might influence river recharge. Although this is likely to be of no or very minor consequence during normal and high-flow conditions (i.e. it is likely to be undetectable) and unlikely to have any impacts on major river systems such as the Richmond River due to the high flow rates described in Section 2.3.2, it could alter the low flow regime of smaller tributaries such as Shannon Brook with potential adverse impacts on water-dependent assets. Furthermore, declining watertable levels in the alluvial aquifer may influence the viability and function of groundwater-dependent ecosystems. The co-produced water, which varies in quantity and quality, when returned to the river after treatment has potential management implications that are discussed in the ‘Operational water management’ causal pathway.

The spatial and stratigraphic extent of drawdown caused by groundwater extraction from the coal seam can be assessed using numerical groundwater models. In the Clarence-Moreton bioregion, a numerical groundwater model is developed for the Richmond river basin, and the results of this model are reported in companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016).

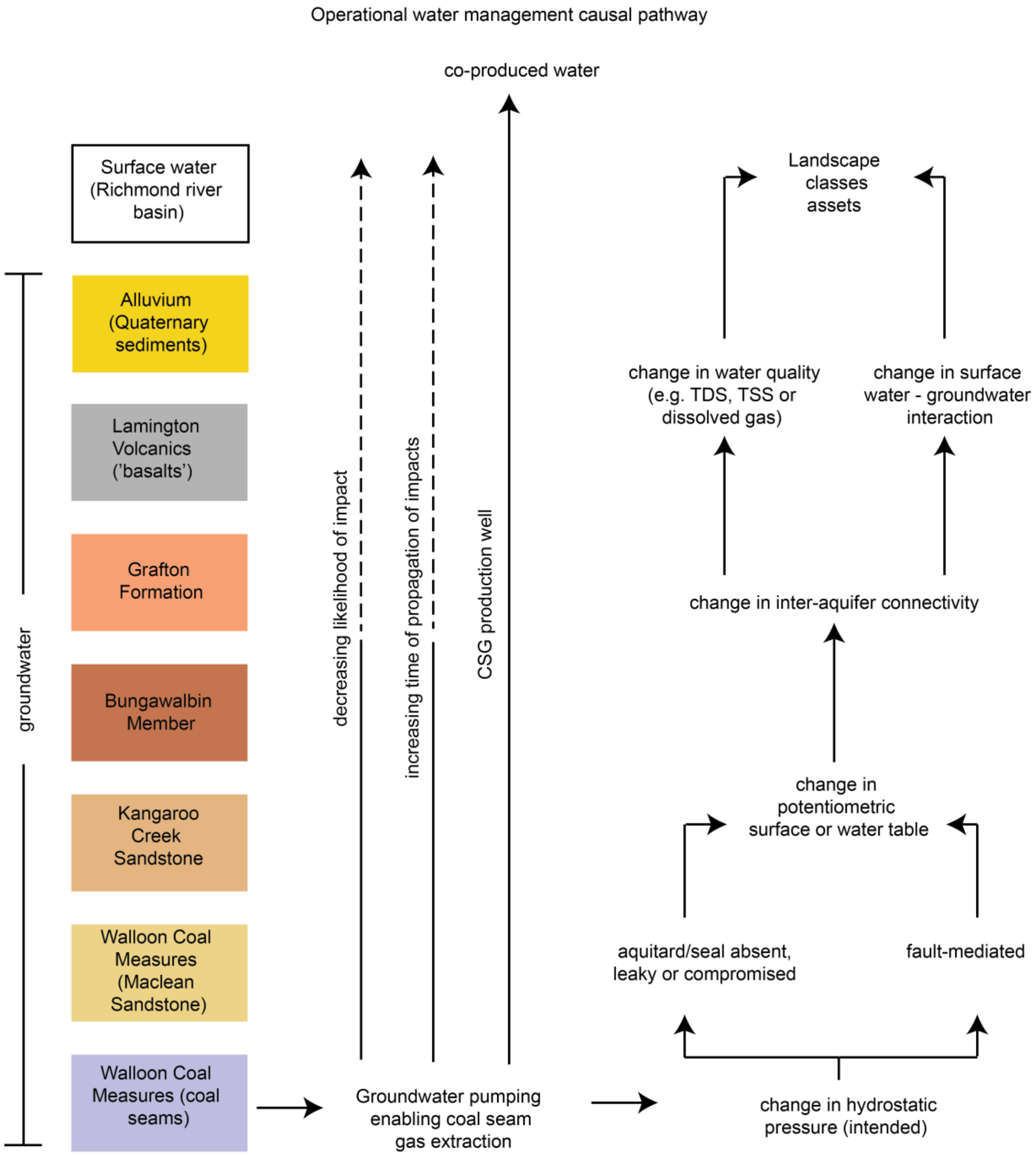

Figure 37 'Subsurface depressurisation and dewatering' causal pathway group – 'Groundwater extraction' causal pathway for coal seam gas operations in the Clarence-Moreton bioregion

Dewatering applies to coal mines and, given that no coal mines are being modelled in the baseline or CRDP in the Clarence-Moreton bioregion, it will not be discussed further in relation to the Clarence-Moreton bioregion.
CSG = coal seam gas, gw corresponds to groundwater; sw corresponds to surface water; TDS corresponds to total dissolved solids; TSS corresponds to total suspended solids

2.3.5.3.1.2 'Subsurface physical flow paths' causal pathway group

One of the main activities of CSG operations is the drilling of wells that extend to the depth of the target coal seams or gas reservoirs (Figure 38). Wells are drilled during the exploration and appraisal phase to evaluate the potential commercial viability of the CSG resources, and during the production phase to depressurise the target coal seams and extract the identified gas resources. In addition, groundwater bores are installed to monitor potential impacts of CSG activities on groundwater levels or groundwater quality.

Maintaining well integrity throughout construction, operation and decommissioning phases is crucial to ensuring sustainable gas production and avoiding adverse environmental impacts. Throughout these stages of the CSG life cycle, preserving well integrity is required to prevent the inter-aquifer mixing of fluids (liquid or gas) and pressure changes, as well as preventing fluids escaping to the surface. Incomplete and/or compromised casing and seals (e.g. through degradation of the well casing or sealing material) could introduce preferential flow pathways along the well path. This newly introduced preferential pathway would have the potential to connect any two or more consecutive or non-consecutive geological layers up to land surface. The same causal pathway also exists for groundwater observation bores and other groundwater bores.

Potential impacts include the escape of gas from the coal seams to the overlying geological layers and potentially to the atmosphere (fugitive emissions). In addition, inter-aquifer mixing could potentially locally compromise the water quality of some aquifers such as the Kangaroo Creek Sandstone and the alluvial aquifer; adverse impacts on surface water systems are thought to be minimal due to the limited scale of the impact.

Leading practice is assumed for the construction and decommissioning of wells, and the impacts associated with compromised well integrity are likely to be of a local scale as the volume of water leakage is likely to be very small. Impacts resulting from a compromised well integrity are therefore limited to the vicinity (<1 km) of the compromised well although such impacts will continue until remedial actions are taken.

More general background on well integrity is provided by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC, 2014a).

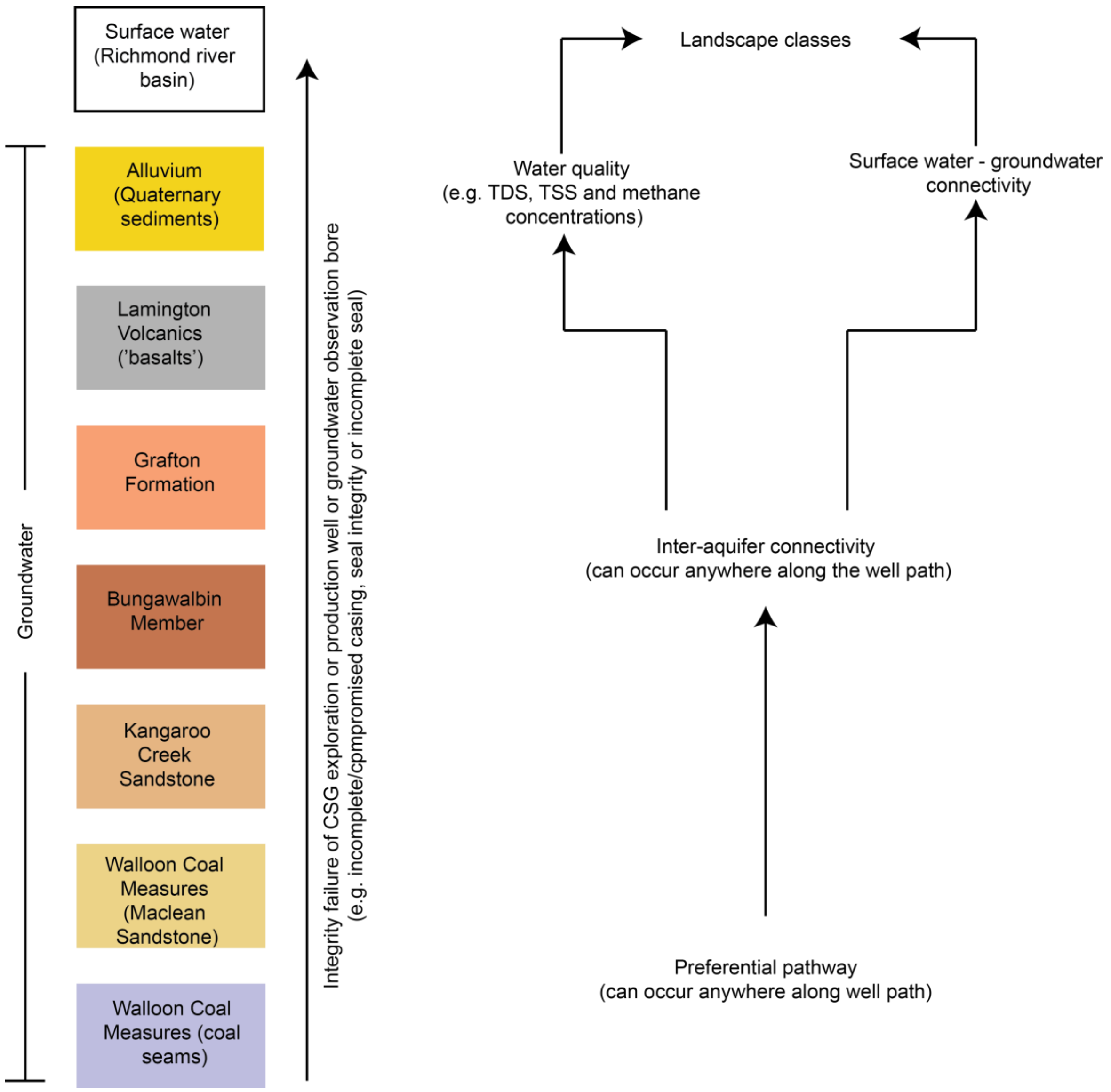

Figure 38 'Subsurface physical flow paths' causal pathway group – 'Failure of well integrity' causal pathway for coal seam gas operations in the Clarence-Moreton bioregion

CSG = coal seam gas, TDS corresponds to total dissolved solids, TSS corresponds to total suspended solids

Hydraulic fracturing (or aquifer stimulation) is designed to increase the permeability within the target coal seams and enhance release and gas flow from the coal seams towards the well through these newly created fractures. The process of hydraulic fracturing during the production life-cycle stage of CSG operations involves high pressure injection of a 'hydraulic fracturing fluid system'. These fluids typically consist of a slurry of water, proppant (a granular material that prevents the produced fractures from closing after the fracturing treatment) and chemical additives.

The water used for this process can either be sourced directly from a nearby river or from an alluvial aquifer; the potential associated impacts are similar to those discussed in the 'Operational water management' causal pathway group.

The intended impact of changing aquifer properties, when conducted properly, would be expected to be limited to the coal seams with a much smaller risk of impacting neighbouring aquifers or aquitards, such as the Maclean Sandstone. The lateral extent to which aquifer properties are changed diminishes further away from the well. No fracture monitoring data for the Richmond river basin are publicly available. However, Johnson et al. (2010) present some examples on the propagation of fractures from the Walloon Coal Measures in the linked Surat Basin. In these examples, in more than 50% of wells where an assessment was conducted, the fractures did not propagate above or below the perforated coal seam interval. Furthermore, where vertical propagation of fractures occurred, there were no reported cases where fractures propagated out of the coal measure and the maximum horizontal propagation that was recorded was 245 m.

Therefore, the scale of this impact is mainly dependent on the number of wells where this process is implemented. Due to the foreign materials added to the water used for hydraulic fracturing, the water quality of the perforated coal seams will be compromised, with a much smaller risk of contaminating neighbouring aquifers since it is a planned and well-monitored operation.

At the end of the fracturing procedure, hydraulic fracturing fluid is recovered from the coal seams (referred to as flowback) to desorb gas and permit its extraction to the surface. The recovered hydraulic fracturing fluid water has potential impacts similar to those discussed in the 'Operational water management' causal pathway group.

More details on the chemical composition of hydraulic fracturing fluids and their potential impacts on water-dependent assets are provided in the National Industrial Chemicals Notification and Assessment Scheme (NICNAS, *in press*). More general background on hydraulic fracturing is provided by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC, 2014b).

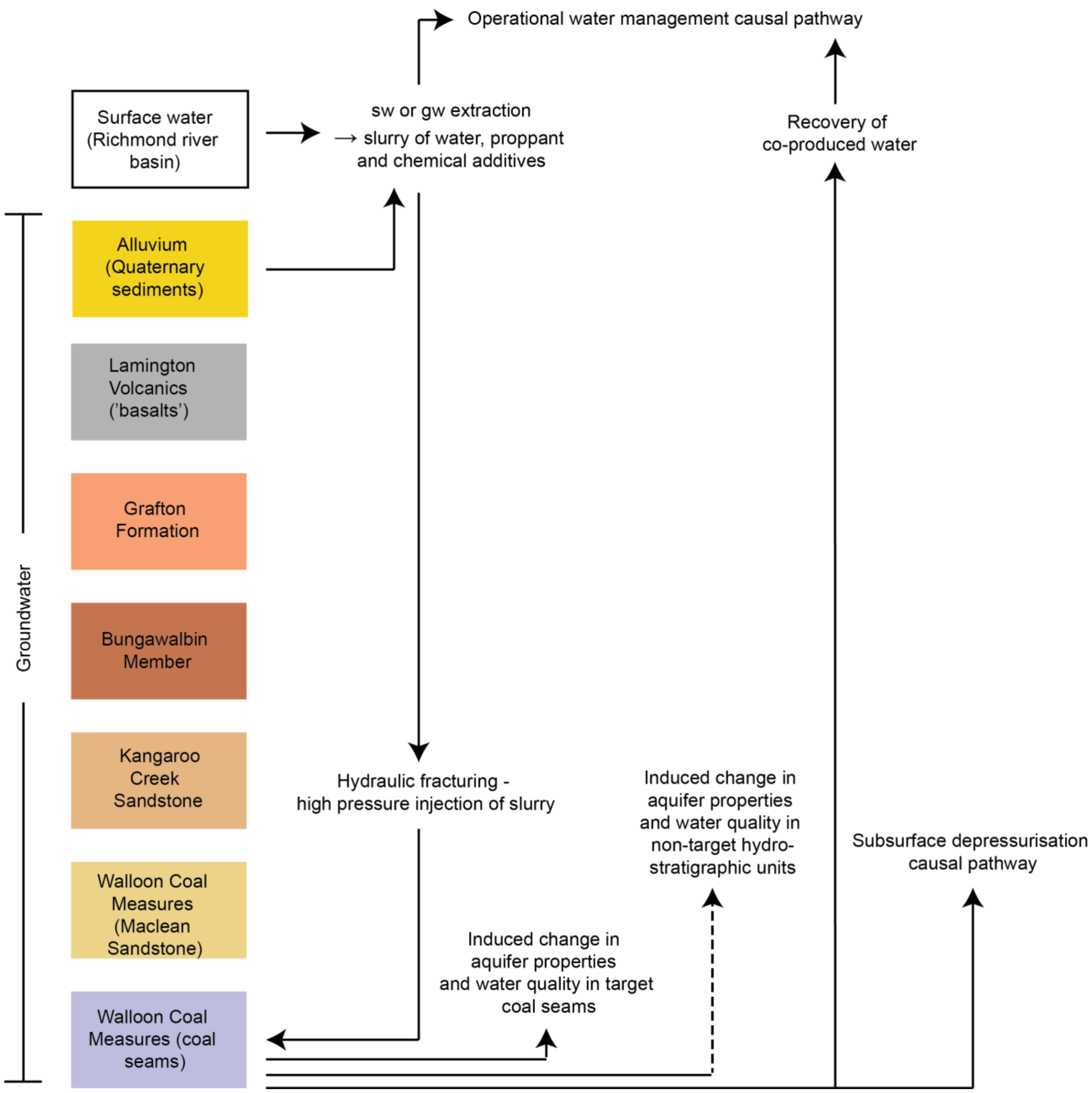

Figure 39 'Subsurface physical flow paths' causal pathway group – hydraulic fracturing causal pathway for coal seam gas in the Clarence-Moreton bioregion

gw corresponds to groundwater; sw corresponds to surface water; dashed line indicates that this process is unlikely to have any influence beyond the target coal seams

2.3.5.3.1.3 'Surface water drainage' causal pathway group

The depressurisation of coal seams and overlying aquifers increases the effective pressures, which could lead to a consolidation of the various geological layers. This may exhibit itself as slight subsidence at the surface, which has the potential of altering the natural surface water drainage pathways (Figure 40) (Coffey Geotechnics, 2013; IESC, 2014c). Depending on the size of the CSG operations, the impacts might be of a small local or larger scale. There are currently no model predictions of subsidence available for the Clarence-Moreton bioregion. However, as the number of wells and projected water extraction volumes in the Richmond river basin are small compared to the CSG fields in Queensland, it is likely that subsidence is minor.

The construction of pipelines or other surface infrastructure related to CSG activities has the potential to permanently alter surface water flow paths. In addition, vegetation clearing during the construction phase may enhance soil erosion (e.g. following heavy rainfall on newly cleared areas), which can adversely affect the quality of surface water runoff.

Effects on surface water direction, volume and quality can have medium-term (5 to 10 years) to long-term (10 to 100 years) cumulative effects on watercourses within and downstream of the additional coal resource development area.

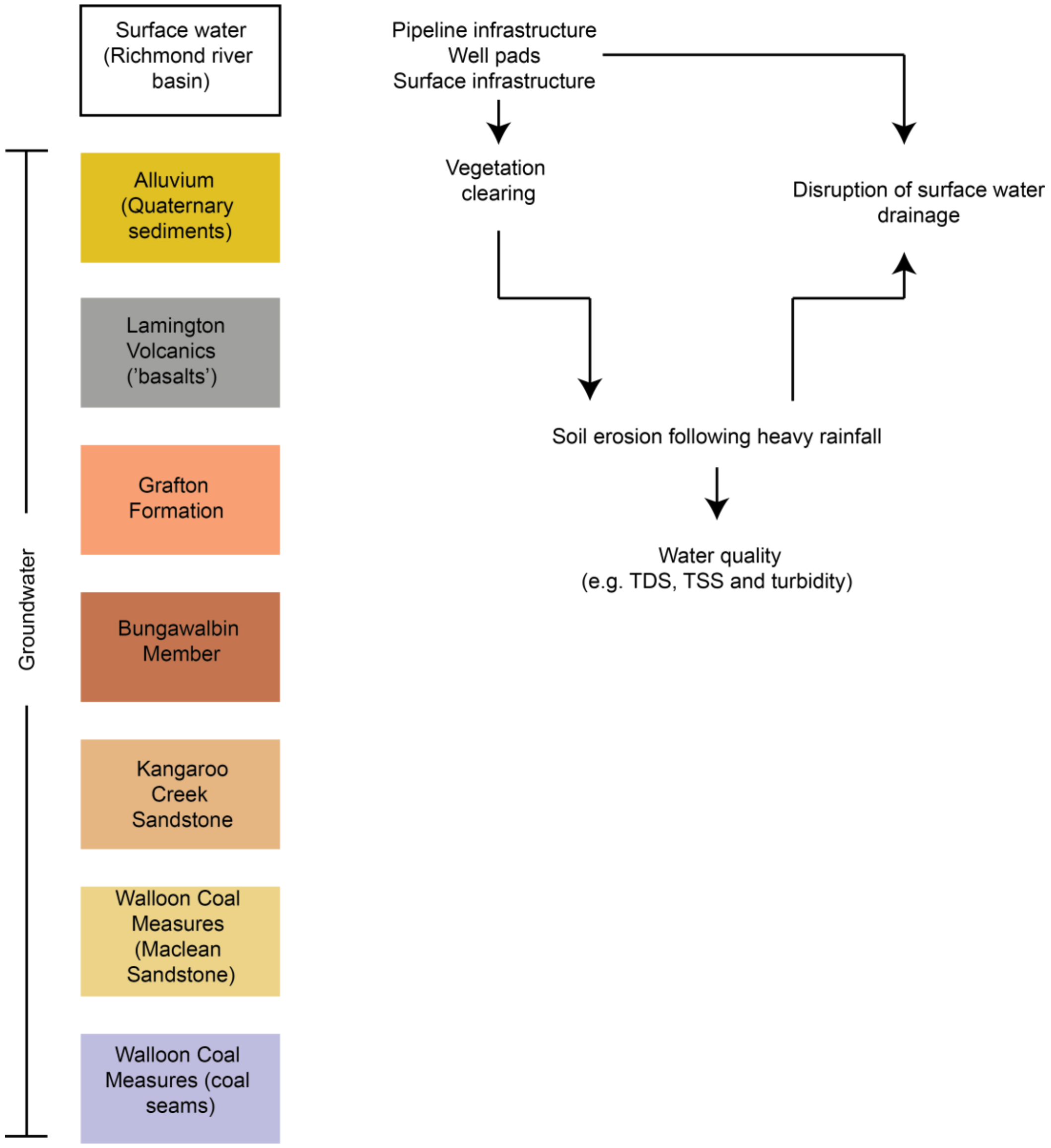

Figure 40 'Surface water drainage' causal pathway group for coal seam gas operations in the Clarence-Moreton bioregion

TDS corresponds to total dissolved solids; TSS corresponds to total suspended solids

2.3.5.3.1.4 'Operational water management' causal pathway group

CSG operations require water during different stages of the life cycle (e.g. for the construction of exploration and appraisal wells and for the construction of development wells). However, significant volumes of water can also be produced during the gas production stage, and ultimately need to be disposed of (Figure 41). The water needed for CSG activities can be sourced either from surface water or groundwater systems. Direct extraction from surface water features such as rivers could affect their flow regime depending on the volume of extraction relative to streamflow. On the other hand, groundwater extraction directly influences groundwater availability as well as watertable levels that could potentially alter surface water – groundwater interactions; the latter can reduce baseflow or enhance river recharge in hydraulically connected river–aquifer systems.

The co-produced water, mentioned in the 'Subsurface depressurisation and dewatering' causal pathway group, may be disposed of via various methods. It can be transported off-site and outside the bioregion, thus eliminating any impacts in the bioregion. After treatment, it can be reinjected to other aquifers in the groundwater system. This can restore groundwater pressures and change the volume and timing of groundwater discharge to springs and watercourses in aquifer outcrop areas (although this would require a large volume of water and is therefore very unlikely to occur in the Clarence-Moreton bioregion based on the conceptual hydrogeological understanding presented in Section 2.3.2). Reinjection can also change aquifer chemical composition, with the extent of water quality changes being limited by local hydraulic properties of conductivity, storativity and time.

Co-produced water can be used for agriculture (such as irrigation) after adequate treatment and amendment; its post-treatment quality should be such that it does not adversely affect soil properties and the water resource.

Alternatively, treated water can be pumped back to the rivers, with potential impacts on their flow regime and water quality. Discharge of co-produced water to rivers and for irrigation can affect watertable levels and soil salt mobilisation along watercourses and near irrigation areas.

Finally, the co-produced water can be directed to storage ponds, with infiltration to the groundwater system posing a water quality risk. Furthermore, containment failure of the storage pond could potentially spread the risk over a much larger area.

Currently, it is not known which treatment options would be preferred if CSG development proceeds in the Richmond river basin. Any treatment and disposal will be subject to NSW Environment Protection Authority regulations.

More general background on co-produced water is provided by the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC, 2014d).

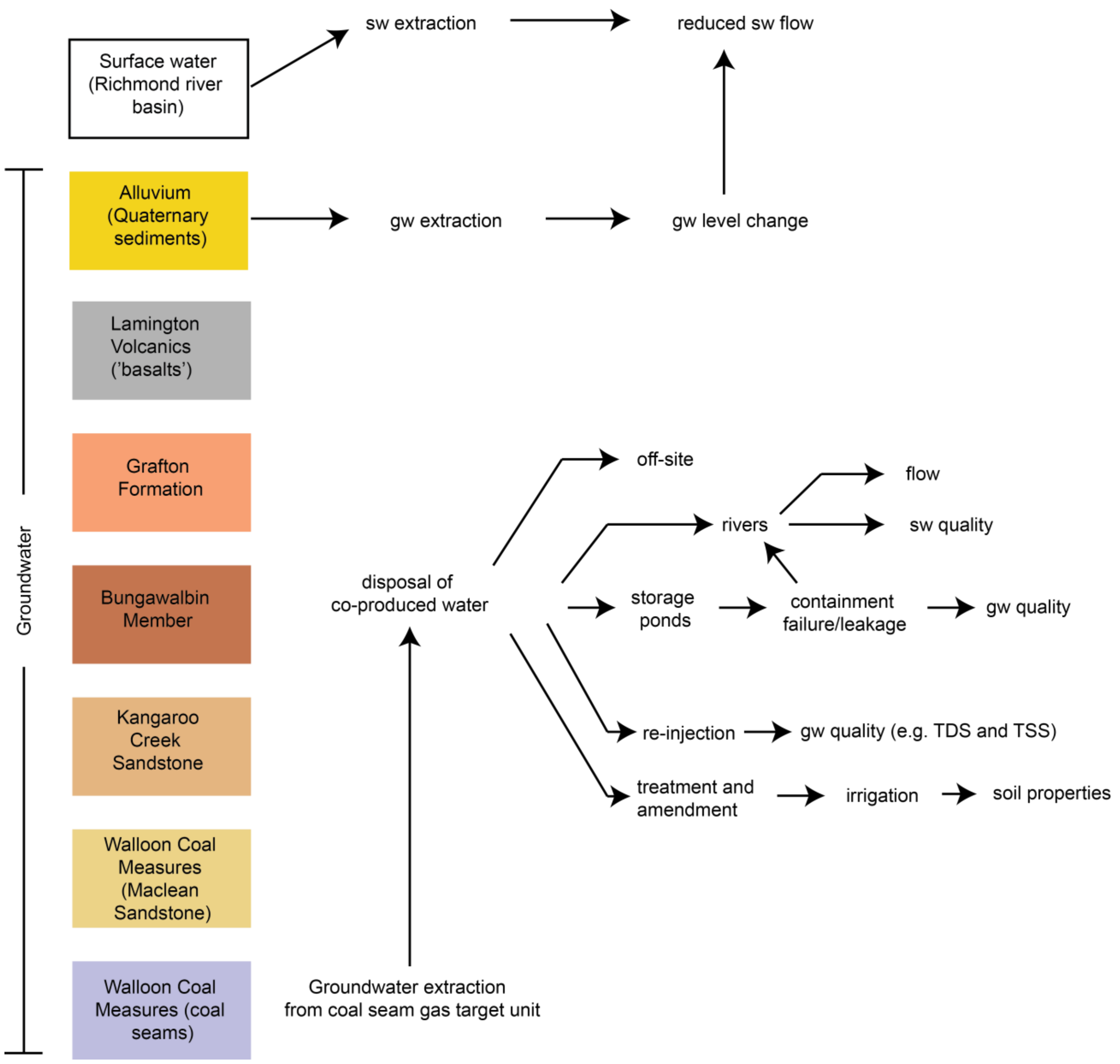

Figure 41 'Operational water management' causal pathway group for coal seam gas operations in the Clarence-Moreton bioregion

gw corresponds to groundwater; sw corresponds to surface water; TDS corresponds to total dissolved solids; TSS corresponds to total suspended solids

2.3.5.3.2 Outcomes and synthesis: linking causal pathways to potential impacts on water dependent assets for the coal resource development pathway

The integrated understanding of the geology, hydrogeology and surface water – groundwater interactions (Section 2.3.2) underpins the development of the numerical groundwater model reported in companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016). This model provides a quantitative assessment of the potential impacts of a CSG development in the Richmond river basin by providing estimates for potential drawdown and hence probabilities for exceeding certain thresholds that are identified by policy makers. This helps identify the direct impact that groundwater extraction has on economic assets and on groundwater-dependent ecosystems. Furthermore, the model estimates the potential changes in exchange fluxes between the surface and the groundwater systems, which will feed into the surface water models (reported in product 2.6.1 for the Clarence-Moreton bioregion (Gilfedder et al., 2016)) to calculate changes in flow indices that are critical in assessing potential impacts on surface water-dependent assets.

A qualitative impact assessment based on sound conceptual understanding of the system is warranted especially in the absence of numerical models (or in areas outside the model domain) and/or in cases where a full receptor impact analysis is not conducted. Knowledge of the geology, hydrogeology and surface water – groundwater interaction in the Richmond river basin provided the conceptual understanding for the identification of the major causal pathways, which were presented in Section 2.3.5.3.1. These causal pathways can support a qualitative assessment of the potential impacts on water-dependent economic, ecological and cultural assets. Hence, and based on this integrated conceptual understanding, an informed decision to classify various assets as either being potentially 'impacted' or 'not impacted' can be made.

The landscape classification introduced in Section 2.3.3 allowed the characterisation of the nature of water dependency among the diverse range of assets identified in the Clarence-Moreton bioregion. The causal pathways for CSG developments can be linked to the landscape classes identified in Section 2.3.3. Table 18 represents a conceptual framework that links various landscape classes with the identified four major causal pathway groups. Some of these landscape classes are exclusively related to groundwater, whereas others are related to surface water; some are related to both groundwater and surface water. Based on the conceptual understanding described in previous sections of this product that highlights how geology, hydrogeology, hydrology and ecology are related, a preliminary assessment was made on whether a particular landscape class can potentially be affected by a particular causal pathway or not. This allows the Assessment team to focus on landscape classes where the conceptual understanding of the Assessment team suggests that a causal pathway exists. Note that only the 'Subsurface depressurisation and dewatering' causal pathway group will be modelled in the Clarence-Moreton bioregion. Impacts that occur via other pathways will be addressed merely as commentary.

The criteria that were adopted to undertake this qualitative assessment relates to the following aspects: (i) the spatial scale of potential impact associated with each causal pathway, for example, 'Failure of well integrity' and 'Hydraulic fracturing' are associated with local impacts, whereas 'Subsurface depressurisation' is associated with large-scale impacts, (ii) issues related to geology and hydrogeology such as topographic relief, recharge/discharge processes, and connection between various geological formations, (iii) tidal influence, (iv) the explicit location of the landscape class relative to the additional coal resource development with special emphasis on whether it is located upstream or downstream of the additional coal resource development, and (v) whether the dependency is on surface water, on groundwater, or both. In order to demonstrate this process, several contrasting examples from Table 18 that highlight the link between various landscape classes and causal pathways are described in more detail below. Note that some landscape classes may extend spatially across a large area. Therefore for some landscape classes, the last column of Table 18 can include asset examples that may or may not be affected by CSG developments; in such cases, if any asset is classified as potentially impacted, then the landscape is marked with a 'Y' (i.e. indicating that there is a causal pathway).

- Example 1 ('Alluvium, high-energy upland, stream or river landscape class (landscape class number 4)): this example refers to the upper reaches (or headwaters) of rivers such as the

Richmond River and its tributaries in the headwaters of the Richmond river basin. As this area is located far away (>30 km), and up-gradient from the potential CSG development area west of Casino, it was deemed that the 'Failure of well integrity', 'Operational water management' and 'Hydraulic fracturing' causal pathways and 'Surface water drainage' causal pathway group are not applicable. Unlike these causal pathways, which are likely to have more localised impacts, the regional-scale groundwater extraction from the Walloon Coal Measures to depressurise the coal seams could potentially affect landscape classes that are not within the vicinity of the potential CSG development area. Consequently, the 'Subsurface depressurisation and dewatering' causal pathway group has the greatest potential to affect wider areas. However, as shown in Section 2.3.2 of this product, recharge rates to the volcanic aquifers in the headwaters of the Richmond river basin and streamflow rates are very high, and there is likely to be only a limited connection between the basalts and the underlying sedimentary bedrock. Consequently, it is unlikely that there are any causal pathways that could link potential CSG developments to this landscape class. The groundwater model will test this conceptual understanding and determine whether such impacts are likely to occur or not.

- Example 2 ('Alluvium, lowland, river' landscape class (landscape class number 12)): examples of this landscape class include Shannon Brook, Myrtle Creek and Wilsons River. Both Myrtle Creek and Wilsons River are relatively far from the potential CSG development areas south and west of Casino (Section 2.3.2), therefore there would unlikely be any causal pathways between CSG activities and these streams. However, other streams in this category such as Shannon Brook flow through the area of potential CSG development west of Casino, and consequently, there are potential causal pathways that could link CSG developments with these streams.
- Example 3 ('Estuarine, all terrain, and tidal-influenced river' landscape class (landscape class number 20)): as outlined in Section 2.3.2, several of the streams within the Richmond river basin are influenced by tides. They are located in the eastern part of the Richmond river basin, but can extend more than 100 km inland due to the low topographic gradients. Even though they are downstream of the additional coal resource development area, there are unlikely to be any causal pathways that link CSG activities and these types of streams due to the tidal influence and the considerable distance from the potential CSG development area.
- Example 4 ('Grassland GDE' landscape class (landscape class number 28a)): this landscape class is restricted to the eastern part of the Richmond river basin near the coast. Due to the considerable distance from the potential CSG development area, there are unlikely to be any causal pathways that could link CSG developments and these landscape classes.
- Example 5 ('Open forest GDE' landscape class (landscape class number 31a): open forest groundwater-dependent ecosystems (GDEs) are widely distributed throughout the Richmond river basin, and are also present within or close to the potential CSG development area west of Casino. Due to this proximity to potential CSG development areas, there are potential causal pathways that could link the CSG developments with these water-dependent assets.

Table 18 Relationship between landscape classes and the four causal pathway groups in the Richmond river basin groundwater modelling domain

[a]'Y' denotes potential impact from the causal pathways that need to be assessed further; 'N' denotes unlikely impact. It is important to note that even if the initial assignment in this table suggests that a causal pathway does exist, the groundwater numerical model may indicate otherwise; note that the opposite scenario is also possible.
[b]Example assets listed are only examples of assets representative of each landscape class within the groundwater modelling zone that may or may not be in the potential impact zone for coal seam gas development.

Landscape class number	Landscape class name	Causal pathway group[a]				Asset examples[b]
		Subsurface depressurisation and dewatering	Subsurface physical flow paths	Operational water management	Surface water drainage	
1	All geology, all terrain, artificial reservoir	N	N	N	N	Toonumbar Dam
2	Alluvium, all terrain, non-floodplain swamp	Y	N	Y	N	Richmond wetlands
3	Alluvium, all terrain, tidal river	N	N	N	N	Richmond River estuary
4	Alluvium, high energy upland, stream or river	N	N	N	N	Findon Creek Leycester Creek
5	Alluvium, low energy upland or transitional, floodplain	Y	Y	Y	Y	None identified
6	Alluvium, low energy upland or transitional, floodplain lake	Y	Y	Y	Y	Serpentine Lagoon Floodplain wetlands (ephemeral) – Mongogarie Creek catchment
7	Alluvium, low energy upland or transitional, river	Y	Y	Y	Y	Wilsons River Richmond River
8	Alluvium, low energy upland or transitional, stream	Y	Y	Y	Y	Mongogarie Creek Marom Creek
9	Alluvium, lowland or transitional, floodplain swamp	N	N	N	N	None identified
10	Alluvium, lowland, floodplain lake	Y	Y	Y	Y	Lower Bungawalbin Catchment Wetland Complex Floodplain wetlands (permanent) – Seelems Creek local catchment
11	Alluvium, lowland, non-floodplain lake	Y	Y	Y	Y	Richmond wetlands
12	Alluvium, lowland, river	Y	Y	Y	Y	Shannon Brook Wilsons River Myrtle Creek
13	Alluvium, lowland, stream	Y	Y	Y	Y	Sandy Creek Tucki Tucki Creek

Landscape class number	Landscape class name	Causal pathway group[a]				Asset examples[b]
		Subsurface depressurisation and dewatering	Subsurface physical flow paths	Operational water management	Surface water drainage	
14	Consolidated sedimentary, high energy upland or low energy upland or transitional, river	N	N	N	N	Richmond River Woodenbong Creek
15	Consolidated sedimentary, high energy upland or low energy upland or transitional, stream	N	N	N	N	Calico Creek Cabbage Tree Creek
16	Consolidated sedimentary, lowland or transitional, non-floodplain swamp	Y	Y	Y	Y	Richmond wetlands
17	Consolidated sedimentary, lowland, stream	Y	Y	Y	Y	Doubtful Creek Four Mile Creek
18	Estuarine, all terrain, non-floodplain swamp	N	N	N	N	Bundjalung National Park Broadwater National Park Swamps with *Cyperus* spp., *Schoenoplectus* spp. and *Eleocharis* spp. GDE
19	Estuarine, all terrain, stream	N	N	N	N	Tuckean Broadwater Swampy Creek
20	Estuarine, all terrain, tidal river	N	N	N	N	Richmond River Evans River
21	Estuarine, lowland, floodplain lake	N	N	N	N	Forested wetlands, Broadwater National Park
22	Fractured rock, high energy upland, river	N	N	N	N	Leycester Creek Toolum Creek
23	Fractured rock, high energy upland, stream	N	N	N	N	O'Donnell Creek Terrace Creek
24	Fractured rock, lowland or transitional, stream	Y	Y	Y	Y	Eden Creek Gradys Creek
25	Waterfalls	N	N	N	N	Tooloom Falls Indigenous site Murray Falls
26	Springs and waterholes	N	N	N	N	Gullyvul Spring Doggies Waterhole

Landscape class number	Landscape class name	Causal pathway group[a]				Asset examples[b]
		Subsurface depressurisation and dewatering	Subsurface physical flow paths	Operational water management	Surface water drainage	
27	Dryland agriculture	Y	Y	Y	Y	Potential distribution of the Grey-headed Flying-fox (*Pteropus poliocephalus*) Youngman Creek local catchment Potential distribution of Slaty Red Gum (*Eucalyptus glaucina*)
27a	Dryland agriculture GDE	Y	Y	Y	Y	Lowland red gum GDE *Eucalyptus tereticornis* woodland to open forest on alluvial plains GDE Paperbark GDE
28	Grassland	N	N	N	N	Potential distribution of Thorny Pea (*Desmodium acanthocladum*) Potential distribution of the Wallum Sedge Frog (*Litoria olongburensis*)
28a	Grassland GDE	N	N	N	N	Wet heath GDE Paperbark GDE Sedgeland/rushland GDE
29	Irrigated agriculture	Y	Y	Y	Y	Water sharing plan for Richmond River Area Walshes Creek local catchment
29a	Irrigated agriculture GDE	Y	Y	Y	Y	Wet heath GDE
30	Mangrove	N	N	N	N	Bundjalung National Park Evans River estuary
30a	Mangrove GDE	N	N	N	N	Swamp oak GDE Mangrove GDE Lowlands scribbly gum GDE
31	Open forest	Y	Y	Y	Y	Potential distribution of the Spot-tailed Quoll (*Dasyurus maculatus maculatus* (SE mainland population)) Bungawalbin National Park

Landscape class number	Landscape class name	Causal pathway group[a]				Asset examples[b]
		Subsurface depressurisation and dewatering	Subsurface physical flow paths	Operational water management	Surface water drainage	
31a	Open forest GDE	Y	Y	Y	Y	Wet bloodwood-tallowwood GDE *Eucalyptus saligna* or *E. grandis*, *E. microcorys*, *E. acmenoides*, *Lophostemon confertus* tall open forest on metamorphics ± interbedded volcanics GDE
32	Rainforest	Y	N	N	N	Toonumbar National Park Nightcap National Park National heritage listed Gondwana rainforests of Australia Potential distribution of Southern Fontainea (*Fontainea australis*) Lowland Subtropical Rainforest on Basalt Alluvium in NE NSW and SE Qld Threatened Ecological community
32a	Rainforest GDE	N	N	N	N	Araucarian complex microphyll vine forest on Cenozoic igneous rocks GDE Lowland rainforest on floodplain GDE Sub-tropical and warm temperate rainforest GDE
33	Shrubland	N	N	N	N	Potential distribution of Sweet Myrtle (*Gossia fragrantissima*) Forested wetlands Broadwater National Park
33a	Shrubland GDE	N	N	N	N	Eastern Darling Downs ecosystems that rely on subsurface presence of groundwater GDE Potential distribution of Dwarf Heath Casuarina (*Allocasuarina defungens*) Wet heath GDE

Landscape class number	Landscape class name	Causal pathway group[a]				Asset examples[b]
		Subsurface depressurisation and dewatering	Subsurface physical flow paths	Operational water management	Surface water drainage	
34	Woodland	Y	Y	Y	Y	Potential distribution of Clear Milkvine (*Marsdenia longiloba*) Potential distribution of the Black-breasted Button-quail (*Turnix melanogaster*) Sawpit Creek local catchment
34a	Woodland GDE	Y	Y	Y	Y	Dry healthy blackbutt-bloodwood GDE Potential distribution of Rupp's Wattle (*Acacia ruppii*) Clarence lowlands spotted gum GDE Foothill grey gum-ironbark-spotted gum GDE
35	Urban	N	N	N	N	St Mary's Catholic Church – Canterbury St, Casino Barlings Creek local catchment Kyogle urban conservation Area – Kyogle

It is worth highlighting that the initial assignment of Table 18 is preliminary; it will be tested with the aid of numerical models whose outcomes are reported in companion product 2.6.1 for the Clarence-Moreton bioregion (Gilfedder et al., 2016) and companion product 2.6.2 for the Clarence-Moreton bioregion (Cui et al., 2016). This means that even if the initial assignment in this table suggests that a causal pathway exists, the groundwater numerical model may indicate otherwise; the opposite scenario is also possible.

The conceptual framework presented in Table 18 allows identification of the level of risk associated with CSG development for each asset. A vulnerable asset assigned to a landscape class that has been identified as being potentially impacted through any of the four causal pathways (i.e. has a 'Y' in column 3 of Table 18) would be in a high-risk category. Conversely, an asset that is a member of a landscape class that is unlikely impacted through any of the four causal pathways (i.e. has an 'N' in column 3 of Table 18) would be in a low-risk category.

2.3.5.4 Gaps

The data gaps and uncertainties relating to the conceptual hydrogeological model outlined in Section 2.3.2 of this product also apply to this section.

The landscape classes were mapped using the currently available spatial data. However, not all spatial data could be obtained for each landscape class (spatial data was either non-existent or non-accessible within the window of data collection for the BA analysis). For example, floodplain mapping is not well represented in the modelled area. Furthermore, while not a gap, not all landscape classes are represented in the groundwater modelling area. This may be the result of landscape classes being specific to certain areas in the bioregion but outside the modelled area (e.g. alluvium lowland or transitional floodplain swamp and alluvium low energy upland or transitional floodplain is only mapped in Queensland).

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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.

activity: for the purposes of Impact Modes and Effects Analysis (IMEA), a planned event associated with a coal seam gas (CSG) operation or coal mine. For example, activities during the production life-cycle stage in a CSG operation include drilling and coring, ground-based geophysics and surface core testing. Activities are grouped into components, which are grouped into life-cycle stages.

additional coal resource development: all coal mines and coal seam gas (CSG) fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012

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.

baseline coal resource development: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012

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 resources and water-dependent assets

coal resource development pathway: a future that includes all coal mines and coal seam gas (CSG) fields that are in the baseline as well as those that are expected to begin commercial production after December 2012

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)

consequence: synonym of impact

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

cumulative impact: for the purposes of bioregional assessments, the total change in water resources and water-dependent assets resulting from coal seam gas and coal mining developments when all past, present and reasonably foreseeable actions that are likely to impact on water resources are considered

current controls: the methods or actions currently planned, or in place, to detect hazards when they occur or to reduce the likelihood and/or consequences of these hazards should they occur

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.

detection score: for the purposes of Impact Modes and Effects Analysis (IMEA), the expected time to discover a hazard, scored in such a way that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the expected time (measured in days) to discover it

direct impact: for the purposes of bioregional assessments, a change in water resources and water-dependent assets resulting from coal seam gas and coal mining developments without intervening agents or pathways 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.

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), change in the quantity and/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

Geofabric: a nationally consistent series of interrelated spatial datasets defining hierarchically-nested river basins, stream segments, hydrological networks and associated cartography

geological formation: stratigraphic unit with distinct rock types, which is able to mapped at surface or in the subsurface, and which formed at 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

groundwater system: see water system

hazard: an event, or chain of events, that might result in an effect (change in the quality and/or quantity of surface water or groundwater)

hazard priority number: for the purposes of Impact Modes and Effects Analysis (IMEA), one of two ranking systems that indicate the relative importance of a hazard. It is the sum of severity score, likelihood score and detection score.

hazard score: for the purposes of Impact Modes and Effects Analysis (IMEA), one of two ranking systems that indicate the relative importance of a hazard. It is the sum of the severity score and likelihood score.

hydrogeology: the study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of interactions between water and rock hydrological response variable: a hydrological characteristic of the system that potentially changes due to coal resource development (for example, drawdown or the annual streamflow volume)

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 and/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).

impact cause: an activity (or aspect of an activity) that initiates a hazardous chain of events

impact mode: the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events.

Impact Modes and Effects Analysis: a systematic hazard identification and prioritisation technique based on Failure Modes and Effects Analysis

inflow: surface water runoff and deep drainage to groundwater (groundwater recharge) and transfers into the water system (both surface water and groundwater) for a defined area

landscape class: for bioregional assessment (BA) purposes, an ecosystem with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. They are present on the landscape across the entire BA subregion or bioregion and their spatial coverage is exhaustive and non-overlapping. Conceptually, landscape classes can be considered as types of ecosystem assets.

life-cycle stage: one of five stages of operations in coal resource development considered as part of the Impact Modes and Effects Analysis(IMEA). For coal seam gas(CSG) operations these are exploration and appraisal, construction, production, work-over and decommissioning. For coal mines these are exploration and appraisal, development, production, closure and rehabilitation. Each life-cycle stage is further divided into components, which are further divided into activities.

likelihood: probability that something might happen

likelihood score: for the purposes of Impact Modes and Effects Analysis (IMEA), the annual probability of a hazard occurring, which is scored so that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the probability of occurrence

lithic: sediment or sedimentary rock that contains a significant proportion of detrital rock fragments (10 to 50%) derived by erosion from older, pre-existing rock outcrop

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.

porosity: the proportion of the volume of rock consisting of pores, usually expressed as a percentage of the total rock or soil mass preliminary assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed

receptor: a point in the landscape where water-related impacts on assets are assessed

receptor impact variable: the characteristics of the system that, according to the conceptual modelling, potentially change due to changes in hydrological response variables (for example, condition of the breeding habitat for a given species, or biomass of river red gums)

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

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

severity: magnitude of an impact

severity score: for the purposes of Impact Modes and Effects Analysis (IMEA), the magnitude of the impact resulting from a hazard, which is scored so that an increase (or decrease) in score indicates an increase (or decrease) in the magnitude of the impact

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

stressor: chemical or biological agent, environmental condition or external stimulus that might contribute to an impact mode

subcrop: 1 - A subsurface outcrop, e.g. where a formation intersects a subsurface plane such as an unconformity. 2 - In mining, any near-surface development of a rock or orebody, usually beneath superficial material.

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.

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-dependent asset register: a simple and authoritative listing of the assets within the preliminary assessment extent (PAE) that are potentially subject to water-related impacts

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)

water use: the volume of water diverted from a stream, extracted from groundwater, or transferred to another area for use. It is not representative of 'on-farm' or 'town' use; rather it represents the volume taken from the environment.

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’.

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