Australian Government

BIOREGIONAL ASSESSMENTS

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

Conceptual modelling for the Galilee subregion

Product 2.3 for the Galilee subregion from the Lake Eyre Basin Bioregional Assessment

2018

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.

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Artesian Spring Wetland at Doongmabulla Nature Refuge, Queensland, 2013

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Executive summary

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 (BA), conceptual models are developed to describe the 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.

Methods

This product details the conceptual model of causal pathways of the Galilee subregion, following the methods described in the companion submethodology M05 on the development of conceptual models. It identifies:

- the key system components, processes and interactions, which essentially define pathways over and through which water can move (Section 2.3.2)
- the ecosystems in the Galilee subregion in terms of landscape classes and their dependence on water (Section 2.3.3)
- baseline and coal resource development pathway (CRDP) (Section 2.3.4)
- causal pathways from coal resource developments using an Impact Modes and Effects Analysis (IMEA) hazard analysis approach (Section 2.3.5).

Summary of key system components, processes and interactions

The Galilee subregion has a protracted geological history of deposition, deformation, uplift and erosion. This history has implications for the degree of connectivity that may exist between various geological units, coal resource development and water-dependent assets. Geological aspects that may influence connectivity include variations in the thickness and extent of the Moolayember and Rewan formations; thickness of sediments that overlay the upper Permian coal measures; and location and extent of faulting, in particular around the margins of the geological Galilee Basin.

The hydrogeological conceptualisation outlines three major groundwater flow systems: aquifers in Cenozoic sediments, Great Artesian Basin (GAB) aquifers (Eromanga Basin), and Galilee Basin aquifers in the Clematis Group, upper Permian coal measures and Joe Joe Group.

In the regional artesian aquifer systems of the GAB (i.e. Hutton Aquifer to Cadna-owie – Hooray Aquifer) groundwater flow moves westerly away from the recharge areas that occur where the aquifers outcrop along margin of the Eromanga Basin. Groundwater flow in the Galilee Basin (Clematis Group, upper Permian coal measures and Joe Joe Group) is more complex than what is apparent in the GAB aquifers. Hydrochemical information suggests that Galilee Basin aquifers may be discharging into the Hutton Sandstone aquifer along parts of the western margin of the Galilee subregion. Also, there are several features that are unique to the hydrodynamics of the Galilee Basin aquifers:

- a north trending groundwater divide. This feature has been found to be common to all Galilee Basin groundwater systems for which groundwater mapping has been undertaken as part of the BA for the Galilee subregion
- trends in coal seam gas (CSG) content, its relationship to groundwater systems and structure.

North of Barcaldine Ridge, a groundwater divide segregates groundwater system into easterly and westerly flow components, with potential for discharge to occur towards the margins of the Galilee Basin. It is hypothesised that regional-scale landscape features and processes may be influencing the hydrodynamics of the Galilee Basin aquifers and the location and formation of this regional groundwater divide.

An apparent north-east trend in the CSG gas content is parallel to direction of groundwater flow that are inferred from potentiometric surface mapping for upper Permian coal measures. The trend in CSG gas content is also parallel to some significant faults that have been mapped at the top of the upper Permian coal measures. One hypothesis that may explain the CSG trend is that groundwater hydrodynamics and geological structure are exerting control on the gas distribution and gas content of the coal seams.

The Galilee subregion encompasses the headwaters of seven major river basins with almost all proposed coal resource developments situated in the headwaters of the Burdekin river basin. In the majority of rivers, water flow is strongly seasonal and, from year to year, flows can vary greatly from almost no flow to significant floods. Surface water – groundwater interactions in the Galilee subregion take the following forms: baseflow from shallow groundwater systems to rivers, losing streams (surface water recharging shallow aquifers), spring discharge to spring outflow pools, discharge to lakes (e.g. Lake Galilee) and shallow groundwater being utilised by deep-rooted plants.

Due to the highly variable nature of surface water flow volumes in any given year, there is a strong dependence on groundwater supplies. Most groundwater in the Galilee subregion is extracted from GAB aquifer systems, in particular the Hutton Sandstone and Cadna-owie – Hooray Aquifer. The most utilised aquifer system in the Galilee Basin is the Clematis Group aquifer. The main uses for groundwater are either for agricultural purposes or town water supplies. Groundwater is also extracted from Cenozoic sediments and is the source of some town water supplies (e.g. Alpha township).

Ecosystems

In the Galilee subregion potential changes to water resources and water-dependent assets from coal resource development may have an impact on ecosystems at the land surface. Dividing the Galilee subregion into landscape classes enables a structured approach for assessing these potential impacts. These landscape classes are expressed as a percentage of the preliminary assessment extent (PAE), identified as the geographic area where potential water-related impacts of coal resource development are assessed.

Landscape classification for the Galilee subregion is based on five elements derived from the Australian National Aquatic Ecosystem (ANAE) classification framework involving topography, landform, groundwater source, water type and water availability. In addition, each area was identified as either remnant or non-remnant vegetation based on Queensland remnant Regional Ecosystem (RE) mapping. This classification produced a typology consisting of 41 landscape classes that were further collapsed into 12 broad landscape groups.

The non-water-dependent landscape classes, 'Dryland' and 'Dryland, remnant vegetation', dominate the area of the PAE (68.54%). Of the water-dependent landscape classes, 26.52% of the area of the PAE consists of floodplain landscape classes with the remaining 4.87% of the area occupied by non-floodplain, water-dependent landscape classes. For both the floodplain and non-floodplain water-dependent landscape classes, most of the area consists of terrestrial groundwater-dependent ecosystems (GDEs).

Coal resource development

Changes in water resources and water-dependent assets due to coal resource development are quantified in the Galilee subregion by considering two potential futures:

- *baseline coal resource development (baseline)*: a future that includes all coal mines and 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*– all coal mines and CSG fields in the Galilee subregion, including expansions of baseline operations that are expected to begin commercial production after December 2012.

In the Galilee subregion, the absence of commercially producing coal mines and CSG fields as of December 2012 means that there are no coal resource developments being quantitatively modelled in the baseline for the purposes of BA. There are 17 proposed new developments in the Galilee subregion in the CRDP, which is the combination of proposed coal mine and CSG developments that the Assessment team has evaluated as most likely to progress to commercial production at some time in the future (post the baseline date of December 2012). There is enough publically available information (e.g. detailed mine development plans and scheduling, results from groundwater and surface water modelling) to include seven of these developments in the numerical modelling being undertaken for the Galilee subregion BA.

The seven coal resource developments to be included in surface water and groundwater models for the Galilee subregion BA are the open-cut coal mines Alpha and Hyde Park, and the combined open-cut and underground coal mines Carmichael, China First, China Stone, Kevin's Corner and South Galilee. Other coal mines (Alpha West, Blackall, Clyde Park, Hughenden, Milray, Pentland and West Pentland) and CSG developments (Galilee Gas, Gunn and Blue Energy) in the CRDP will not be assessed by hydrological modelling in this iteration of the BA. However, qualitative analysis of potential coal resource development-related impacts to water resources and water-dependent assets for the non-modelled CRDP will be reported in companion product 3-4 (impact and risk analysis) for the Galilee subregion.

Hazard analysis

Coal resource development hazards with the potential to impact hydrology are identified using IMEA as outlined in companion submethodology M11 for hazard analysis. A large number of hazards are identified, many of which are beyond the scope of a BA or are assumed to be adequately addressed by site-based risk management processes and regulation. Hazards that are beyond the scope of a BA are those that are not causing impacts via water-related pathways (e.g. hazards related to fire), as are hazards that result in surface water – groundwater effects beyond changes in water quantity or salinity. Hazards that have potential for cumulative impacts for coal mine development include: dewatering and depressurisation around coal mine developments, fracturing and subsidence that can occur above underground coal mine longwall panels, and effects of mine infrastructure on surface water systems. For CSG operations hazards include: depressurisation of coal seams, well integrity and co-produced water management-related issues. The hazards are grouped according to four causal pathway groups (refer to Appendix B in companion submethodology M05 for developing a conceptual model of causal pathways).

Causal pathways for coal seam gas

The most advanced CSG project in the Galilee subregion is the Glenaras CSG Project. As of December 2015, Galilee Energy Limited had refined the CSG well designs for the Glenaras pilot wellfield and was conducting an extended pump test to assess CSG flow rates to surface. It is possible that the potential for cumulative impacts from CSG development may only become significant once a project (or several projects) ramp up towards a production phase. Four causal pathway groups have been identified for CSG projects.

'Subsurface depressurisation and dewatering' causal pathway group includes the depressurisation of coal seams by removal of groundwater. This is required to produce CSG to the surface from the coal seams. In the Galilee subregion, the main target seams for CSG development are in the upper Permian coal measures. Factors that can affect the extent to which depressurisation can occur and propagate away from target coal seams include:

- local geological complexity (e.g. lithological variation, structures)
- configuration of groundwater flow systems (e.g. aquifers, aquitards, flow direction), hydraulic properties, connectivity of aquifer systems and CSG reservoirs
- rate and duration of pumping (extent of depressurisation is time dependent)
- gas desorption pressure and depth of coal seams
- overburden thickness.

Due to these various complexities, depressurisation at depth in the coal measures does not necessarily equate to the same magnitude of depressurisation near surface.

'Subsurface physical flow paths' causal pathway group includes the causal pathways of 'Failure of well integrity' and 'Hydraulic fracturing'. The impacts associated with compromised well integrity are likely be of a local scale; that is, they are restricted within the close vicinity of the compromised well. However, such impacts may continue until remedial action is taken. It is uncertain whether hydraulic fracturing will become a technique that is readily applied in the Galilee Basin as CSG development is in an early phase. For instance, at the Glenaras pilot wellfield, the drilling of horizontal CSG wells along target coal seams is considered by the proponent to be a more applicable technology for increasing gas flow to CSG wells rather than hydraulic fracturing.

'Surface water drainage' causal pathway group encompasses causal pathways relating to changes to the surface drainage network. Disruption or large-scale changes to the surface drainage network may potentially lead to a loss or redirection of runoff.

'Operational water management' causal pathway group is required for CSG operations due to the use of water during different stages of the development life cycle. Co-produced water from groundwater pumping may be disposed of via various methods, which are unknown due to the very early development stages of CSG projects in the Galilee subregion. Any treatment and disposal would be subject to regulatory oversight and approval by Queensland state agencies.

Causal pathways for open-cut and underground coal mines

'Subsurface depressurisation and dewatering' causal pathway group around coal mine workings has the potential to directly affect the regional groundwater system, and indirectly affect surface water – groundwater interactions in aquifer outcrop areas. There will be a resultant drop in groundwater levels and pressures (drawdown) around mine areas as all proposed coal mine developments in the Galilee subregion will extend deeper than the watertable.

In an open-cut coal mine groundwater drawdown can cause a drop in pressure around the mine area and create the potential for groundwater in the vicinity to flow towards the mine area, depending on the local geological configuration. Drawdown around a mine could potentially lower the watertable, which may decrease water availability to nearby groundwater-dependent ecosystems (GDEs), riparian environments, deep-rooted tree species (e.g. river red gum *Eucalyptus camaldulensis*), or induce changes to baseflow in river systems. Changes to baseflow may result in local changes to river flow regime such as decreased river flow and duration of flow during low-flow periods.

In an underground coal mine depressurisation will occur to a varying degree around the underground mine workings. This hydrologic depressurisation could be impeded vertically by aquitards in the surrounding geological sequence. Deeper mine workings may also have the potential to increase the lateral extent of the effects of depressurisation and drawdown. Any depressurisation from underground mine workings would be additive to any drawdown associated with dewatering around nearby open pits.

Fracturing and subsidence above underground mine longwall panels (involving causal pathway groups ' Subsurface physical flow paths' and 'Surface water drainage') may occur to varying degrees above underground longwall mines in the Galilee subregion. Generally, areas affected by subsidence and fracturing are greatest above or immediately adjacent to areas where longwall coal mining has taken place. Although it is a relatively localised effect that occurs within mining lease areas, cumulatively the combined areas of the proposed underground coal mines could be of significance for the Belyando river basin, a significant tributary to the Burdekin River.

All underground mining is proposed to occur in coal seams in the upper Permian coal measures. The extent to which fracturing and subsidence may change hydrology depends on increased aquifer connectivity due to preferential flow along fractures, or increased flow through an aquitard compromised by fracturing, increased hydraulic conductivity and lower groundwater levels. At surface, the potential changes may include local changes in topography, ponding of water, redirection of surface flows, some changes to surface water flow regime, and if fracturing reaches the surface there is potential for increased recharge to groundwater. The degree of change is strongly dependent on site-specific geological conditions.

'Surface water drainage' causal pathway group focuses on potential changes to the surface water regime. Early in the development of a mine site, where the installation of diversion drains is required, bund walls and other measures will divert surface water flows, including overland flow, around the mine site to continue down slope of the coal mine development. Changing surface water drainage may result in changes to some components of the water balance. Redirection of flow to other parts of the catchment may also increase surface water flows locally in areas where it previously did not occur. Whether these changes are significant or not will vary from site to site. The cumulative area that is excised from the Belyando river basin by operational mines identified in the CRDP for the Galilee subregion may be significant.

Gaps

Developing the conceptual models of causal pathways has been based on available plans and discussions with the various proponent companies as projects are at various stages of development and regulatory approval. Knowledge gaps in the conceptual model of causal pathways for the Galilee subregion include: gaps in geological and hydrological knowledge, refinement of mapping and classification of the ecosystems of the PAE, detail on scheduling and operations for coal resource development and finalisation of amount of external water required from off-site sources for coal mine projects.

Further work

The causal pathways described in this product guide how the modelling product 2.6.2 (groundwater numerical modelling) is conducted and how product 3-4 (impact and risk analysis) is framed in the Galilee subregion.

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- 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
- Independent reviewer: Mac Kirby (CSIRO), Peter Cook (NCGRT).

Currency of scientific results

The modelling results contained in this product were completed in January 2016 using the best available data, models and approaches available at that time. The product content was completed in October 2017.

All products in the model-data analysis, impact and risk analysis, and outcome synthesis (see Figure 1) were published as a suite when completed.

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 is 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, has undertaken 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.

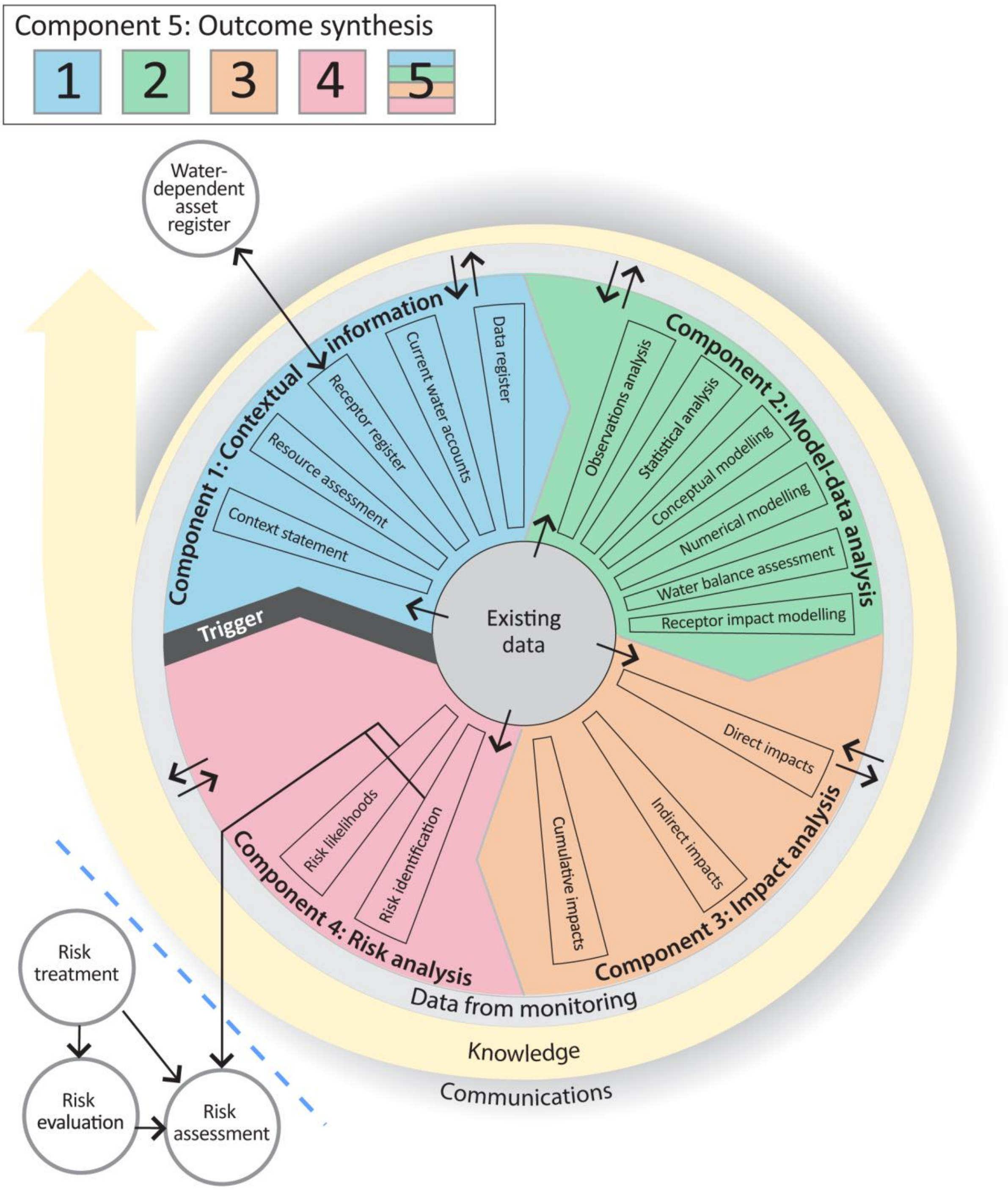

Figure 1 Schematic diagram of the bioregional assessment methodology

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.

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.

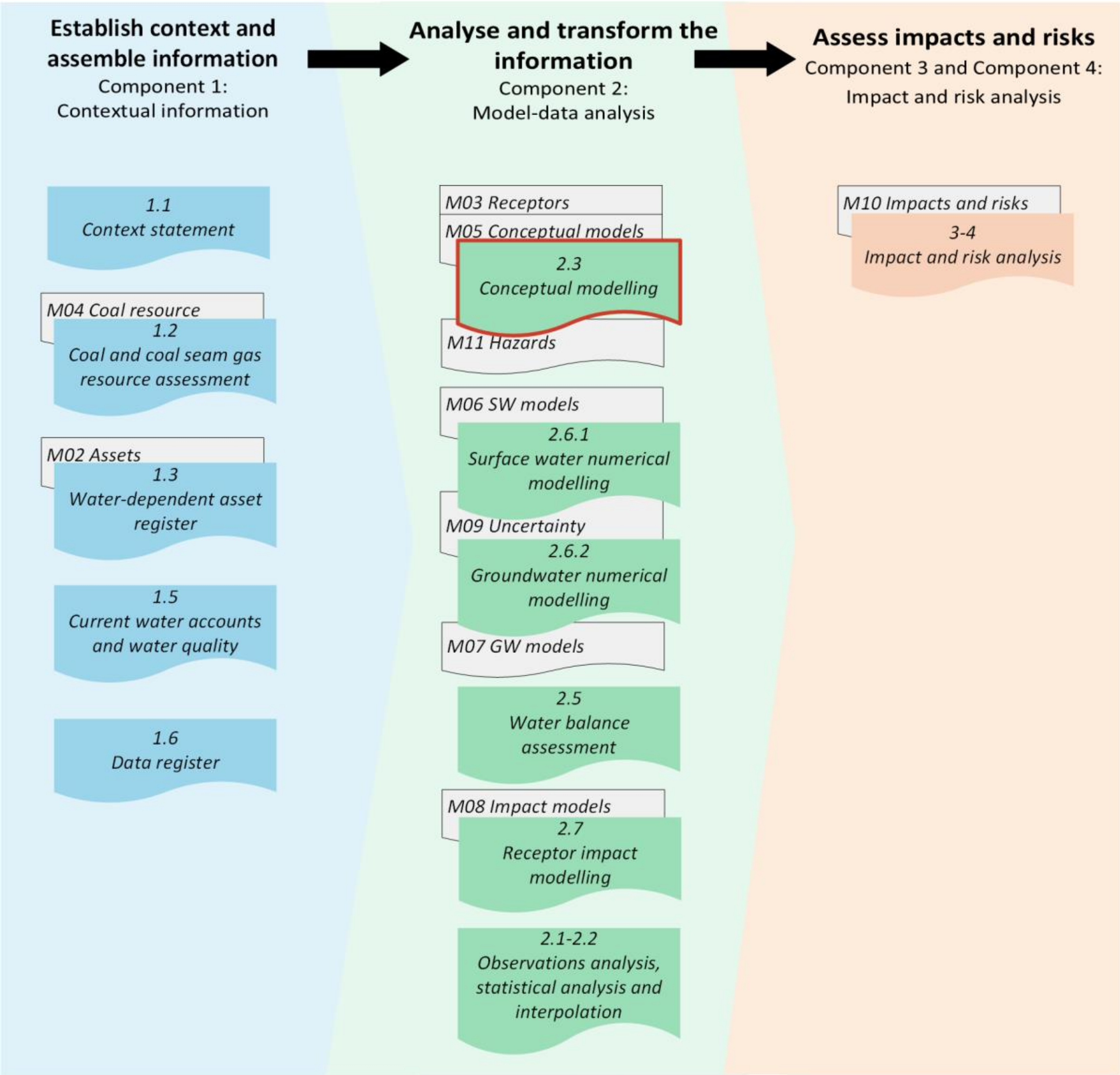

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Galilee subregion

For each subregion in the Lake Eyre Basin 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 Galilee subregion	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 Galilee subregion	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	PDF, HTML
Component 3 and Component 4: Impact and risk analysis for the Galilee subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Galilee subregion	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 Lake Eyre Basin 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.

[b]*Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (Barrett et al., 2013)

About this technical product

The following notes are relevant only for this technical product.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.
- All maps created as part of this BA for inclusion in this product used the Albers equal area projection with a central meridian of 140.0° East for the Lake Eyre Basin bioregion and two standard parallels of –18.0° and –36.0°.
- Contact bioregionalassessments@bom.gov.au to access metadata (including copyright, attribution and licensing information) for all datasets cited or used to make figures in this product. At a later date, this information, as well as all unencumbered datasets, will be published online.
- 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 Galilee subregion

This product firstly summarises key system components, processes and interactions for the geology, hydrogeology and surface water in the Galilee subregion. 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); product 2.7 (receptor impact modelling) describes the subsequent causal pathways from the hydrological changes to the impacts

(represented by the receptor impact variables, which are linked to the landscape classes and assets).

The product concludes by describing causal pathways for the baseline and CRDP, which guide how the modelling (product 2.6.1 (surface water numerical modelling), product 2.6.2 (groundwater numerical modelling) and product 2.7 (receptor impact modelling)) is conducted, and how product 3-4 (impact and risk analysis) is framed.

2.3.1 Methods

Summary

The conceptual model of causal pathways characterises the *causal pathway*, the logical chain of events – 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 Galilee subregion 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 subregion; (ii) landscape classification; (iii) definition of the coal resource development pathway (CRDP); (iv) hazard analysis; (v) identification of causal pathways from the coal resource development to hydrological changes; and (vi) description of the resulting causal pathways for the CRDP for the Galilee subregion.

The Galilee subregion is a greenfield coal resource development area. The regional hydrogeological conceptualisation (Section 2.3.2) is a first for the geological Galilee Basin and demonstrates many important hydrogeological features of the subregion, including how groundwater flow systems may interact with aquifers in the overlying Eromanga Basin. Section 2.3.2 also highlights existing knowledge gaps and uncertainties in the conceptualisation of the subregion.

The landscape classification (Section 2.3.3) for the Galilee subregion characterises the nature of water dependency for assets identified in companion product 1.3 for the Galilee subregion (Sparrow et al., 2015). The aim of the landscape classification is to systematically define geographical areas into classes based on similarity in physical and/or biological and hydrological character. The 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.

There were no commercially producing coal mines or coal seam gas (CSG) fields as of December 2012 in the Galilee subregion. Hence there are no coal mines or CSG fields included in the baseline coal resource development (baseline). However, the Assessment team's evaluation of the potential coal resource developments listed in companion product 1.2 for the Galilee subregion (Lewis et al., 2014) was used to determine the CRDP. There are 14 identified coal resources included in the CRDP for the Galilee subregion, of which the 7 most advanced coal mining proposals have sufficient data and information available for them to be included in the quantitative (modelled) assessment of potential cumulative impacts to water resources. Three CSG projects are also included in the CRDP, although none are sufficiently well advanced in their appraisal, planning or various regulatory assessment processes to be included in the modelled assessment for the Galilee subregion.

The magnitude of potential hydrological change relating to coal mine developments in the modelled CRDP is quantified through modelling outlined in companion product 2.6.1 (Karim et al., 2018) and companion product 2.6.2 (Peeters et al., 2018) for the Galilee subregion. Product 2.7 (receptor impact modelling) will utilise the landscape classification as a basis to quantify the magnitude and uncertainty of hydrological changes and how it will propagate through ecological systems. Quantified impacts and risks resulting from hydrological changes will be outlined in product 3-4 (impact and risk analysis). Product 3-4 (impact and risk analysis) will also include commentary on the potential impact of coal resource developments that are not included in the modelled CRDP.

2.3.1.1 Background and context

This product presents information about the conceptual model of causal pathways for the Galilee subregion, which was developed using 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 Galilee subregion is described in Section 2.3.1.2, with more specific details in the individual sections that follow.

Conceptual models are abstractions or simplifications of reality. A number of conceptual models are developed for a 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 logical chain of events – 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.

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 subregion (as presented in Section 2.3.2). Essentially Section 2.3.2 provides a comprehensive conceptualisation of data and interpretations presented in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018). Section 2.3.2 also highlights knowledge gaps and uncertainties, and how these gaps may improve the understanding of the system.

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 subregion 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 subregion 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 CSG fields that are commercially producing as of December 2012. For the Galilee subregion, there were no commercially producing coal mines or CSG fields 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* – 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 emphasises 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 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).

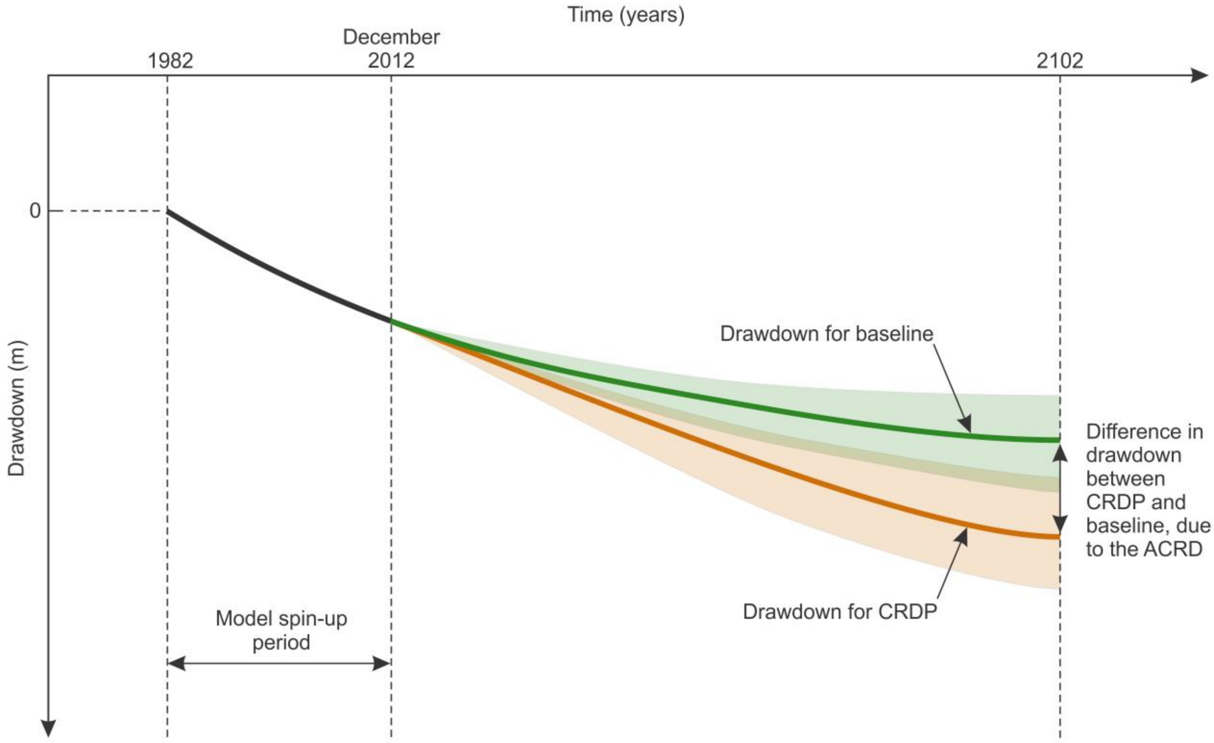

Figure 3 Generic example of drawdown at a specific location over time for the baseline coal resource development (baseline) and coal resource development pathway (CRDP). The difference in drawdown between CRDP and baseline is due to the additional coal resource development (ACRD)

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

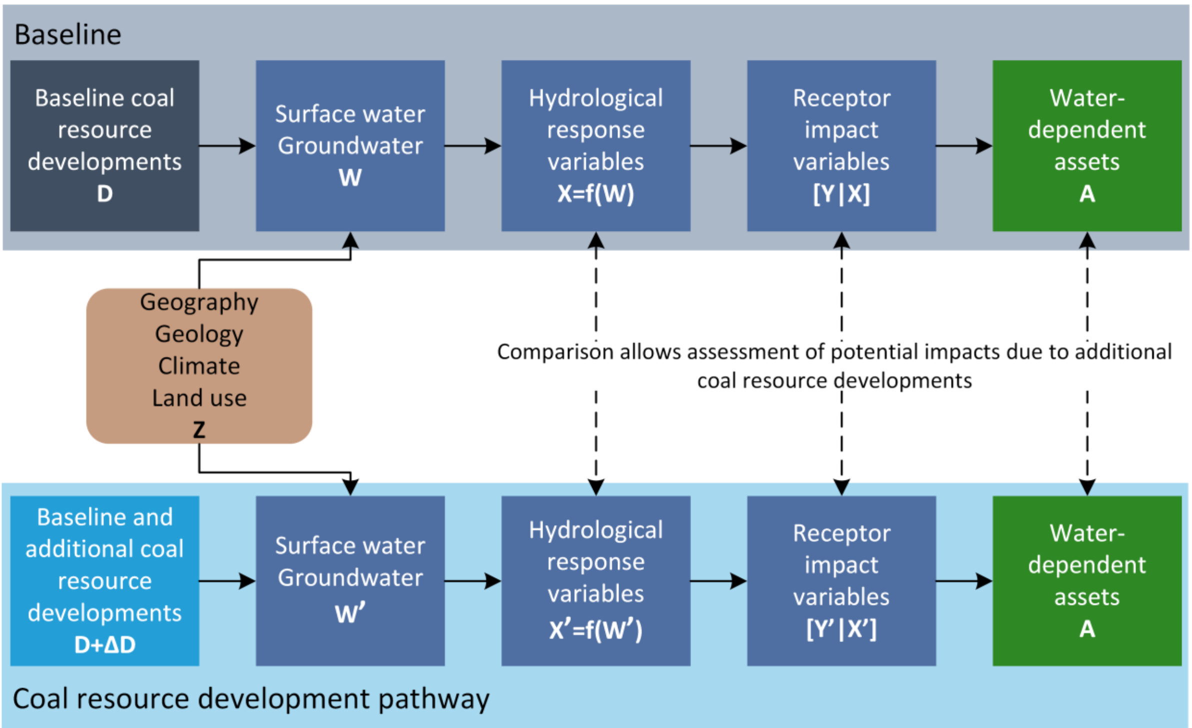

Figure 4 The difference in results between the coal resource development pathway (CRDP) and baseline coal resource development (baseline) provides potential impacts due to additional coal resource development (ACRD)

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).

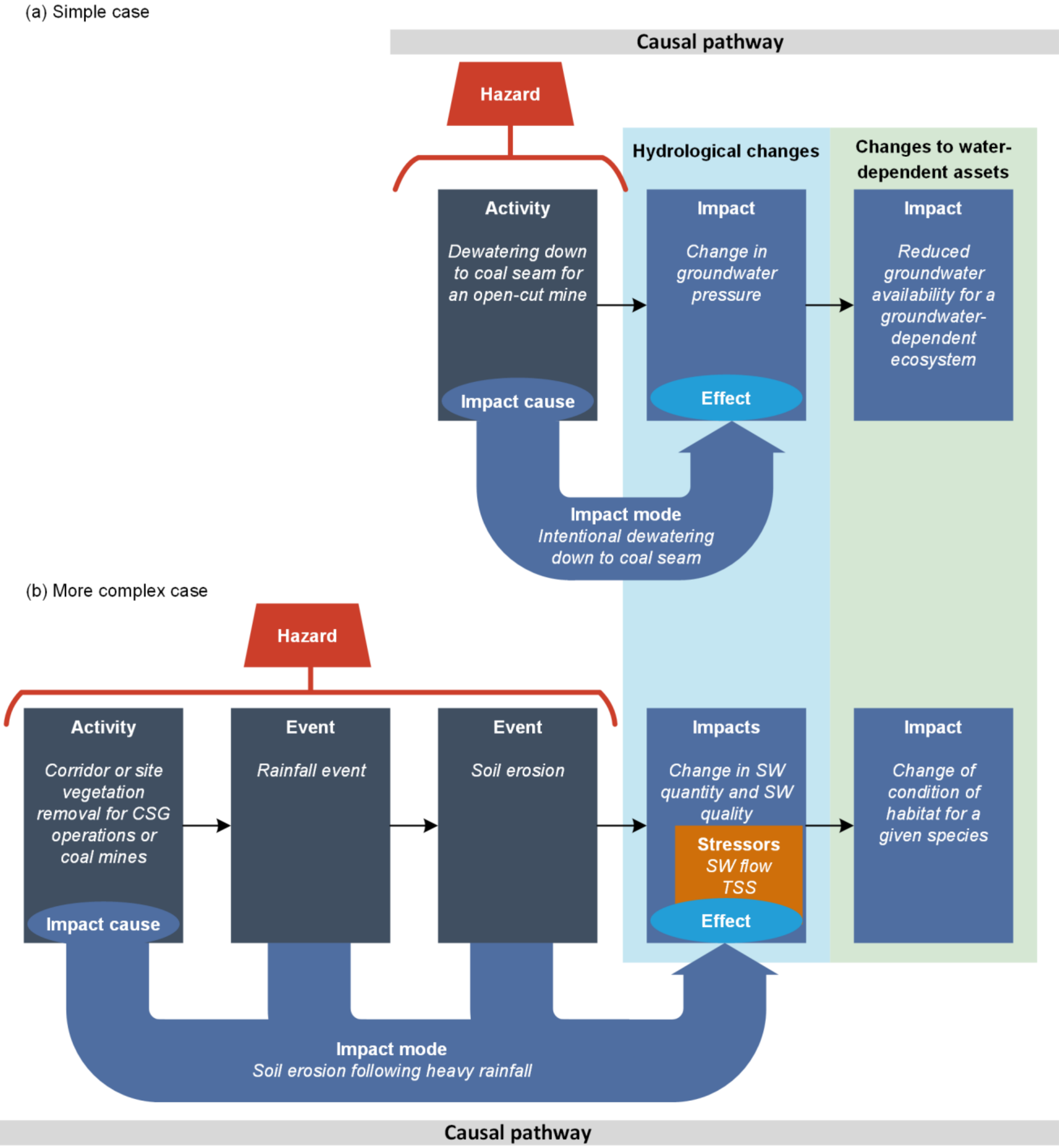

Figure 5 Hazard analysis using the Impact Modes and Effects Analysis (IMEA). This figure shows how hazards identified using IMEA are linked to changes in hydrology and water-dependent assets via causal pathways

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.

This product only specifies the causal pathways from coal resource development to hydrological response variables (see Figure 4). For the Galilee subregion, the subsequent causal pathways (from hydrological response variables to impacts on landscape classes and water-dependent assets) are reported in the receptor impact modelling (companion product 2.7 for the Galilee subregion (as listed in Table 2)). These causal pathways are reported for only those landscape classes with potential hydrological changes, as reported in surface water numerical modelling (companion product 2.6.1 for the Galilee subregion (Karim et al., 2018)) and groundwater numerical modelling (companion product 2.6.2 for the Galilee subregion (Peeters et al., 2018)).

2.3.1.2 Developing causal pathways

The systems summary (Section 2.3.2) for the Galilee subregion draws upon existing contextual information compiled as part of the BA (specifically companion product 1.1 (Evans et al., 2014) and companion product 1.5 (Evans et al., 2015) for the Galilee subregion) as well as the new understandings and interpolations presented in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018). The hydrogeological conceptualisation presented in this product is a first for the geological Galilee Basin and demonstrates many features of the subregion, including how groundwater flow systems in the Galilee Basin could interact with aquifers in the overlying Eromanga Basin. Section 2.3.2 also highlights knowledge gaps and uncertainties in the conceptualisation of the subregion.

The conceptualisation of hydrological and hydrogeological systems provides the framework to assess if there is potential for effects from hazards associated with coal resource development activities to propagate through the hydrological systems.

A hazard analysis conducted for the Galilee subregion (Section 2.3.5.2) was based on information from the proposed CSG operations and coal mines (as outlined Section 2.3.4.1) and their water management plans (Section 2.3.4.2). The hazard analysis for the Galilee subregion was completed during a one-day workshop in March 2015 with experts from CSIRO, Geoscience Australia and the Department of the Environment.

Two workshops involving external stakeholders (including representatives from industry, and the Queensland and Commonwealth governments) were run as part of development of the conceptual models for causal pathways work for the Galilee subregion.

The first workshop was in October 2014 and focused on the development of the CRDP (Section 2.3.4). Outcomes of this workshop determined which developments outlined in Lewis et al. (2014) would be likely to commence within a reasonably forseeable (10–15 years) time frame. The results are presented in Section 2.3.4. A key outcome from the workshop was that no coal resource developments are included in the baseline for the Galilee subregion because there are no commercially operating coal mines or CSG fields as of December 2012 (See Section 2.3.1.1 and Figure 3).

The second workshop, held in August 2015 in Brisbane, focused on the conceptual models for the causal pathways. This workshop explored possible regional and cumulative hazards in the Galilee subregion that may connect a coal resource development activity to potential hydrological changes that may then affect water-dependent assets. Results and causal pathways are outlined in Section 2.3.5. The companion product 1.3 for the Galilee subregion (Sparrow et al., 2015) outlined water dependent assets situated in the Galilee subregion. This workshop outlined possible cumulative hazards that may occur at regional scale, rather than for specific coal resource developments in the Galilee subregion, and identified possible causal pathways that may link hazards and water-dependent assets.

One of the outcomes of the workshop is that causal pathways are not needed for the baseline because there are no coal resource developments in the baseline for the Galilee subregion.

A landscape classification (Section 2.3.3) was developed to characterise the nature of water dependency for assets identified in the companion product 1.3 for the Galilee subregion (Sparrow et al., 2015). The aim of the landscape classification is to systematically define geographical areas into classes based on similarity in physical and/or biological and hydrological character. The 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.

The landscape classes (Section 2.3.3) conceptually form the impact-receiving layer at surface and can potentially be connected via subsurface and/or surface hydrological pathways to hazards associated with coal resource development activities. Hydrological impacts from activities could propagate along connective pathways and induce a hydrological change to a landscape class at surface (Section 2.3.5.3). Within BAs, all modelling of potential ecological impacts is organised by and conditioned upon the landscape classes in a potential area of impact. Potential areas of impact are areas where hydrological changes due to coal resource development have been delineated through modelling outlined in companion product 2.6.1 (Karim et al., 2018) and companion product 2.6.2 (Peeters et al., 2018) for the Galilee subregion. Further detail on how landscape classes are utilised in the Galilee subregion is outlined in the receptor impact modelling (companion product 2.7 for the Galilee subregion (as listed in Table 2)).

Section 2.3.1.1, Section 2.3.5.1 and companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016) provide further detail on methods for developing conceptual models for causal pathways.

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2.3.2 Summary of key system components, processes and interactions

Summary

The protracted geological history of deposition, deformation, uplift and erosion that has occurred in the Galilee subregion has implications for the degree of hydraulic connectivity that may exist between various geological units, coal resource development and water-dependent assets. This geological overview includes a brief review of the geological history. Specific aspects of the geological framework that are likely to have an important bearing on hydraulic connectivity include: variations in the thickness and extent of Moolayember Formation; areas where the Hutton Sandstone is in direct contact with Clematis Group or upper Permian coal measures; thickness of sediments and sedimentary rocks that overlie the upper Permian coal measures; and location and extent of faulting, in particular around the margin of the geological Galilee Basin.

The hydrogeological conceptualisation outlines three major groundwater systems hosted in different geological basins: (i) Cenozoic aquifers, (ii) Great Artesian Basin (GAB) aquifers (Eromanga Basin), where the main aquifers are the regional watertable aquifer developed in Winton-Mackunda formations and the Wallumbilla Formation and the GAB regional artesian aquifer sequence (Hutton Sandstone to Cadna-owie—Hooray Sandstone), and (iii) Galilee Basin, which comprises the Clematis Group aquifer, and aquifers in the upper Permian coal measures and Joe Joe Group.

Groundwater flow as inferred from potentiometric surface mapping of the regional watertable in the Eromanga Basin is controlled by local and regional topography and focuses towards major drainage lines. The GAB regional artesian aquifers outcrop as a prominent ridge along the eastern margin of the Eromanga Basin. Much of the groundwater flow is inferred to head in a westerly direction away from outcrop areas. West of outcrop areas, GAB regional artesian aquifer is confined by the Rolling Downs Group aquitard. In GAB outcrop areas, some east-directed flow towards the GAB aquifer margin forms a largely unconfined local groundwater system on the eastern side of the ridge. A line of springs has formed in the vicinity where GAB regional artesian aquifers become confined by the overlying Rolling Downs Group aquitard. Another line of springs occurs as discharge areas at base of ranges for local east-directed groundwater systems.

Groundwater flow in the Galilee Basin (Clematis Group aquifer, upper Permian coal measures and Joe Joe Group) is more complex than in overlying GAB aquifers. Features that are unique to the hydrodynamics of the Galilee Basin aquifers are: (i) a north–south trending groundwater divide, located to the north of the Barcaldine Ridge. This feature has been found to be common to all Galilee Basin groundwater systems for which groundwater mapping has been undertaken as part of the BA for the Galilee subregion and (ii) trends in coal seam gas (CSG) content, its relationship to groundwater systems and structure.

The major groundwater divide segregates the Galilee Basin groundwater systems into easterly and westerly flow components, with potential discharge occurring towards the margins of the

Galilee Basin. One hypothesis is that regional-scale landscape features and processes may be influencing the hydrodynamics of the Galilee Basin aquifers and the location and formation of this regional groundwater divide. Some examples of landscape features and processes include broad topographically elevated areas situated between the Great Dividing Range and the Eromanga Basin margin that encompasses lakes Galilee and Buchanan, and headward erosion and incision of the Carmichael River offsetting the location of the Great Dividing Range.

CSG pressure in coal seams may be less of an influencing factor, as trends in CSG cross-cut the groundwater divide. Furthermore, the groundwater divide feature is common to all aquifers in the Galilee Basin; it is not a feature that only occurs in the upper Permian coal measures. Distribution of CSG resources is inferred to be influenced by east trending geological structures in the upper Permian coal measures and inferred groundwater flow direction that occurs in the vicinity of identified CSG resources.

Surface water – groundwater interactions in the Galilee subregion take the following forms: baseflow from shallow groundwater systems to rivers, losing streams (surface water recharging shallow aquifers), spring discharge to outflow pools, discharge to lakes (e.g. Lake Galilee) and shallow groundwater utilised by deep-rooted plants. The Galilee subregion encompasses the headwaters of seven major river basins with almost all proposed coal mine developments situated in the headwaters of the Burdekin river basin. Surface water flow is strongly seasonal and, from year to year, can vary greatly from almost none to significant floods. Mean annual potential evaporation far exceeds rainfall, particularly in the summer months when rainfall is highly variable for most of the subregion. The lack of continuous surface water flow throughout the year shows that groundwater-controlled baseflow to rivers is often not sufficient to keep rivers continuously flowing during prolonged low rainfall periods.

Due to variability of surface water resources there is a strong dependence on groundwater supplies. Groundwater is utilised for agricultural purposes, town water supplies and industry. Most groundwater in the Galilee subregion is extracted from GAB aquifer systems, the Hutton Precipice and the Wyandra-Hooray aquifers. In the Galilee Basin, most extraction occurs from the Clematis Group aquifer.

2.3.2.1 Scope and overview

This section summarises the conceptual understanding of geological and hydrogeological systems of the Galilee subregion and how they interact with each other, and specifically builds on information in companion products 1.1, 1.2, 1.5 and 2.1-2.2 for the Galilee subregion (Evans et al., 2014; Lewis et al., 2014; Evans et al., 2015; and Evans et al., 2018, 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 be impacted by potential coal resource development in the subregion. Section 2.3.5 discusses specific causal pathways in the context of coal mines and CSG operations.

Some components of the conceptualised geology and hydrogeology contain more detail than others, such as the thickness of overburden in the Galilee subregion and hydrodynamics of major aquifer systems in the Galilee Basin. This is because they have a specific relevance to hydraulic connectivity as well as potential causal pathways in the Galilee subregion.

2.3.2.2 Geology and hydrogeology

The protracted geological history of deposition, deformation, uplift, and erosion that has occurred in the Galilee subregion has implications for the degree of connectivity that may exist between various geological units, coal resource development and water-dependent assets. Examples of water-dependent assets that are of interest to a BA include: aquifers, water supply bores, groundwater-dependent ecosystems, springs, surface water-dependent ecosystems and rivers.

2.3.2.2.1 Geology

Aspects of the geological history and geological framework are outlined in Figure 6 and Section 2.1.2 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018; also companion product 1.1 (Evans et al., 2014)). Other summaries of the geological history for individual basins included within the subregion include Cook et al. (2013) and McKellar and Henderson (2013). A brief overview of the geological history is as follows:

- The Galilee Basin sequence lies unconformably on much older rocks that belong to the North Australian Craton and Thomson Orogen, as well as sedimentary rocks of the Drummond, and Adavale basins. Deposition in the Galilee Basin was initiated in the Koburra Trough. It then progressively spread into other depositional centres such as the Powell and Lovelle depressions. A major erosional event occurred after the cessation of deposition of the very thick Upper Carboniferous to lower Permian Joe Joe Group sequence (average thickness 466 m). Above this significant unconformity, the Galilee Basin sequence comprises the upper Permian coal measures, and Early to Middle Triassic Rewan Group, Clematis Group and the Moolayember Formation. Average thickness for these units are 93 m, 148 m, 117 m and 182 m, respectively (Evans et al., 2018). In these upper sequences, unconformities of lesser magnitude occur at the end of the Permian and at the end of the Early Triassic.
- The Early Jurassic to Late Cretaceous Eromanga Basin constitutes most of the cover over the Galilee Basin. A significant hiatus of approximately 65 million years separated cessation of deposition in the Galilee Basin and initiation of the Eromanga Basin. In the Galilee subregion, the Eromanga Basin sequence is thickest in the Powell and Lovelle depressions (up to 1800 m), which suggests that these regions continued as depocentres during the Jurassic-Early Cretaceous, in contrast to the Koburra Trough, which had ceased active subsidence.
- Exposed and subsurface extents of Cenozoic sediments are scattered across the Galilee subregion as remnants of isolated lacustrine, spring and fluvial depositional events. These remnants of small depocentres have unique depositional histories, although there may be some similarities in timing of depositional events. Basaltic volcanics occur around the north-eastern margin of the Galilee subregion (see Figure 13 in Section 2.1.2.2.5 of companion product 2.1-2.2 (Evans et al., 2018)). The youngest alluvial sediments are associated with current drainage. The Cenozoic sediments, while a thin cover of the much bigger Galilee and Eromanga geological sequences, are a crucial interface between groundwater systems in underlying aquifers and surface water systems.

Figure 7, Figure 8, and Figure 9 show some of the features of the geological architecture demonstrated by the Galilee subregion geological model (see companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018)). The locations of the cross-sections are shown in Figure 6.

Figure 7 is a north-east oriented cross-section through the central portion of the Galilee subregion. It shows the faulted nature of the western margin of the Galilee Basin, with fault movement along the Hulton-Rand structure offsetting the Galilee Basin sequences against the Maneroo Platform. Figure 7 also shows how Moolayember Formation thins near the western margin of the Galilee Basin allowing direct contact between the Clematis Group, and the overlying Hutton Sandstone, which is a part of the Eromanga Basin.

Outcrop of Hooray and Hutton sandstones forms a prominent ridge that demarcates the eastern margin of the Eromanga Basin. The broad topographic high is apparent between the margin of Eromanga Basin and the Great Dividing Range, and includes the closed basins that encompass lakes Buchanan and Galilee. Carmichael and China Stone coal projects are situated on the eastern flank of the Great Dividing Range.

Prominent in Figure 8 is a fault block associated with the Barcaldine Ridge. Here, an up-thrown block of Joe Joe Group sedimentary rocks abuts against Triassic-aged sedimentary rocks of the Galilee Basin (Rewan Group, Clematis Group and Moolayember Formation). The Barcaldine Ridge fault blocks demarcate the boundary between the northern and southern Galilee Basin. Also apparent is the significant thickness of Eromanga Basin strata that occurs in the southern Galilee Basin.

Figure 9 is a north-easterly cross-section through the southern Galilee Basin and the Powell Depression. Most of the Galilee Basin sequence is missing in the Powell Depression with much of the infill comprising sedimentary rocks of the Eromanga Basin. As with Figure 7, it is apparent that two sub-parallel ridges along the eastern margin form the most prominent topographic high in the Galilee subregion.

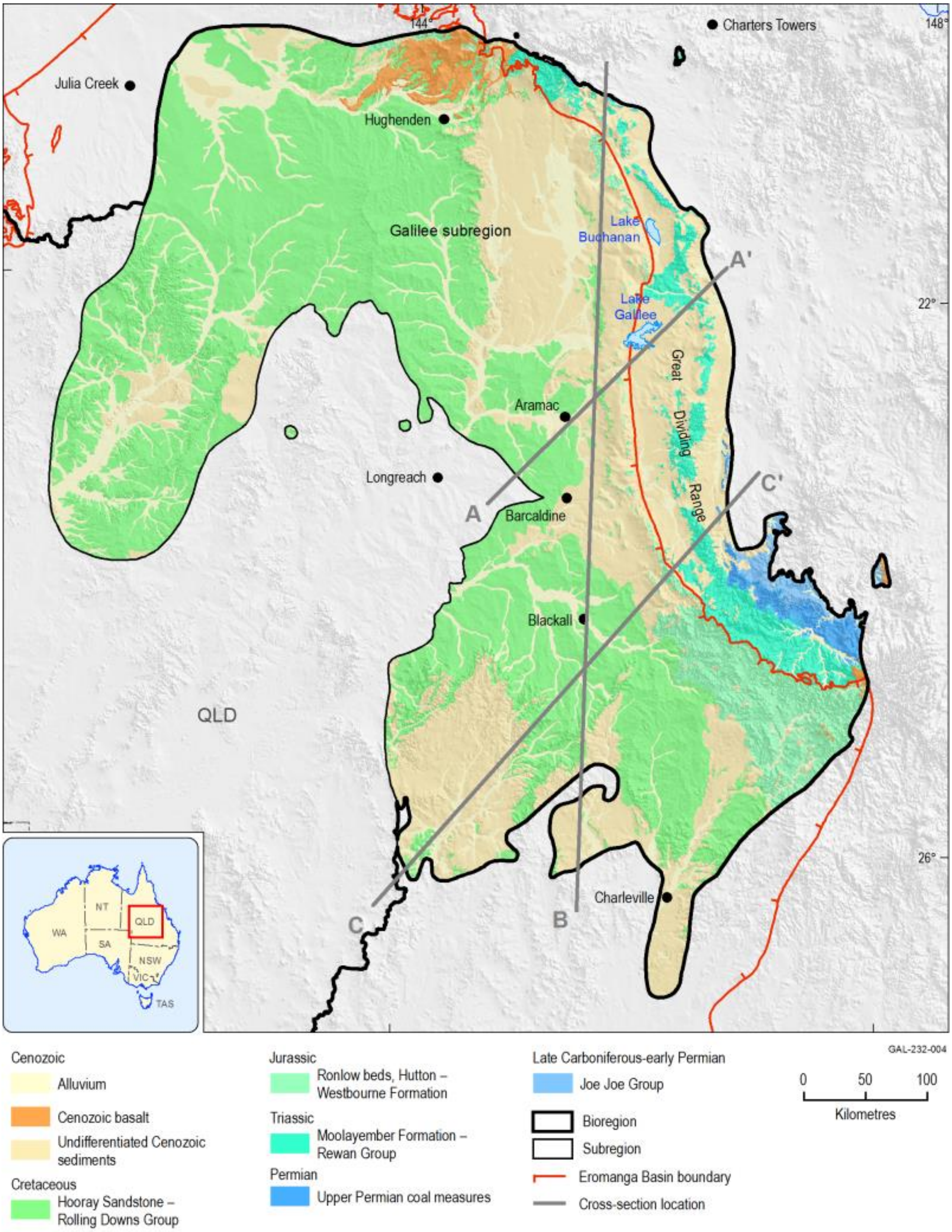

Figure 6 Surface geology of the Galilee subregion and location of geological cross-sections

Cross-sections A to A', B to B' and C to C' are shown in Figure 7, Figure 8 and Figure 9, respectively.
Data: Geoscience Australia (Dataset 1, Dataset 2)

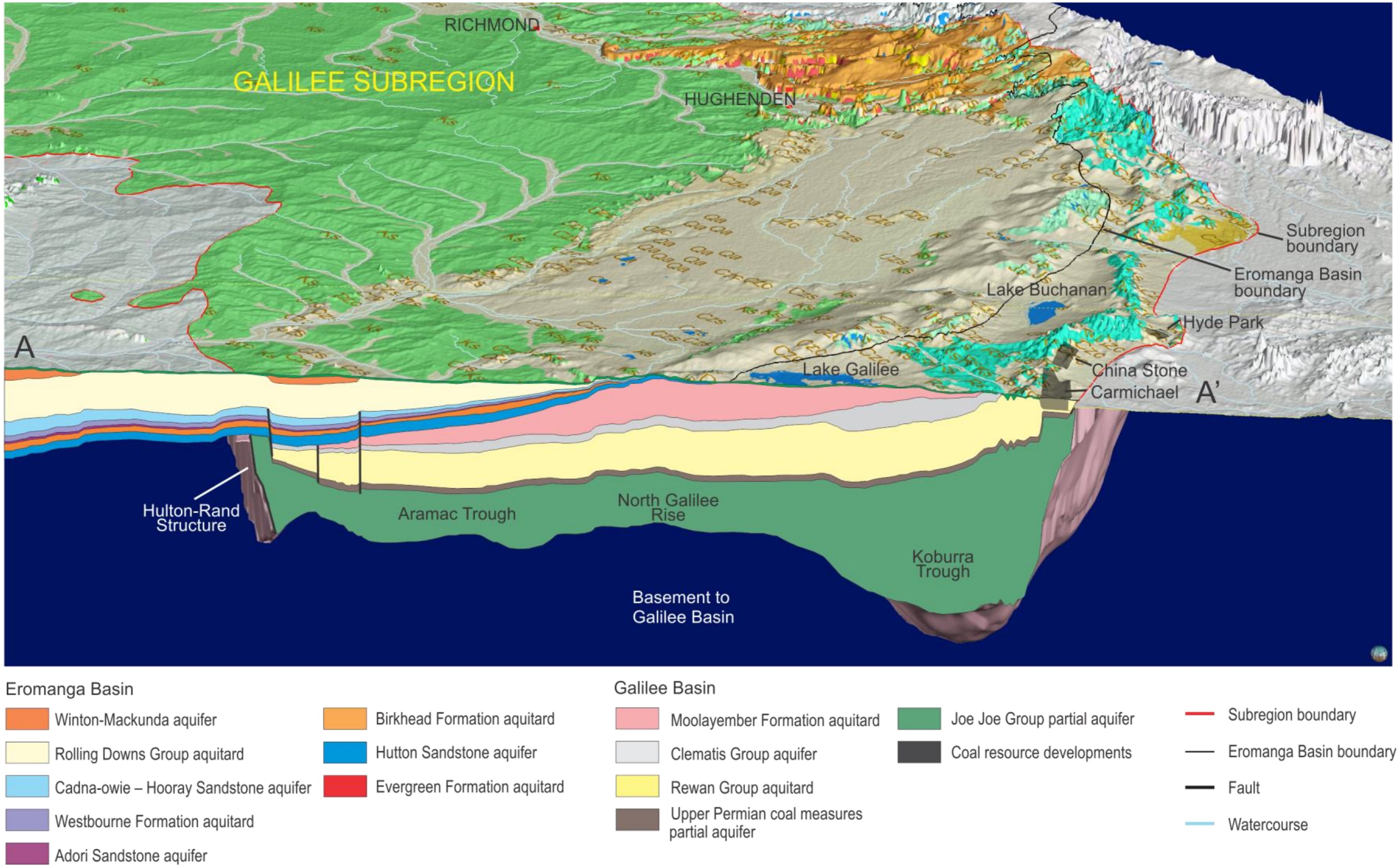

Figure 7 Geological cross-section of the Galilee and Eromanga basins. Cross-section A to A', looking north-west

The cross-section represents a slice through Galilee subregion three dimensional geological model (Evans et al., 2018) along a line. Location of geological cross-section line is shown in Figure 6.
The legend in this figure only applies to the cross-section. The legend for the surface geology is outlined in Figure 6.
Data: Bioregional Assessment Programme (Dataset 3)

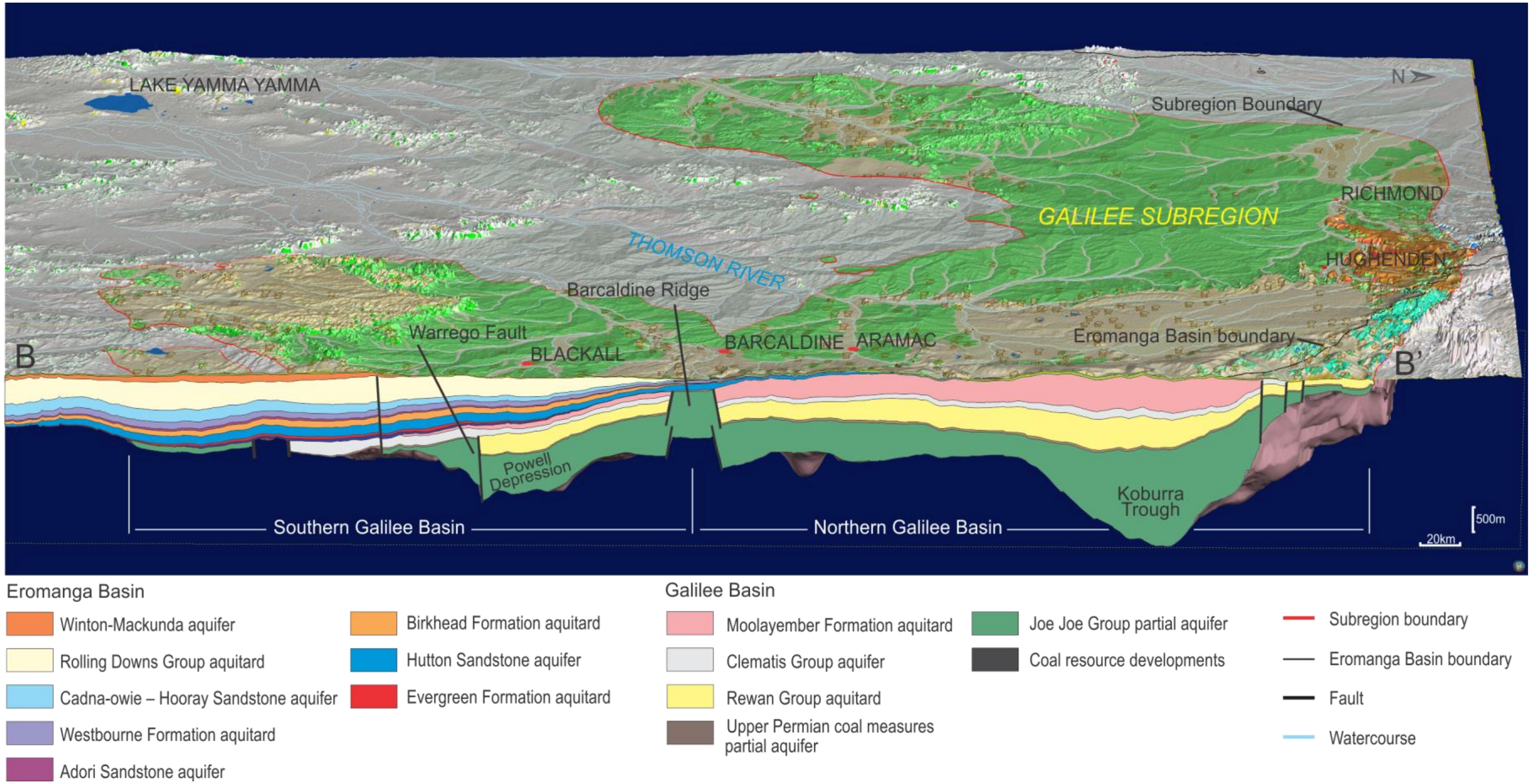

Figure 8 Geological cross-section of the Galilee and Eromanga basins. Cross-section B to B', looking west

The cross-section represents a slice through Galilee subregion three dimensional geological model (Evans et al., 2018) along a line. Location of geological cross-section line is shown in Figure 6. The legend in this figure only applies to the cross-section. The legend for the surface geology is outlined in Figure 6.
Data: Bioregional Assessment Programme (Dataset 3)

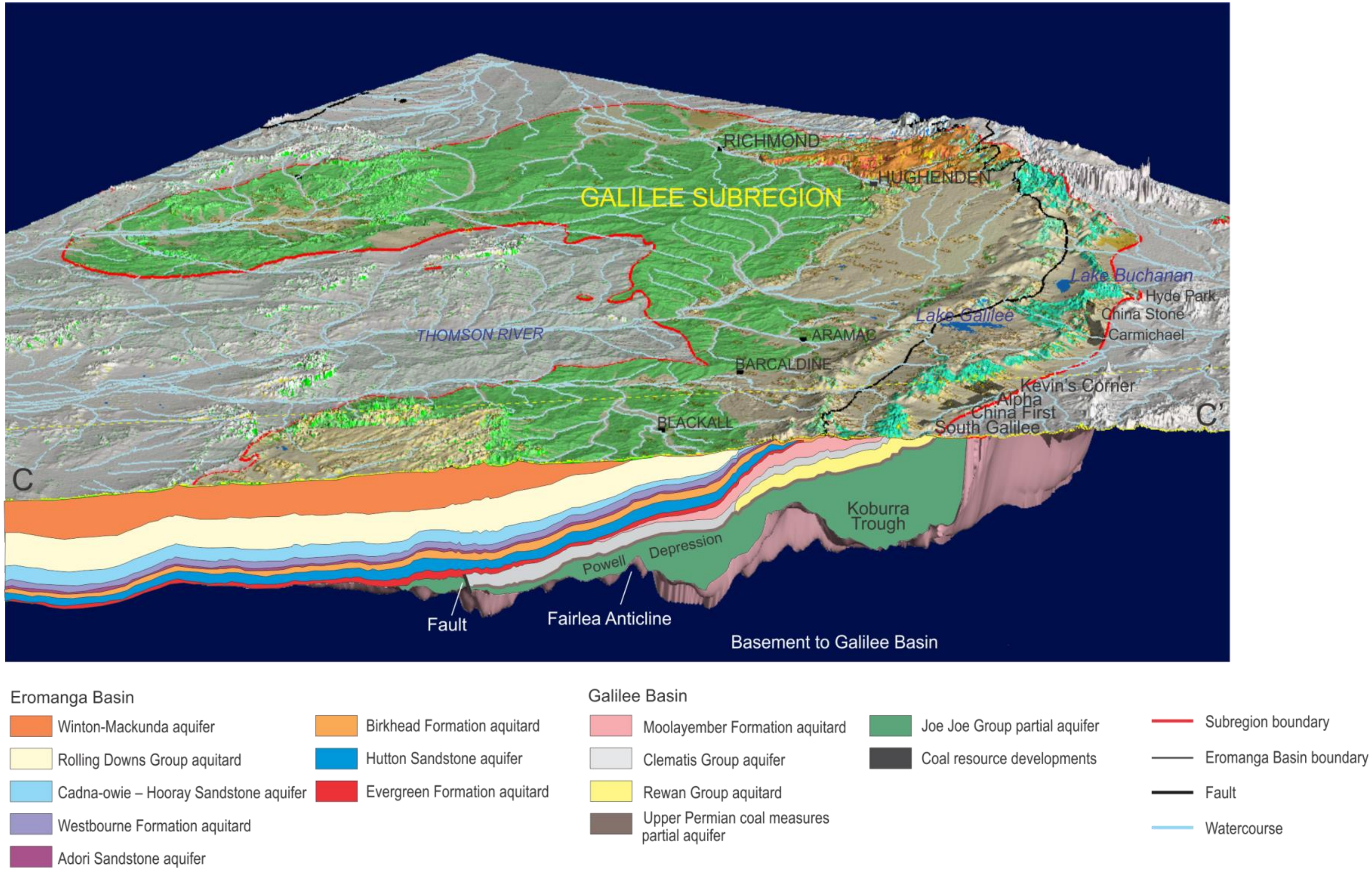

Figure 9 Geological cross-section of the Galilee and Eromanga basins. Cross-section C to C’, looking north-west

The cross-section represents a slice through Galilee subregion three dimensional geological model (Evans et al., 2018) along a line. Location of geological cross-section line is shown in Figure 6.
The legend in this figure only applies to the cross-section. The legend for the surface geology is outlined in Figure 6.
Data: Bioregional Assessment Programme (Dataset 3)

2.3.2.2.1.1 Overburden thickness to the upper Permian coal measures

The upper Permian coal measures are the primary target for CSG and coal mining development in the Galilee subregion. Overburden thickness is one of several significant factors that affect the degree of connectivity between aquifers that may occur in the coal measures and water-dependent assets. The overburden or cover to the upper Permian coal measures is the combined thickness of the Cenozoic sediments, Eromanga Basin sequence, and the Moolayember Formation, Clematis Group and Rewan Group of the Galilee Basin (Figure 10).

Outcrop of upper Permian coal measures occurs along the eastern margin of the Galilee subregion. Westwards from the outcrop areas, overburden thickens to over 500 m. The only area of relatively thin overburden away from the eastern margin of the subregion is in the vicinity of the Barcaldine Ridge, where the overburden thins to considerably less than 400 m. On the Barcaldine Ridge overburden to the upper Permian coal measures consists almost entirely of Eromanga Basin strata, which in turn is overlain by a thin veneer of Cenozoic sediments.

It is apparent from Figure 10 that the Barcaldine Ridge is rather complex and consists of at least two blocks that trend in an easterly direction away from the western margin of the Galilee Basin. On the westernmost block, the upper Permian coal measures have been eroded away exposing a ridge of geological basement rocks that protrudes eastwards into the Galilee Basin sequence. The second block is situated immediately to the south-east of Barcaldine township. This block is defined by the area where the overburden thins significantly to less than 400 m. In this area the whole sequence of Triassic aged sedimentary rocks (Rewan Formation to Moolayember Formation sequence) is missing and has presumably been eroded away. Erosion of the Triassic aged sequence would have been facilitated by upward movement of the fault-bound block that underlies this segment of the upper Permian coal measures. A cross-section (Figure 8) through the second (easternmost) block that defines the Barcaldine Ridge suggests that the amount of apparent offset that has occurred along the faults that define the boundaries of this block is in the order of 500 m. Overburden thickness contours (Figure 10) suggest that the influence of Barcaldine Ridge structures diminishes eastwards of the second block and is not apparent near the eastern margin of the Galilee subregion.

Much of the overburden cover comprises the Eromanga Basin sequence. In the Galilee subregion, the Eromanga Basin sequence is thickest in the Powell and Lovelle depressions (up to 1800 m), which suggests that these regions continued to act as depocentres during the Jurassic-Early Cretaceous. This is in contrast to the Koburra Trough, which had ceased active subsidence by this period.

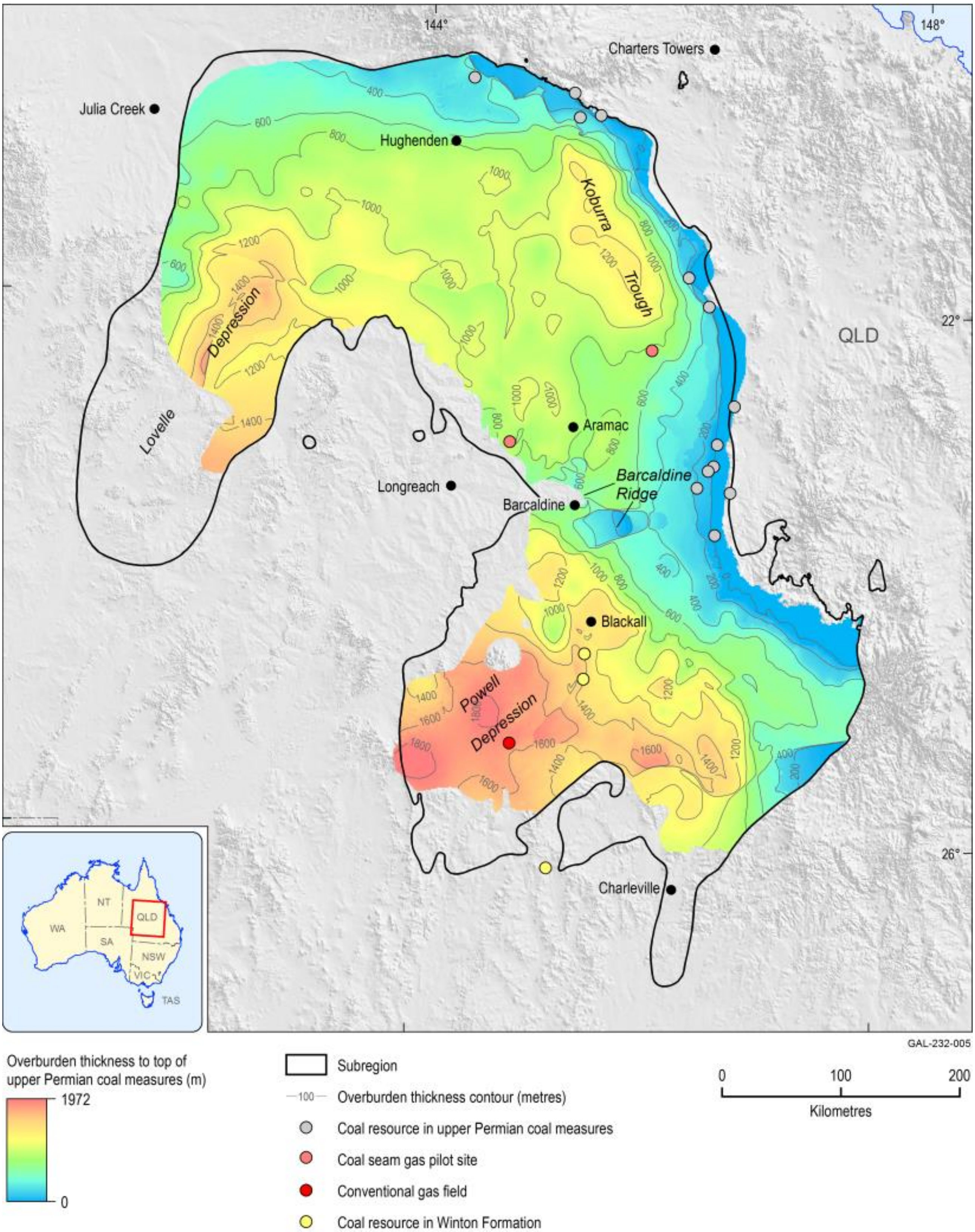

Figure 10 Thickness of sedimentary cover above the upper Permian coal measures

Data Bioregional Assessment Programme (Dataset 4), Geoscience Australia (Dataset 5), Bureau of Meteorology (Dataset 6)

2.3.2.2.1.2 Potential basin connectivity

Of prime interest towards understanding groundwater and hydrocarbon movement is the identification of potential connectivity of aquifers between different geological basins, and ultimately connectivity of underlying aquifers with surface alluvial aquifers. Understanding the connection of aquifers with deeper basins helps identify potential pathways for fluid migration.

The greatest potential for connectivity can be through the direct contact of aquifers in each basin, either through overlap of their stratigraphic extent, or from their juxtaposition along faults. Fault zones can potentially be either conduits or barriers to groundwater movement (Bense et al., 2013).

Potential connectivity between Galilee and Eromanga basins

The Galilee subregion geological model demonstrates that, in some areas there is direct contact between major aquifers in the Eromanga Basin (e.g. Hutton Sandstone aquifer) and the Clematis Group aquifer and upper Permian coal measures in the underlying Galilee Basin.

The Moolayember Formation, an aquitard of variable hydraulic character, is either thin or absent near the western margins of the Galilee Basin (Figure 11; see also Figure 16 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018)), enabling aquifer contact between basins. The Rewan Group, the next aquitard down-sequence in the Galilee Basin, extends an effective sealing cover westwards towards the Maneroo Platform (Figure 11). The combined extent of these aquitards is limited to the south-west, and enables a large area of aquifers in the Galilee Basin sequence to abut the Eromanga Basin sequences on three sides of the Maneroo Platform.

Small areas of Clematis Group aquifer are in direct contact with overlying Hutton Sandstone or Precipice Sandstone aquifer (Eromanga Basin) in the vicinity of the Maneroo Platform (to the north-west of Barcaldine) and near the southern margin of the Galilee Basin, south of Blackall.

Large areas of upper Permian coal measures partial aquifer as well as the deeper Joe Joe Group partial aquifer are also in direct contact with the base of the Eromanga Basin across parts of the southern Galilee Basin, in a narrow zone adjoining the Maneroo Platform along the western margin of the Galilee subregion (north-west of Barcaldine). Here, the Joe Joe Group and upper Permian coal measures partial aquifer are overlain predominantly by the Hutton Sandstone aquifer. A thin zone of deeper Galilee aquifers (Joe Joe Group) along the north-western edge of the Galilee subregion (south of Julia Creek) are in direct contact with the Cadna-owie – Hooray aquifer and Hutton Sandstone aquifer. In the southern Galilee subregion, the above mentioned Galilee Basin sequences are in contact with the Precipice Sandstone aquifer.

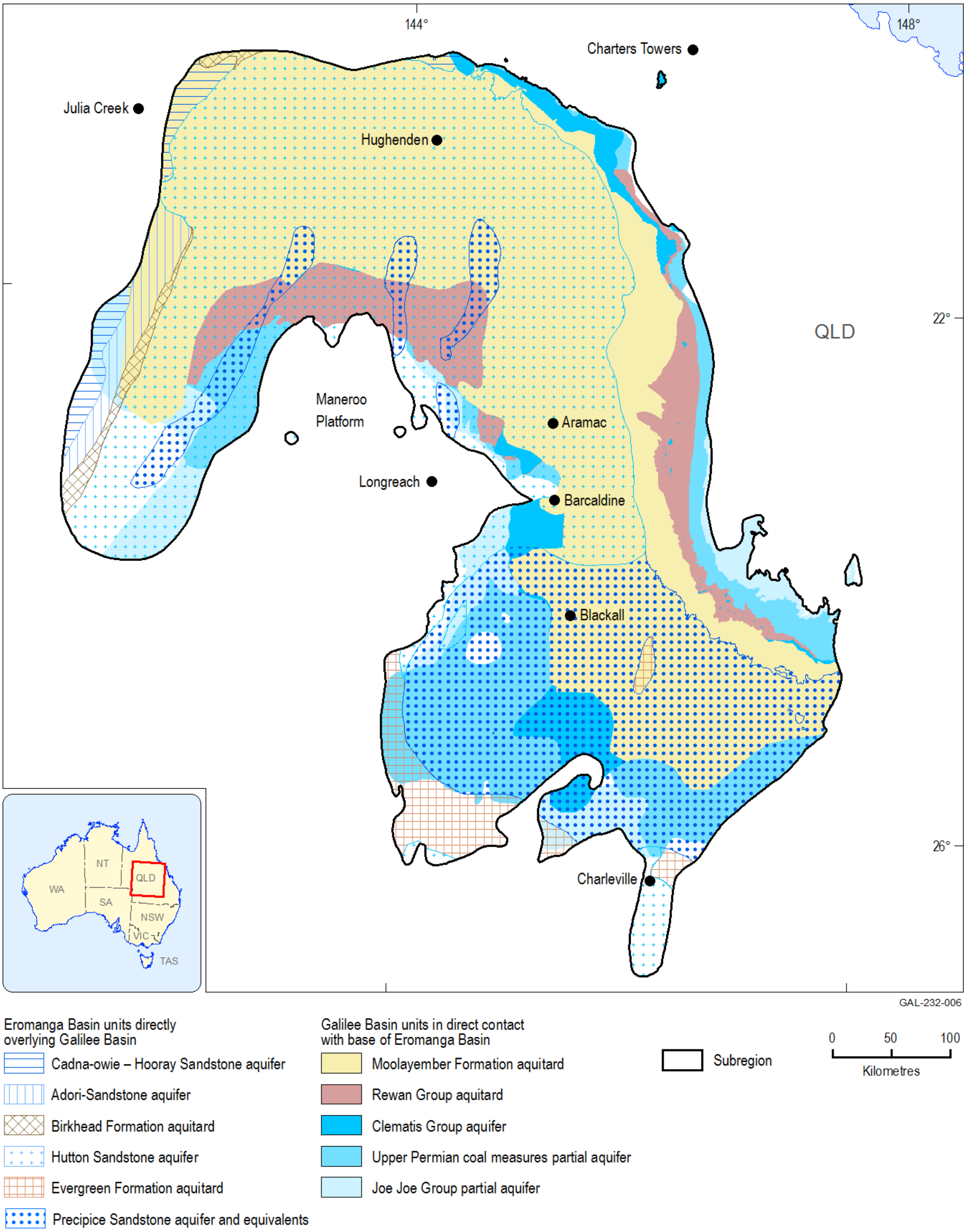

Figure 11 Areas of potential hydraulic connectivity between the Galilee and Eromanga basins

Potential areas of inter-aquifer connectivity may occur particularly in areas where the Rewan Group and Moolayember Formation are missing from underneath the Eromanga Basin in the Galilee subregion. This would allow potentially more permeable sequences, such as Clematis Group, upper Permian coal measures and Joe Joe Group, to be in direct contact with the base of the Eromanga Basin.
Data: Bioregional Assessment Programme (Dataset 3, Dataset 7), Geoscience Australia (Dataset 8)

Potential for structural connectivity within the Galilee and Eromanga basins

Marsh et al. (2008) noted that, on a regional scale, stratigraphic sequences in the Galilee Basin and overlying areas of the Eromanga Basin appear to be relatively free from structural overprint. Research since 2008 has improved knowledge of the geological structure and its complexity. For example, there is faulting associated with the Barcaldine Ridge (Figure 8, Figure 10) and recent work outlined in Comet Ridge Ltd (2016) has improved structural understanding of deeper parts of the Galilee Basin. The structural style of the southern Galilee Basin differs from the northern parts in that it has extensive subtle folding inherited from underlying structural deformation associated with inversion of the Adavale Basin.

It is difficult to make a general categorisation about the hydraulic characteristics of faults, whether they may be a potential conduit or a barrier (or have little effect), as their effects on the groundwater flow regime are commonly poorly understood (Moya et al., 2014; Bense et al., 2013). This can depend on a number of factors including fault orientation, fault type and movement history, amount of offset, the present day stress regime, and type of fault infill. Faults can act as barriers if they juxtapose an aquifer against an aquitard or if the faults are filled with significant amounts of clay gouge. Alternatively, faults can act as conduits if there is sufficient fracture connectivity or if a fault is orientated favourably with regards to the present-day stress regime.

Major faults do occur in the Galilee subregion (e.g. Figure 7, Figure 8, and Figure 9) The Cork Fault has had vertical displacement in the Cenozoic with locally up to 420 m displacement at the base of Eromanga sequence (Ransley et al., 2015). Aside from the Holberton-Cork-Wetherby fault structures in the Lovelle Depression, it appears that many of the more significant faults occur near the margins of the Galilee subregion, in particular the western margin adjoining the Maneroo Platform. Many faults here are reactivated basement reverse faults such as the Hulton-Rand and Tara structures, which have had vertical displacement during the Paleozoic and Mesozoic and were generally syn-depositional with basin sequences (Vine et al., 1965; Moya et al., 2014). At present, vertical displacement on some of these features (at top of Hutton Sandstone) ranges from 350 m (Hulton-Rand Structure), 265 m (Tara Structure), 165 m (Maranthona Monocline) and 50 to 120 m (Darriveen, Longreach and Corfield faults on basement over the Maneroo Platform). The Maranthona Monocline apparently ceased movement after Cadna-owie Formation deposition in the Early Cretaceous (Moya et al., 2014). For further detail on structures see Section 2.1.2.3.3 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018).

Most fault activity in the Galilee Basin occurred during the early Permian and late Permian, and thus mainly affected the Joe Joe Group. Up-sequence in and above the upper Permian coal measures, tectonic activity and disruption was minimal to absent. Many other faults do not extend far up sequence from basement, but instead may transition upwards into folds. Upper Permian coals overlying faults in the Aramac Depression at Rodney Creek are not displaced; however, they are known to be folded with increased cleat development along this structure (Bradshaw et al., 2009). One exception may be faulting associated with the Barcaldine Ridge structures. Continued fault movement along these structures has resulted in Triassic-aged sequences being eroded from across the Barcaldine Ridge.

Polygonal faulting is widespread in the Cretaceous Rolling Downs Group aquitard and the Winton-Mackunda aquifer across the subregion (Ransley et al., 2015). Although this faulting is intraformational within finer-grained rocks and with displacement up to 60 m, it generally terminates against thick sandstone beds within these hydrostratigraphic units. Polygonal faults, however, commonly reinitiate upwards from the top of these aquifers. Local aquifer compartmentalisation can result from total or partial juxtaposition against an aquitard.

Reactivation of the regional faults occurred again in the Cenozoic. Most monoclines mapped at surface throughout the basin resulted from this phase of movement. Structural abutment of aquifers against basement blocks and highs, as with faults, may either suppress hydrologic connectivity or force upward connectivity.

2.3.2.2.2 Hydrogeology

Figure 12 defines the hydrostratigraphy of the major hydrogeological systems and outlines which units are acting as either an aquifer or an aquitard (or depending on scale, as both).

Conceptually, the aquifers outlined in Figure 12 form a stacked series of groundwater systems. The configuration of these groundwater systems is dependent on a number of factors including the geological framework, the hydraulic properties of the various geological units and topography. The geological framework configuration and the hydraulic properties of the hydrostratigraphic units will determine what potential interaction occurs between the different groundwater systems. Some general background references on groundwater system concepts and their application include Fetter (2001) and Toth (2009).

There are three major hydrogeological systems present in the Galilee subregion. These are the Cenozoic, Eromanga Basin and Galilee Basin systems. In the Eromanga Basin, the major groundwater systems are the regional watertable aquifer developed in the Winton-Mackunda-Wallumbilla formations, and the deeper confined regional groundwater systems that occur principally in the Hutton Sandstone, Adori Sandstone and Cadna-owie – Hooray aquifer.

In the Galilee Basin, the main groundwater systems occur in the Clematis Group aquifer, the upper Permian coal measures and Joe Joe Group.

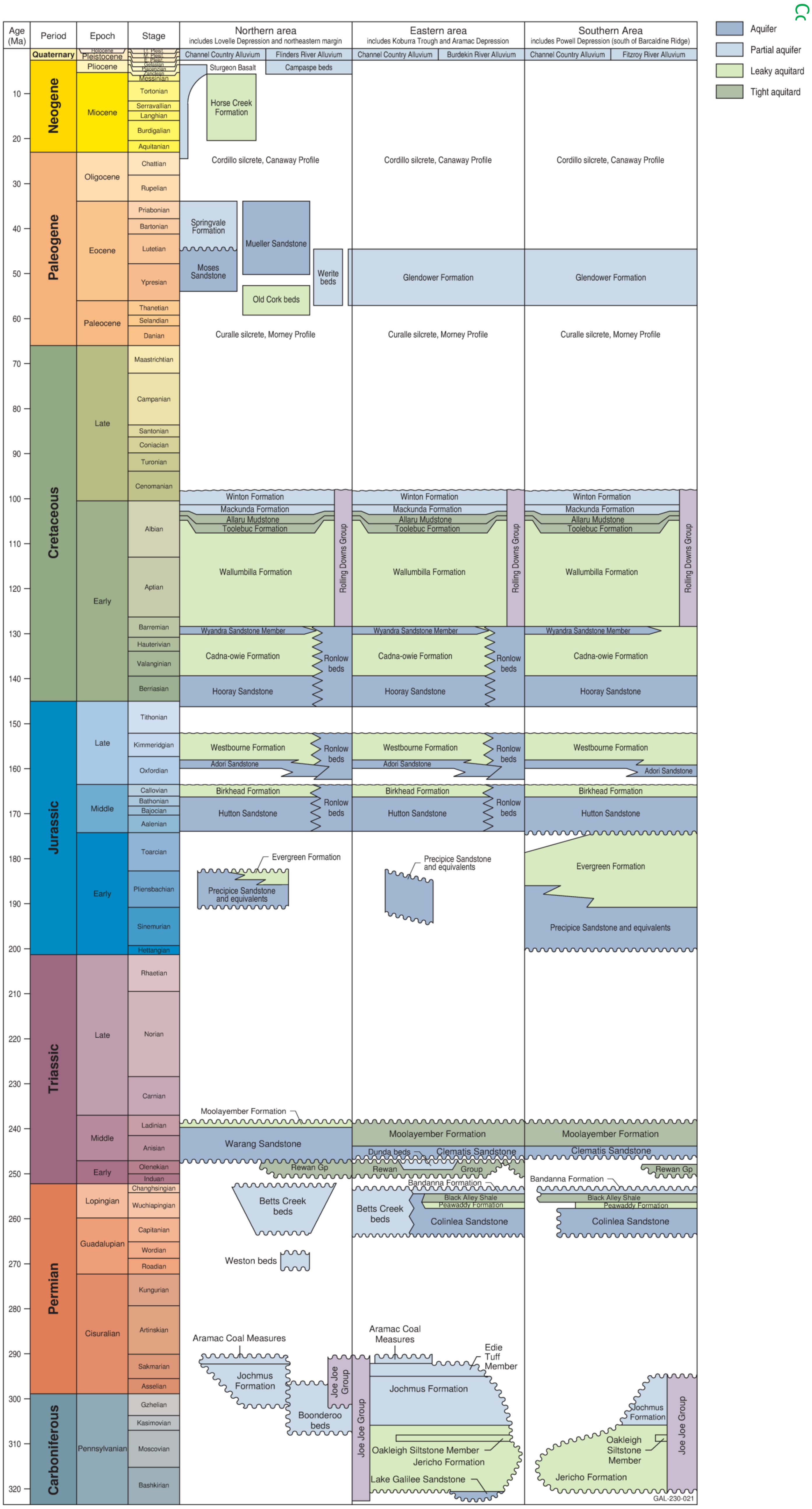

Figure 12 Detailed hydrostratigraphy for the Cenozoic cover, Eromanga Basin and Galilee Basin sequences

Time periods for hydrostratigraphic sequences are: (i) Cenozoic cover - Paleogene to Quaternary; (ii) Eromanga Basin: Jurassic to Late Cretaceous; (iii) Galilee Basin - late Carboniferous to Middle Triassic.
After Figure 9 in Section 2.1.2 of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018).

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

2.3.2.2.2.1 Cenozoic aquifers

Aquifers in Cenozoic sediments overlie all other (older) hydrostratigraphic units and are commonly associated with present-day surface drainage systems. Depending on the local geology groundwater systems in Cenozoic aquifers may be either connected or disconnected from deeper aquifers. Depth to groundwater in Cenozoic sediments is mostly less than 20 m from surface. Distribution of Cenozoic sediments and watertable mapping for the Cenozoic aquifer in Belyando river basin are respectively outlined in Figure 13 (Section 2.1.2) and Figure 56 (Section 2.1.3) of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018).

Groundwater flow for these Cenozoic aquifers is characteristically controlled by local- to regional-scale topographic features, with the flow direction focusing towards major surface drainage features such as rivers and lakes. While the overall groundwater flow direction varies, it moves consistently away from catchment divides. Lake Buchanan and Lake Galilee occur in closed lake basins situated between the Great Dividing Range and the ranges that demarcate the edge of the Eromanga Basin (see also Figure 7 and Figure 18). Conceptually, these lakes may receive groundwater discharge from Cenozoic aquifers that are in the vicinity of the lakes.

Recharge to Cenozoic aquifers can be via rainfall, intermittent flooding of low-lying areas, streams losing water to the shallow watertable, or upwards leakage to shallow aquifers from deeper aquifer systems. Discharge can take the form of baseflow to major drainage or lakes, evapotranspiration, pumping from groundwater bores or leakage to underlying aquifers. Whether evapotranspiration directly from groundwater sources occurs in an area is partially dependent on the type of vegetation present (e.g. river red gums, *Eucalyptus camaldulensis var. obtusa*) and local hydrogeology. Generally, evapotranspiration could be considered a contributing mechanism if depth to watertable is less than 20 m. Where Cenozoic aquifers extend beyond the Galilee subregion boundary, discharge could take the form of throughflow, moving out of the Galilee subregion.

2.3.2.2.2.2 Regional watertable aquifer — Eromanga Basin

The shallowest groundwater system in the Eromanga Basin is developed in the Winton-Mackunda formations, Alluru Mudstone and Wallumbilla Formation, to the west of the Great Dividing Range. Depending on local geological conditions, this aquifer can in places be overlain by the Cenozoic aquifer system. Details on the potentiometric surface mapping for Winton-Mackunda formations, Alluru Mudstone and Wallumbilla formations are shown in Figure 57 and Figure 58 of Section 2.1.3 of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018). The Wallumbilla Formation and Alluru Mudstone comprise much of the Rolling Downs Group aquitard, which is the regional seal for the deeper confined GAB aquifers (Section 2.3.2.2.1.1). Although these units regionally act as an aquitard to underlying aquifers, on a more local scale sandier facies in the Wallumbilla Formation can be used as local water source. Potentiometric surface mapping suggests there is little change in the watertable geometry when transitioning from the Wallumbilla Formation into the Winton-Mackunda aquifer. As a result, the potentiometric surface mapping was combined for all these aquifers. These aquifers are, for the most part, unconfined. There is some potential for these aquifers to be locally confined where the Cenozoic sediments form a thick layer over the top of the aquifer sequence.

Depth to groundwater in this aquifer can be up to 50 m below surface. Depth to groundwater will vary depending on the local geology and location of bores in the landscape. Groundwater mounding can occur under topographically high areas, whereas shallow groundwater may occur nearer to major drainage lines in topographically lower areas (Figure 13). Again, the flow direction is strongly controlled by surface topography, with inferred flow occurring from topographically high areas towards low areas and major drainage lines. Discharge can take the form of baseflow to rivers, evaporation, pumping from bores, or leakage into overlying or underlying aquifers. Where the regional watertable aquifer extends beyond the Galilee subregion boundary, discharge may also occur as throughflow, with groundwater moving westwards out of the Galilee subregion. Groundwater quality varies considerably with average total dissolved solids (TDS) for Winton-Mackunda formations and the Wallumbilla Formation being 3548 mg/L and 2377 mg/L respectively.

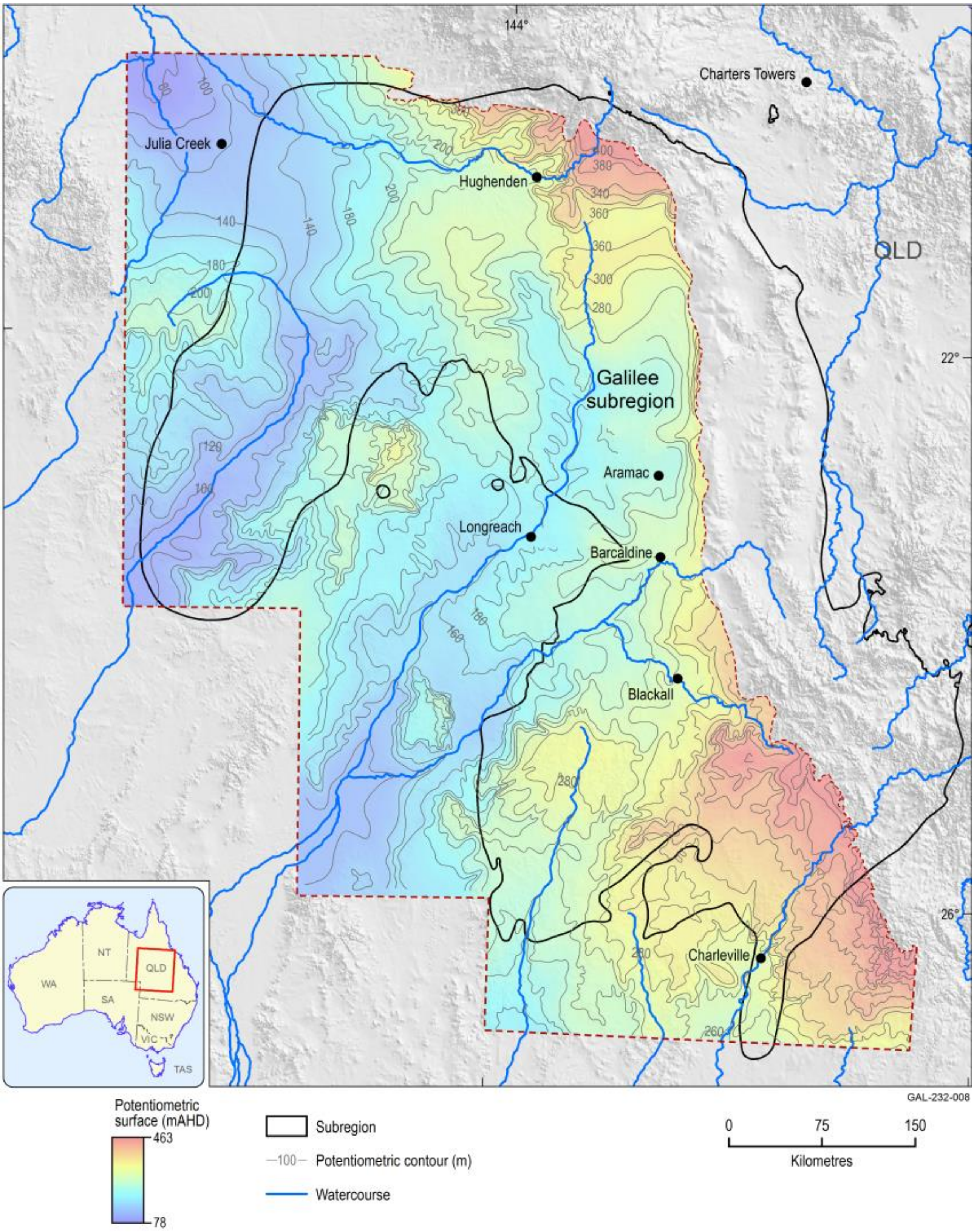

Figure 13 Groundwater flow in shallow aquifers in the Winton-Mackunda Formation and Wallumbilla Formation

Groundwater has potential to flow from areas with high groundwater levels (red to yellow colours) towards areas with lower groundwater levels (blue colours). The rate of flow is partially dependent on hydraulic characteristics of the geological framework. Groundwater flow in the surficial aquifer tends to focus towards major drainage lines.
Data: Bioregional Assessment Programme (Dataset 7, Dataset 9)

2.3.2.2.2.3 Confined Great Artesian Basin regional groundwater systems — Eromanga Basin

The confined GAB regional groundwater system includes the Hutton and Cadna-owie – Hooray aquifers. Other aquifers in this system are the Adori Sandstone aquifer; the Wyandra Sandstone aquifer, which is a part of the Cadna-owie Formation; and the Ronlow beds, which occur around the north-eastern margin of the Eromanga Basin. The distribution of these hydrostratigraphic units is outlined in Section 2.1.2.2.5, while the potentiometric surface mapping for the Hutton and Cadna-owie – Hooray groundwater systems is detailed in Section 2.1.3.2.2 of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018).

Where the recharge areas for the aquifers that comprise the confined GAB regional groundwater systems outcrop, they form a distinct topographic high that follows the eastern margin of the Eromanga Basin (see Figure 7 and Figure 9). West of the outcrop areas, the aquifers become progressively buried by the Rolling Downs Group aquitard. The Rolling Downs Group aquitard includes the Wallumbilla Formation, Toolebuc Formation and Alluru Mudstone and forms a regional seal that confines the underlying GAB regional groundwater systems. The Rolling Downs Group aquitard segregates the confined GAB aquifers from aquifers in the overlying Winton-Mackunda formations. The sealing qualities of the Rolling Downs Group aquitard can vary and are dependent on proximity to faults, including polygonal faulting (Ransley et al., 2015) and the thickness of the aquitard sequence.

Overall, regional groundwater flow in GAB aquifers is in a westerly direction away from topographically elevated areas located along the margins of the Eromanga Basin. The continuity of groundwater flow in the regional aquifer can be disrupted by faults that may offset the aquifer sequence. Figure 14 is an example of potentiometric surface mapping for a confined GAB aquifer, in this case the Hutton Sandstone aquifer, which demonstrates variation in groundwater flow directions that may occur in the Galilee subregion. In the outcrop areas, the GAB aquifers are unconfined, but become confined to the west of areas of outcrop by the Rolling Downs Group aquitard. Artesian conditions will occur where groundwater levels in GAB aquifers exceed the local topographic ground level.

Recharge from rainfall occurs in areas of outcrop along the Eromanga Basin margin (see Section 2.1.3.3.5 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018)) by rainfall or at depth through upward leakage from underlying aquifers that are in direct contact with GAB aquifers; for example, areas where the Clematis Group is in direct contact with the Hutton Sandstone, near the western margin of the Galilee subregion (Figure 11 and Figure 14). Potentially, episodic recharge to these aquifers may also occur during high-flow events or flooding in areas where surface drainage has cut into the recharge areas. This has been found to be an important recharge mechanism where the confined GAB regional aquifers outcrop (and are unconfined by overlying sedimentary rocks) along the western margin of the Eromanga Basin (Miles et al., 2015). Some examples where potential episodic recharge may occur include areas where the Alice River and Flinders River cross-cut recharge areas for the confined GAB regional aquifers.

Discharge can take the form of leakage from confined GAB regional aquifers upwards through the Rolling Downs Group aquitard, but also as natural groundwater throughflow across the subregion boundary. Other significant forms of discharge include springs and bores. Evans et al. (2015) provide an estimate of discharge from bores for various confined GAB regional aquifers.

The Barcaldine Springs complex occurs either side of ranges that comprises GAB aquifer outcrop (Figure 14, inset (a)). While groundwater flow in the confined GAB regional aquifers is predominantly to the west, a local eastward flow component is evident (Figure 14, inset (a)) in the outcrop area. The eastward flow component forms a local scale groundwater system that discharges as a line of springs near the eastern boundary of the GAB aquifer as outcrop springs. A number of springs in the eastern line occur in the vicinity of surface drainage; therefore, there is also some potential for leakage to occur into nearby Cenozoic alluvium. Many of the springs that are to the west of the GAB regional aquifer outcrop are situated on the Rolling Downs Group aquitard outcrop. Drill-hole data and surface geology suggest that, here, the aquitard is relatively thin or missing; therefore, in these areas the confined GAB regional aquifers are discharging at low points in the landscape where the Rolling Downs Group aquitard is compromised (Figure 14).The western spring line also coincides with the Moocha-Nogoa structure (Section 2.1.2 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018)). It is possible that structural disruption along this feature may provide some control on the expression of these springs at surface. Further information on the Barcaldine Springs complex can be found in Fensham et al. (2016).

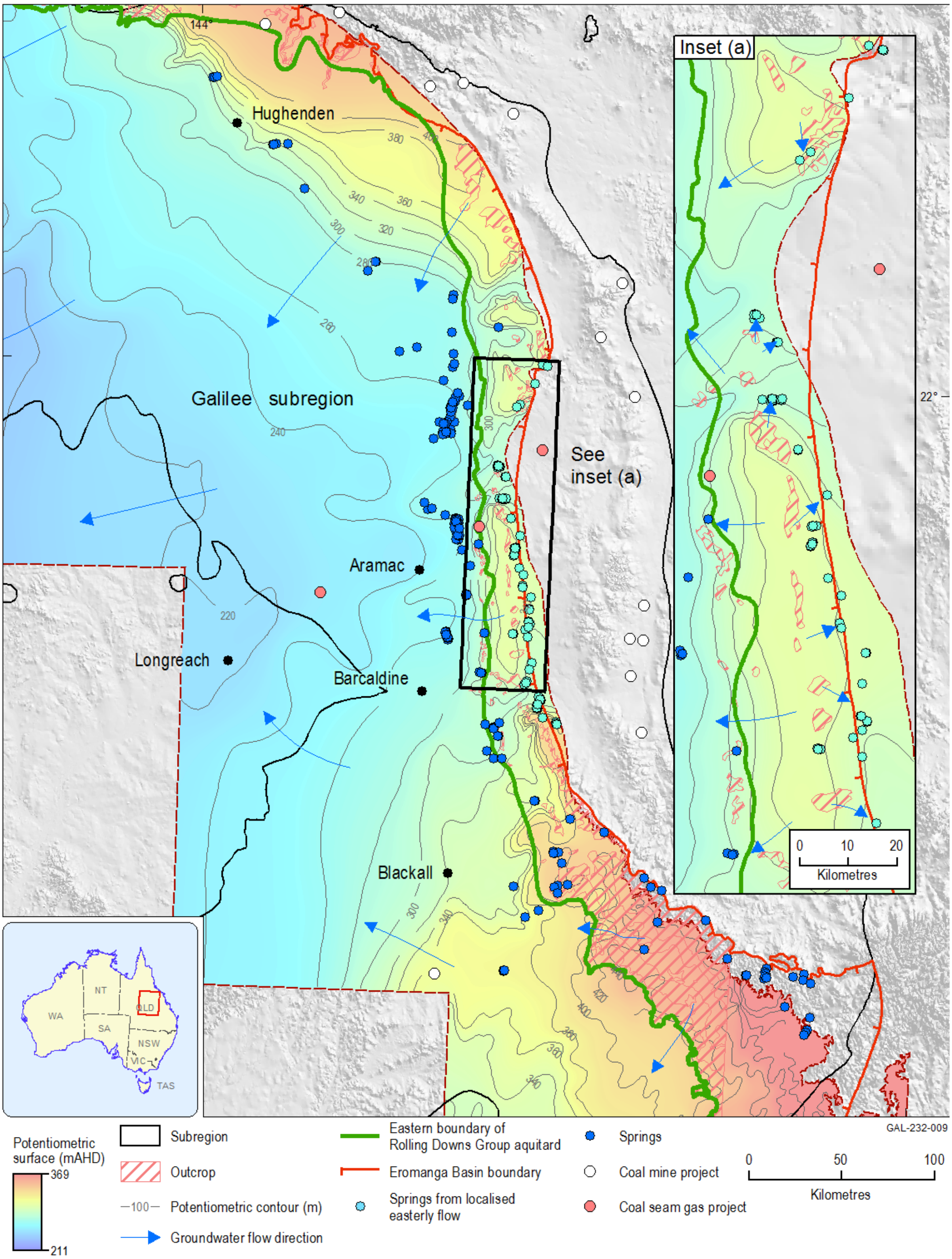

Figure 14 Conceptualisation of confined Great Artesian Basin regional groundwater systems, using the Hutton Sandstone aquifer potentiometric surface mapping as an example

Potentiometric surface mapping for the Hutton Sandstone aquifer is used as an example to demonstrate the variation in lateral groundwater flow direction that may occur in confined Great Artesian Basin regional aquifers. Groundwater has the potential to flow from areas with high groundwater levels (red to yellow colours) towards areas with lower groundwater levels (blue colours). The rate of flow is partially dependent on hydraulic characteristics of the aquifer.

Inset (a) details the flow directions around a groundwater mound that has developed under a topographically elevated area that comprises GAB aquifer outcrop (the recharge beds). Groundwater flow directions are away from the groundwater mound (predominantly to west and east).

Data: Bureau of Meteorology (Dataset 6), Bioregional Assessment Programme (Dataset 7, Dataset 11, Dataset 12), Queensland Department of Natural Resources and Mines (Dataset 10)

2.3.2.2.2.4 Clematis Group groundwater system – Galilee Basin

The Clematis Group aquifer includes the Warang Sandstone and the Clematis Sandstone aquifer. Distribution of the groundwater in the Clematis Group is outlined in Section 2.1.2.2.5, while details on the potentiometric surface mapping and hydrochemistry can be found in Section 2.1.3 of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018). The Clematis Group aquifer outcrop occurs just east of the crest of the Great Dividing Range. For the most part, the Clematis Group aquifer is confined by the underlying Rewan Group aquitard and overlying Moolayember Formation aquitard, except in the vicinity of outcrop areas.

The hydrodynamics of the Clematis Group aquifer (Figure 15) is quite different to what occurs in overlying Eromanga Basin aquifers. It is likely there is more compartmentalisation of the aquifer through the development of groundwater divides as well as structural complexity around the Barcaldine Ridge. As much of Clematis Group aquifer is confined, it is possible that some recharge would occur through leakage through underlying and overlying aquifers. Some recharge to the Clematis Group groundwater system may also occur through rainfall in outcrop areas.

An erosional hole in the Clematis Group, associated with the Barcaldine Ridge, forms a dividing barrier in the Clematis Group aquifer groundwater system. South of the Barcaldine Ridge (Figure 15), the groundwater flow potential in the Clematis Group aquifer is generally westward into the basin with some minor eastward flow from the crest of Great Dividing Range towards margins of Clematis Group outcrop.

North of the Barcaldine Ridge, a north-trending groundwater divide (Figure 15) segregates inferred groundwater flow into eastward and westward directed flow components. The part of the Clematis aquifer where the north-trending groundwater divide occurs is deeply buried by overlying sedimentary rocks (mostly Moolayember Formation). If this groundwater divide was projected to surface, it would be located under a topographically elevated area (greater than 300 m AHD) that lies between the crest of the Great Dividing Range and the ranges that occur along the margin of the Eromanga Basin (see Figure 7 and Figure 9 for examples).

On the east side of the groundwater divide, from the Clematis Group aquifer potentiometric mapping (Evans et al., 2018) it is inferred groundwater flow focuses towards the Carmichael River basin and the Doongmabulla Springs complex. This occurs because the Carmichael River and its tributaries have incised into outcrop of the Clematis Group and Moolayember Formation forming topographic low area in the landscape. West of the groundwater divide, flow is inferred to go westwards towards the margin of the Galilee Basin. Here, parts of the Clematis Group are in direct contact with the overlying Hutton Sandstone (Evans et al., 2018), which may provide potential pathways for leakage and interconnection between the two aquifers.

There is some hydrochemical evidence that suggests there is potential for discharge to occur from the western margin of Galilee Basin into overlying aquifers in the Eromanga Basin such as the Hutton Sandstone aquifer (Evans et al., 2018). Discharge rates and volumes though are unknown. Discharge along the eastern margin of the Clematis Group aquifer is likely to contribute baseflow to tributaries of the Carmichael River and is also likely to be the primary source aquifer for the Doongmabulla Springs complex (Evans et al., 2018; Lewis et al., 2018). GHD Pty Ltd (2013) outlined some baseflow modelling estimates for the Carmichael River. It suggests that the baseflow contribution increases dramatically along the reach of the Carmichael River where the Clematis Group subcrops beneath the alluvium and downstream from the Doongmabulla Springs complex. Baseflow contribution then decreases east of where the Clematis Group and Dunda beds subcrop beneath the river. Pumping of bores is another form of discharge from the aquifer.

The Doongmabulla Springs complex consists of 187 spring vents that form around 160 discrete wetland areas (Fensham et al., 2016). The springs and wetland areas occur adjacent to Dyllingo Creek and its tributaries, near the geological contact between the Clematis Group aquifer and overlying Moolayember Formation aquitard. The springs are situated in areas where either the Moolayember Formation aquitard thins, or where the Clematis Group aquifer and Dunda beds outcrop beneath the alluvium in the creek valley. Many of the springs are situated on alluvium overlying either the Moolayember Formation or the Clematis Group. Potentiometric surface mapping (Figure 14) for the Clematis Group aquifer suggests that east of the groundwater divide the regional groundwater flow is towards the Carmichael River. The springs coincide with a low point in potentiometric surface mapping, suggesting that the springs are acting as discharge points for the Clematis Group aquifer and, to a much lesser degree, the Dunda beds.

Further detail on the hydrogeology of the Doongmabulla Springs complex and the dynamics of the hydrology of the spring wetlands is provided in Section 3.4 and Section 3.5 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018). As outlined in Lewis et al. (2018), there is significant local complexity in the hydrogeology of the Doongmabulla Springs complex, with contributions to spring discharge occurring from both confined and unconfined parts of the Clematis Group aquifer, as well as unconfined sections of the Dunda beds aquifer. Lewis et al. (2018) noted that most of the springs occur where the Moolayember Formation substrate fails as an aquitard over confined portions of the Clematis Group aquifer. Whereas, springs in the eastern part of the complex, are associated with outcropping parts of the unconfined Clematis Group aquifer and unconfined aquifers in the Dunda beds.

As outlined in Fensham et al. (2016) and Lewis et al. (2018), it has been hypothesised by other researchers that the upper Permian coal measures may be a significant contributing aquifer to the the Doongmabulla Springs complex. It is less plausible that the upper Permian coal measures is a direct groundwater source for the springs, as potential vertical groundwater flow would be significantly impeded by the overlying Rewan Group aquitard. Data from Shoemaker 1, a CSG exploration well drilled within a few kilometres of Doongmabulla Springs complex, suggest that the Rewan Group aquitard is around 330 m thick and the top of the upper Permian coal measures is 653 m below surface (Comet Ridge Ltd, 2010). The Rewan Group aquitard separates the Clematis Group aquifer from the upper Permian coal measures. Investigations (drill stem testing) undertaken as part of the Shoemaker 1 drilling programme measured the reservoir pressures of some coal seams in the upper Permian coal measures. Groundwater levels calculated from the results of these drill stem tests suggest that potential exists for vertical groundwater movement to occur from the upper Permian coal measures to the Clematis Group. However, the relatively low hydraulic conductivity of the Rewan Group, when compared to the Clematis Group, combined with its significant thickness would act to restrict vertical groundwater flow across the aquitard. This would decrease the potential for the upper Permian coal measures to significantly contribute to discharge at the springs.

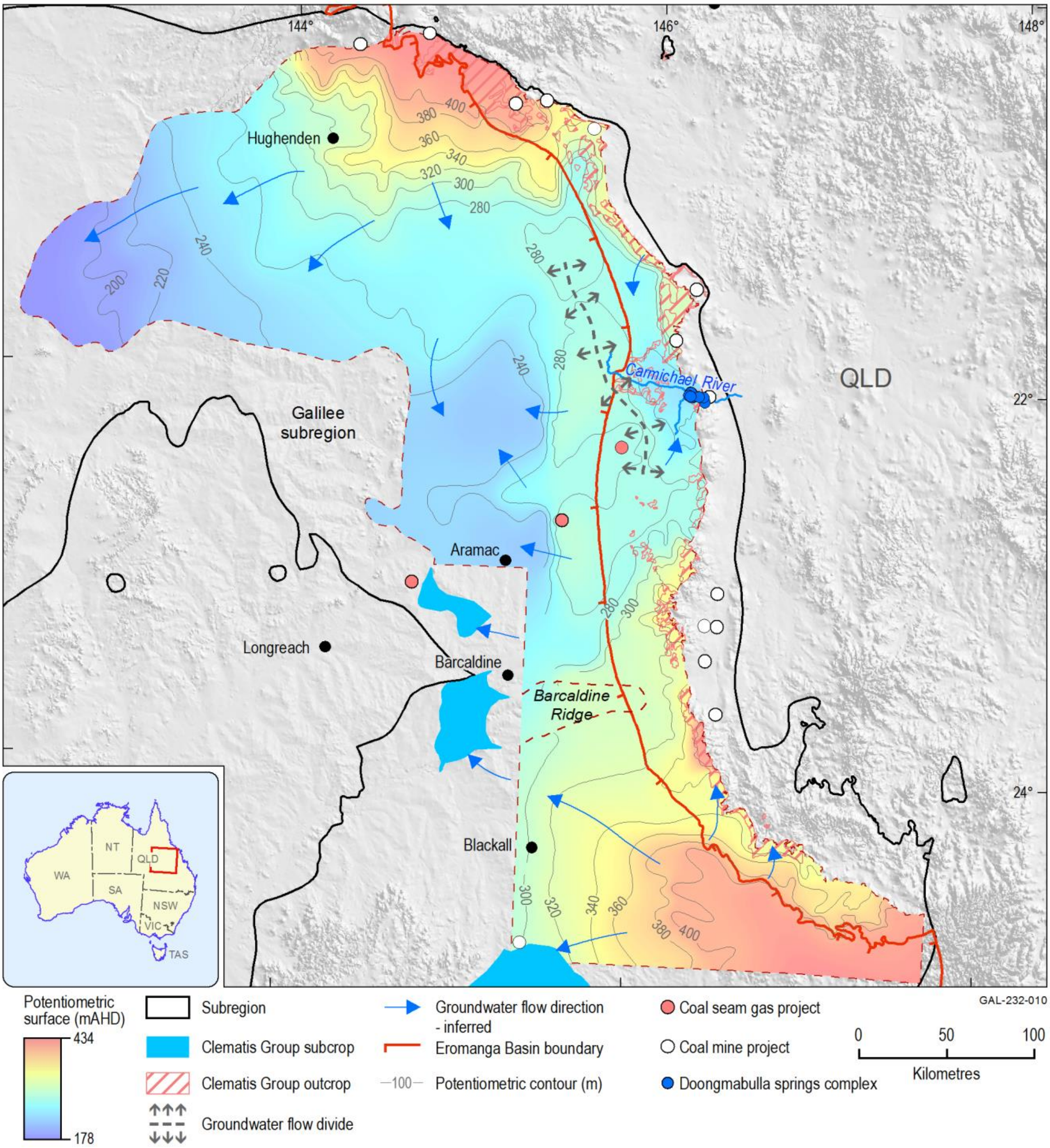

Figure 15 Conceptualisation of Clematis Group groundwater system using potentiometric surface mapping for the Clematis Group aquifer

Groundwater has the potential to flow from areas with high groundwater levels (red to yellow colours) towards areas with lower groundwater levels (blue colours). The rate of flow is partially dependent on hydraulic characteristics of the aquifer.
Blue arrows – groundwater flow direction inferred from Clematis Group potentiometric surface.
Data: Bureau of Meteorology (Dataset 6), Bioregional Assessment Programme (Dataset 7, Dataset 9, Dataset 11, Dataset 12, Dataset 13), Queensland Department of Natural Resources and Mines (Dataset 10)

2.3.2.2.2.5 Groundwater systems in the upper Permian coal measures and Joe Joe Group – Galilee Basin

Distribution of upper Permian coal measures and Joe Joe Group is detailed in Section 2.1.2.2.5, whereas details on hydrochemistry and potentiometric surface mapping are available from Section 2.1.3.2.2 of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018).

Aquifers in upper Permian coal measures are, for the most part, overlain by Rewan Group aquitard and underlain by Joe Joe Group. The upper Permian coal measures and Joe Joe Group can be in direct contact with the overlying Hutton Sandstone and other GAB aquifers around parts of the western margin of Galilee subregion and the Barcaldine Ridge (Figure 16).

Groundwater systems in the upper Permian coal measures and Joe Joe Group are confined except in outcrop areas along the eastern margin of the Galilee subregion. Section 2.1.3.2.2 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018) shows that there is considerable variation in hydraulic conductivity both spatially and vertically by up to two orders of magnitude (so by a factor up to 100) in the upper Permian coal measures. Thus, the aquifers are highly heterogeneous and anisotropic. Although less is known about hydraulic properties for the Joe Joe Group, for the most part it tends to act as a regional aquitard or, at a more local scale, as a partial aquifer.

Generally, the inferred flow directions in the groundwater systems of the upper Permian coal measures and Joe Joe Group are similar to what has already been described for the Clematis Group aquifer. In Figure 16, potentiometric surface mapping from upper Permian coal measures is used as an example of a groundwater system because potentiometric surface mapping for the Joe Joe Group is of limited extent. However, available potentiometric surface mapping suggests that general trends in groundwater flow direction are similar for aquifers in both the Joe Joe Group and upper Permian coal measures.

As what was noted for the Clematis Group aquifer, it is apparent that a broad groundwater divide exists to the north of the Barcaldine Ridge and that there is potential for groundwater flow to occur eastwards and westwards of the divide towards the margins of the basin. Again, if projected to the surface, the groundwater divide would occur in the topographically elevated area situated between the Great Dividing Range and ranges that demarcate the margin of the Eromanga Basin.

The upper Permian coal measures could receive some recharge through rainfall in areas of outcrop or where confined, as leakage from underlying and overlying hydrostratigraphic units. The Joe Joe Group is the lowermost hydrostratigraphic unit for the Galilee Basin. While a possibility, it is not known if the Joe Joe Group receives any recharge as leakage from hydrostratigraphic units in the underlying Drummond and Adavale basins, which occur beneath the Galilee Basin (for further detail see Section 2.1.2.3.4 in Evans et al. (2018)).

Discharge would be via groundwater extraction or through leakage along the margins of the units into overlying aquifers such as the Hutton Sandstone, where the intervening aquitard is absent. As mentioned previously, there is some hydrochemical evidence (Section 2.1.3.2.1 in Evans et al. (2018)) that suggests that discharge is occurring from Galilee Basin groundwater systems into the overlying Hutton Sandstone aquifer along the western margin of the Galilee Basin, although the rate and volume of discharge are unknown.

Along the eastern margin of the Galilee subregion, inferred groundwater flow focusses towards the topographically low area situated between the Kevin's Corner and China Stone coal projects, in particular in the vicinity of the Mellaluka Springs complex. Discharge can take the form of springs, or where connection exists, as upwards leakage to overlying Cenozoic aquifers. For instance, the Mellaluka springs complex is situated away from major drainage lines (GHD Pty Ltd, 2013) but is discharging through Cenozoic sediments. Conversely, in some other areas, clay layers in Cenozoic sediments may be thick enough to act as confining layers to impede significant upward leakage into shallow Cenozoic aquifers.

Some unusual features in Galilee Basin groundwater systems and their possible influence on coal seam gas distribution

Regional potentiometric surface mapping completed as part of the BA for the Galilee subregion represents a new contribution to understanding groundwater systems in the Galilee Basin. As described in previous sections, this new mapping has identified some interesting features. These include:

- north-trending groundwater divide situated to the north of the Barcaldine Ridge. This is a feature common to all Galilee Basin groundwater systems for which groundwater mapping has been undertaken as part of the BA for the Galilee subregion
- trends in CSG content and its possible relationship to groundwater systems and geological structure.

There are a number of factors that may influence the location of the groundwater divide and trends in CSG content as outlined in Evans et al. (2018) and this section. These factors include: hydrodynamics of Galilee Basin groundwater systems, surface topography and landscape evolution, variations in hydraulic conductivity and porosity, possible compartmentalisation in Galilee Basin aquifers, geological structures (e.g. major faults, fold hinges), or hydrocarbons pressurising deep parts of the groundwater system.

This groundwater divide in Galilee Basin underlies a broad elevated topographic area at surface, situated between the Great Dividing Range and the Eromanga Basin margin. Other present-day landscape features may be an influential factor on the position of the groundwater divide. For example, the Carmichael River and its tributaries (Figure 15 and Figure 18) have cut farther westward into the Great Dividing Range than many other rivers in its vicinity. Pressures in groundwater systems would have to accommodate the presence of Carmichael River, which would effectively move the groundwater divide westward. The effect of the Carmichael River on Clematis Group aquifer is apparent in Figure 15, with inferred groundwater flow directed towards the Carmichael River from areas located well away from it.

The zone of higher gas contents (Figure 16) is situated between areas where groundwater discharge may occur at the margins of the Galilee Basin. It is also parallel to some large faults that have been mapped at the top of the upper Permian coal measures (Figure 16). One hypothesis that may explain the CSG trend is that groundwater hydrodynamics and geological structure have modified the gas distribution and content in the coal seams. For example, Burra et al. (2014) and Hamilton et al. (2015) discuss examples in the Sydney and Surat basins respectively, where it is postulated that regional groundwater hydrodynamics have influenced gas distribution and gas content in the coal seams.

For the Sydney and Surat basin examples, groundwater flow is conceptualised to occur from elevated outcrop areas found at the sedimentary basin margin towards the central parts of the basins. However, for the Galilee Basin there is no obvious pathway for basin margin recharge to reach CSG-bearing coal seams at depth. The major groundwater divide (Figure 16) segregates coal seams with relatively high biogenic gas contents from any possible recharge that may occur around the eastern margin of the basin.

Section 2.1.2.2.5.4 of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018) outlines the gas content distribution for upper Permian coal measures in the Galilee Basin. I'Anson (2013) also outlined gas content distributions and gas saturation levels for coals. Gas content measurements (> 4 m^3/t dry ash free (DAF)) and gas saturation levels in the coals define a distinct south-west trending CSG fairway in the vicinity of the Glenaras and Gunn projects (see trend arrow in Figure 16). The trend of this CSG fairway is contrary to the northerly trend of the groundwater divide (Figure 16). From these lines of evidence it can be inferred that pressure from gas-charged coal seams is unlikely to have influenced the development of the regional groundwater divide.

There are occurrences of hydrocarbons in the Joe Joe Group (see Hawkins and Green, 1993). More recently, Comet Ridge Ltd (2016) has defined a tight gas resource in the Lake Galilee Sandstone, a hydrocarbon reservoir situated at the base of the Joe Joe Group. Another hypothesis could be that the groundwater divides may in part be a response to structural accumulation of gas in deeper sections of Galilee Basin and that pressure at deeper levels may be influencing groundwater systems at shallower levels in the Joe Joe Group and upper Permian coal measures. However, reports on available gas isotope data (companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018); I'Anson, 2013) suggest that gases in the upper Permian coal measures have a predominantly biogenic origin. Evans et al. (2018) demonstrate that the gas content of the coal seams peak between 800 and 1200 m and then decline, even though coal seams can occur down to depths of 2000 m. These lines of evidence suggest that there may be minimal influence through migration of gas from deeper sources, as gas contents in the coals do not increase or stay constant with depth. The CSG appears to have been generated in the coal seams mainly via biogenic processes.

There is potential for hydrocarbons to influence the groundwater pressure regime (e.g. tight gas accumulations in the Lake Galilee Sandstone in the Joe Joe Group, or underlying geological basins such as the Adavale, Drummond and Belyando basins) below the coal measures.

Overall, an improved understanding of structural geology, stratigraphy, lithological variations, aquifer compartmentalisation and distribution of rock properties such as porosity and hydraulic conductivity on a regional scale would assist in better understanding the dynamics of deep groundwater systems in the Galilee Basin. Investigations of landscape history and processes in the Carmichael river basin may also assist with understanding the evolution of groundwater systems in the Galilee Basin.

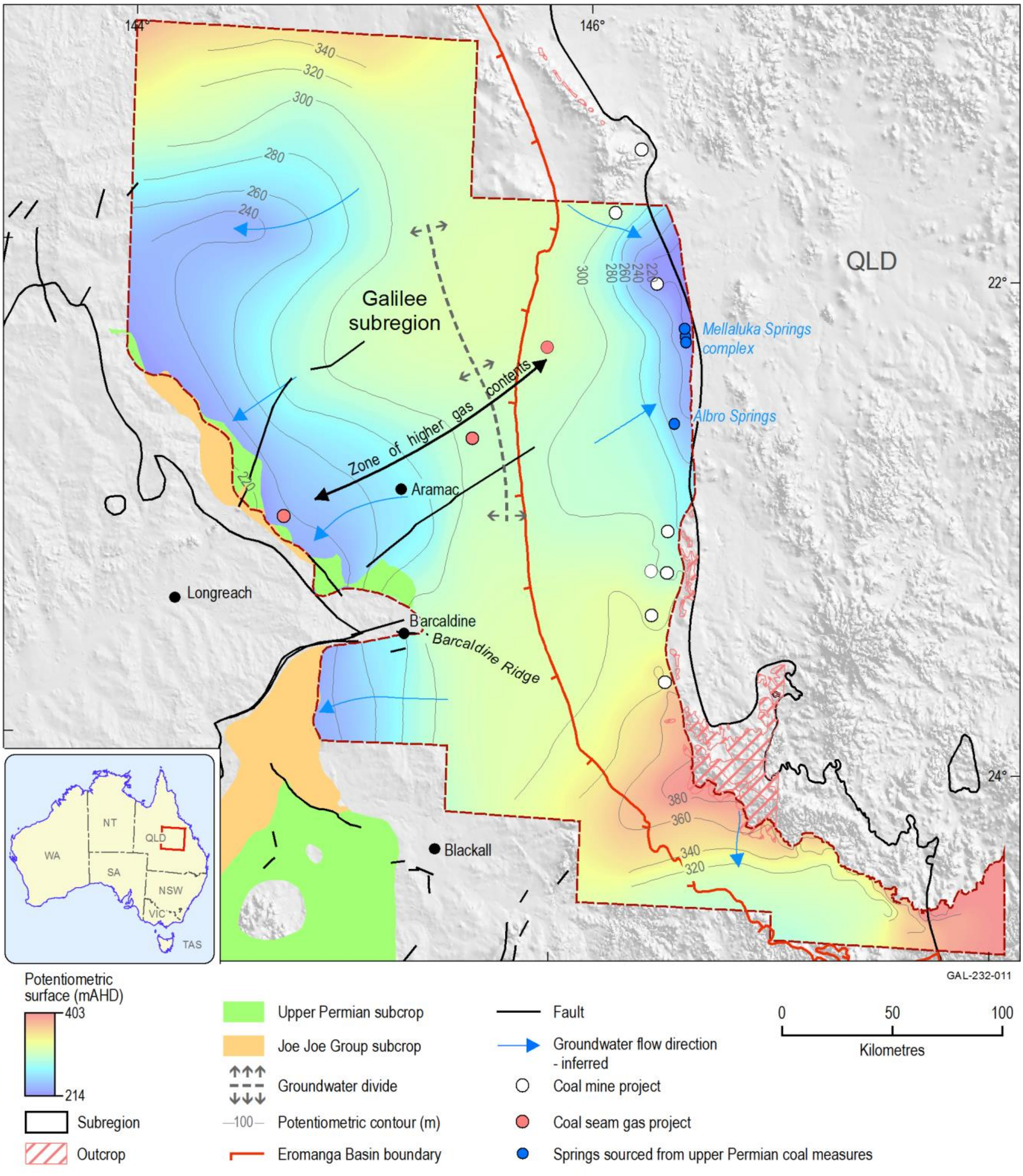

Figure 16 Conceptualisation of groundwater systems in upper Permian coal measures and Joe Joe Group using potentiometric surface mapping from upper Permian coal measures

Groundwater has the potential to flow from areas of high groundwater level (red to yellow colours) towards areas with lower groundwater level (blue colours). The rate of flow is partially dependent on hydraulic characteristics of the geological framework of the aquifer.
'Zone of higher gas contents' arrow represents broad trend in south-west trend gas content outlined in Figure 26 (Section 2.1.2.2.5.4 of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018)).
Data: Geoscience Australia (Dataset 2), Bureau of Meteorology (Dataset 6), Bioregional Assessment Programme (Dataset 7, Dataset 9, Dataset 11, Dataset 13), Queensland Department of Natural Resources and Mines (Dataset 10)

2.3.2.2.3 Surface water – groundwater interactions

Surface water – groundwater interactions in the Galilee subregion are indicated by discharge from shallow groundwater systems to rivers, losing streams (surface water recharging shallow aquifers), spring discharge creating outflow pools, discharge to lakes (e.g. Lake Galilee and Lake Buchanan), shallow groundwater (less than 20 m to watertable) being transpired by deep-rooted plants such as river red gums (*Eucalyptus camaldulensis var. obtusa*) and groundwater-dependent ecosystems.

Many of the surface water – groundwater interactions and their relationships with groundwater systems have already being outlined in Section 2.3.2.2.2. These include possible source aquifers for some spring groups and the identification of stream reaches that may interact with a particular aquifer (e.g. Carmichael River and Clematis Group aquifer).

Whether a stream is gaining or losing can be dependent on several factors including local geology, depth to groundwater, shape and depth of the river channel, and climate. As discussed in Section 2.3.2.3, most rivers in the Galilee subregion are subject to prolonged no-flow periods during any given year. Figure 17 is a schematic of a mid-section of a Queensland catchment in wet and dry periods and is representative of what may be happening in areas such as the Belyando River and upper reaches of the Thomson River. In the wet period, river flow and flooding may recharge shallow aquifers in alluvial sediments. Groundwater stored in these aquifers may return to river baseflow if sufficiently shallow, or be used as water source for vegetation in riparian zones and on floodplains in dry periods. Eventually, however, once groundwater levels fall below the base of the river channel, baseflow will cease. If groundwater levels are high and a connection exists, shallow groundwater may still discharge to deep pools in a river channel or billabongs on a floodplain. These areas may act as refugia for fauna and flora during dry periods.

Losing streams are defined as a situation where the stream is flowing and the base of the river channel is higher than the local watertable. If a hydraulic connection exists, then there is potential for a stream to lose water to the shallow watertable. Alternatively if there is a barrier (e.g. a thick clay layer), then a stream may be disconnected from the shallow watertable.

Further details on depth to groundwater and its utilisation by ecosystems are outlined in companion product 2.7 for the Galilee subregion (Ickowicz et al., 2018) as well as Section 3.4 in companion product 3-4 (Lewis et al., 2018).

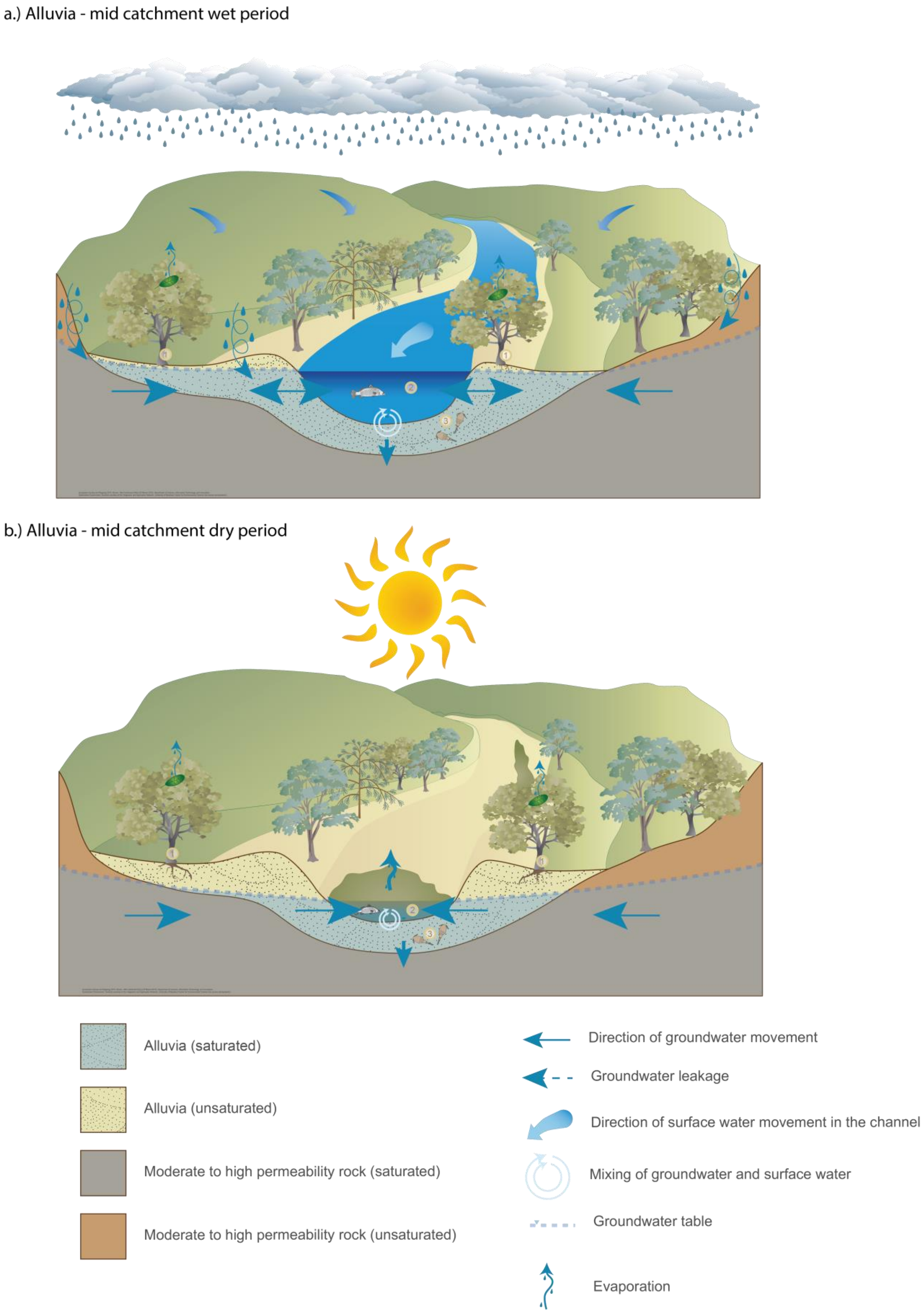

Figure 17 Hydrological conceptual model of alluvia in the mid-catchment reaches during a.) wet and b.) dry periods

Source: adapted from DSITI (Dataset 14), a.) 'Alluvia – mid-catchment – wet' and b.) 'Alluvia – mid-catchment – dry', © The State of Queensland (Department of Science, Information Technology and Innovation) 2015

2.3.2.3 Surface water

Companion product 1.1 for the Galilee subregion (Evans et al., 2014) provided some background information on surface water systems in the Galilee subregion, with companion product 1.5 (Evans et al., 2015) providing further detail on surface water usage and water quality.

Major river basins and associated drainage are outlined in Figure 18. The Galilee subregion straddles the Great Dividing Range and includes the headwaters of six major river basins. These are the eastward draining Burdekin and Fitzroy river basins; the Cooper Creek – Bulloo and Diamantina river basins, which drain westwards; the northward draining Flinders-Norman river basin; and the Warrego river basin, which drains southwards.

Much of the Galilee subregion lies in the Cooper Creek – Bulloo and Diamantina river basins (Figure 18). However, most of the proposed coal mine developments are located in the Burdekin river basin. The most advanced coal mine developments are situated on the western side of the Belyando river basin. Proposed CSG projects occur in the Cooper Creek – Bulloo river basin. However, these projects are at a less advanced stage (see Section 2.3.4 and companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis et al., 2014)). As of December 2016, there are no commercially producing coal resource developments in the Galilee subregion.

Streamflow in the Cooper Creek – Bulloo and Diamantina river basins are strongly seasonal and, from year to year, flows can vary greatly from almost no flow to significant floods. Streamflow in the portions of the Burdekin, Fitzroy and Flinders-Norman river basins that lie within the Galilee subregion are characterised as dry seasonal flows. Although flows vary greatly between months with minimal to no flow from July to October, most flows occur between December and April. The flow regime for Warrego river basin, while highly variable, is classed as perennial (companion product 1.1 for the Galilee subregion (Evans et al., 2014)). Much of the river flow in the Warrego river basin occurs between December and April.

There are some closed drainage basins that are associated with significant lakes such as Lake Galilee and Lake Buchanan and they occur between the Great Dividing Range, and the ranges that demarcate the eastern edge of the Eromanga Basin (Figure 18). These lake basins are largely confined on their western side by series of hills that define a long arcuate ridge that runs parallel to the Great Dividing Range. These hills mostly comprise outcropping Eromanga Basin rocks, in particular, the Hutton Sandstone and Ronlow beds.

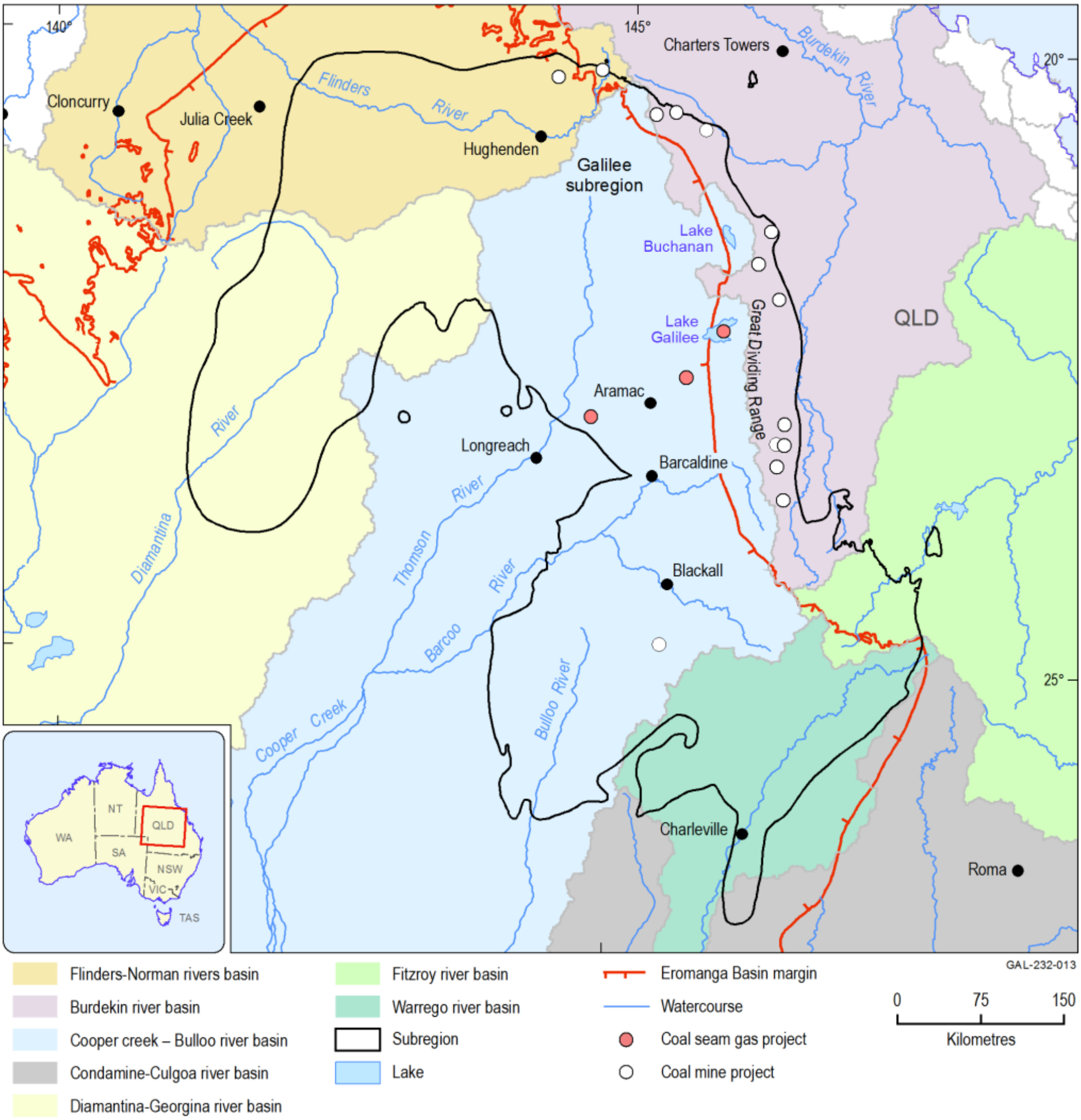

Figure 18 Major river basins, lakes and coal and coal seam gas projects in the Galilee subregion

Data: Bureau of Meteorology (Dataset 6, Dataset 15), Geoscience Australia (Dataset 2), Bioregional Assessments Programme (Dataset 11)

2.3.2.4 *Water balance*

Surface water and groundwater balances include a number of components such as rainfall, runoff, evaporation, aquifer recharge, storage, discharge, leakage and water extraction. An estimation of annual groundwater and surface water extraction is outlined in companion product 1.5 for the Galilee subregion (Evans et al., 2015).

Mean annual potential evaporation far exceeds rainfall, particularly in the summer months (companion product 1.1 for the Galilee subregion (Evans et al., 2014)) and rainfall, for the most part, is highly variable across the subregion. These major components of the water balance assert a significant control on the availability of surface water in the Galilee subregion. These factors are likely to dominate the water balance for small closed lake basins such as Lake Galilee and Lake Buchanan (Figure 18). Potential evaporation may also influence availability of surface water in spring pools that are associated with some spring vents. Further detail on variations in hydrology of spring pools is outline in Section 3.5 in companion product 3-4 (Lewis et al., 2018).

As outlined in Section 2.3.2.3, the Galilee subregion is situated in the headwaters of seven major river basins, all of which flow out from the Galilee subregion. While limited, available streamflow data suggest that surface water flows are extremely variable in all river basins and that most streams in the Galilee subregion have prolonged no-flow periods. Hence, surface water in rivers is only available for limited periods in a given year. The lack of continuous surface water flow throughout the year in most river basins suggests that groundwater discharge is not sufficient to keep most streams continuously flowing during prolonged low rainfall periods. Exceptions may be along tracts of the Carmichael River and Warrego River.

Due to variability in the availability of surface water resources, there is a strong dependence by agriculture and town water supplies on groundwater resources, particularly in the area encompassed by the Eromanga Basin (Figure 18). Most groundwater in the Galilee subregion is extracted from GAB aquifer systems, the Hutton-Precipice and the Wyandra-Hooray aquifers. The most utilised aquifer system of the Galilee Basin sequence is the Clematis Group aquifer. The main uses for groundwater were either agricultural purposes or town water supplies. Groundwater is also extracted from Cenozoic sediments and can be the source of some town water supplies (e.g. Alpha township).

2.3.2.5 Gaps

Knowledge gaps in the conceptualisation of surface water and groundwater systems of the Galilee subregion include:

- Influence of geological structural features (e.g. Barcaldine ridge, major faults) on regional groundwater flow in the Galilee Basin, for example, is there compartmentalisation in the aquifers?
- Refined understanding of structural geology, lithological variations, aquifer compartmentalisation and distribution of rock properties such as porosity and hydraulic conductivity on a regional scale would assist in understanding the dynamics of deep groundwater systems in the Galilee Basin. This would improve understanding of groundwater fluxes between the Galilee and overlying sedimentary basins.
- Influence of landscape processes and evolution on groundwater systems in the Galilee Basin. For instance, did incision of the Carmichael River result in the westward migration of the north-trending groundwater divide that affects some of the groundwater systems in the Galilee Basin?
- There is limited groundwater quality and isotopic data for groundwater systems in the Galilee Basin. These data would aid in better understanding connective groundwater pathways and groundwater fluxes between aquifers.

- The extent of connectivity between Cenozoic aquifers and deeper groundwater systems such as regional aquifers in the Eromanga Basin would assist in quantifying how much groundwater moves between the various aquifer systems and what bearing this may have on groundwater – surface water interactions.
- The stratigraphy of the upper Permian coal measures is in the process of being revised by Phillips et al. (2016). Some consideration should be given to incorporating the new stratigraphic subdivisions as outlined by Phillips et al. (2016) into future reiterations of the Galilee subregion geological model. Also, potentiometric mapping should be reviewed in light of new stratigraphic understandings. This may in turn improve hydrogeological understanding of the upper Permian coal measures.
- Quantification of surface water – groundwater interactions in the Galilee subregion. Very little is known about them. This would assist in management of water-dependent assets. This could include mapping areas where river systems could be interacting with groundwater systems (either as gaining or losing streams).
- Diffuse recharge estimates for GAB aquifers are lower than what was originally estimated by Kellett et al. (2003). Studies to revaluate recharge estimates should be undertaken for GAB recharge areas. Also, the potential for episodic recharge to GAB aquifers along eastern margin of the Eromanga Basin is poorly known. It may be an important component for water balance, as is the case along the western margin of Eromanga Basin.
- Long-term groundwater time-series water level data for aquifers in Galilee Basin, as well as more groundwater quality data (especially salinity) would improve understanding of groundwater systems and the conversion of drill-stem test pressure data to equivalent hydraulic head.
- There is limited information on the variability and extent of baseflow for rivers in the Galilee subregion. Although Section 2.1.5 in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018) provides an initial estimate of possible baseflow for two major river reaches, estimates could be refined if some of the data gaps outlined in Section 2.1.5 were addressed.
- More stream gauge and surface water quality data would allow for better characterisation of the surface water systems.
- More detailed understanding is needed about the volume of discharge at springs and its relationship to groundwater pressures in the vicinity of spring vents.

Further discussion on gaps and opportunities for future work are also outlined in Section 3.7 in companion product 3-4 for the Galilee subregion (Lewis et al., 2018).

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2.3.3 Ecosystems

Summary

The Galilee subregion is within the Lake Eyre Basin bioregion and is the largest subregion being assessed by the Bioregional Assessment Programme. The Galilee preliminary assessment extent (PAE) occupies diverse environments, from the mountains of the Great Dividing Range through to vast expanses of semi-arid and arid inland Australia. It includes rivers that flow into Kati Thanda – Lake Eyre, the Gulf of Carpentaria, the Pacific Ocean and the Murray–Darling Basin. Key features of the Galilee PAE are its large area, sparse human population density and unpredictable rainfall resulting in natural and human systems driven by resource pulses and boom-bust dynamics. The low human population results in the natural vegetation being relatively unmodified. For BA purposes, a landscape classification was developed to present a conceptualisation of the main biophysical and human systems at the surface of the Galilee PAE and to identify ecosystems with characteristics that are expected to respond similarly to changes in groundwater and/or surface water as a consequence of coal resource development.

The approach taken was developed in close collaboration and with strong guidance from experts that have extensive experience with the landscapes of the PAE both in Queensland and SA and who have contributed to the development of similar classification systems. The classification and typology were developed and refined following a six-step approach. The classification is based on five elements derived from the Australian National Aquatic Ecosystem (ANAE) classification framework involving topography, landform, water source, water type and water availability. In addition, each area was identified as either remnant or non-remnant vegetation based on the Queensland remnant Regional Ecosystem (RE) mapping. This classification produced a typology consisting of 20 landscape classes derived from polygons, 10 landscape classes from lines (streams) and 1 landscape class from points (springs). These 31 landscape classes were then collapsed into 11 broad landscape groups that were either non-water dependent, floodplain or non-floodplain. The non-water-dependent landscape group, 'Dryland', dominated the area of the PAE (68.54%). Of the water-dependent landscape classes, 26.52% of the area of the PAE consists of floodplain landscape classes with the remaining 4.87% of the area occupied by non-floodplain, water-dependent landscape classes. For both the floodplain and non-floodplain water-dependent landscape classes, the majority of the area consists of terrestrial groundwater-dependent ecosystems (GDEs).

In this section, each landscape group is described and representative areas are mapped. Nationally listed species and ecological communities are listed. Aspects of water dependency within each landscape group are also documented.

2.3.3.1 Landscape classification

2.3.3.1.1 Methodology

The Galilee subregion is within the Lake Eyre Basin bioregion and is the largest subregion being assessed by the Bioregional Assessment Programme. The Galilee PAE occupies diverse environments from the mountains of the Great Dividing Range through a large area of semi-arid and arid inland Australia to the shores of Kati Thanda – Lake Eyre. Key features of the Galilee PAE are its large area, sparse human population density and unpredictable rainfall resulting in natural and human systems driven by resource pulses and boom-bust dynamics. Low human population density results in the natural vegetation being relatively intact. Dominant land use in the PAE is grazing of sheep and cattle on natural pastures (grazing natural vegetation). Other land uses are nature conservation, production forestry (confined to the wetter east-central edge of the PAE) and other minimal use. There is no pasture modification or intensive agricultural production within the PAE. Urban settlement is limited in extent.

As a consequence of its size and diversity, the Galilee PAE contains a large number and diverse range of assets that span ecological, sociocultural and economic values. As addressed for this Assessment, the subregion has over 4400 assets that comprise over 800,000 individual spatially discrete elements (companion product 1.3 for the Galilee subregion (Sparrow et al., 2015)). Many of these assets are large in extent; for example, Diamantina National Park, a park in south-west Queensland, has an area of 507,000 ha.

For BA purposes, a landscape classification was developed to characterise the nature of water dependency among these assets. Specifically, landscape classification is used to characterise the diverse range of water-dependent assets into a smaller number of classes for further analysis. It is based on key landscape properties related to patterns in geology, geomorphology, hydrology and ecology. The aim of the landscape classification is to systematically define geographical areas into classes based on similarity in physical and/or biological and hydrological characteristics. The landscape classification includes all natural and human ecosystems in the PAE. This section describes the methodology and datasets used to arrive at the landscape classification for ecosystems within the Galilee PAE.

The landscape classification developed in this product provides a mechanism by which receptor impact modelling (product 2.7) can be undertaken on a large (>4000) number of assets. The rationale for this process is that a landscape class represents a water-dependent ecosystem that has a characteristic hydrological regime. As part of the landscape classification process in this product, the landscape classes are classified into landscape groups. Landscape groups are sets of landscape classes that share hydrological properties. Subsequent in the BA process, the landscape groups are amalgamated into larger entities to enable receptor impact modelling (product 2.7) to take place. There is no direct interaction between landscape classes and hydrological modelling, either groundwater or surface water, in the BA context. Not all of the landscape classes defined in this product will be affected by the coal resource development pathway in the Galilee subregion (refer to Section 2.3.4).

Multiple classification methodologies have been developed to provide consistent and functionally relevant representations of water-dependent ecosystems. An Australian example is the Australian

National Aquatic Ecosystem (ANAE) classification framework. The approach outlined here has built on, and integrated, these existing classification systems. It has used predominantly existing classes within data associated with aquatic and groundwater-dependent ecosystems (GDEs), remnant vegetation and land use mapping. The landscape classification was carried out on data layers consisting of polygons (e.g. remnant vegetation, wetlands), lines (stream network) and points (springs and spring complexes).

2.3.3.1.1.1 Classification and typology of landscape elements (polygons)

The approach taken was developed in close collaboration, and with strong guidance, from experts that have extensive experience with the landscapes of the PAE both in Queensland and SA. These experts have contributed to the development of similar classification systems such as the ANAE (Aquatic Ecosystems Task Group, 2012a). The classification and typology were developed and refined following a six-step approach that is summarised in Table 3.

The classification is based on five elements derived from the ANAE. The first division is based on topography and is at level 2 (landscape scale) of the ANAE structure. The Galilee PAE is divided into floodplain and non-floodplain areas based on the *Land Zones of Queensland* (Wilson and Taylor, 2012). All polygons that are Land Zone 3 have been classified as ‘floodplain’ with all other land zones classified as ‘non-floodplain’. Land Zone 3 is defined as recent Quaternary alluvial systems or, in simpler terms, alluvial river and creek flats (Queensland Herbarium, Dataset 1). Land Zone 3 includes inland lakes and associated wave-built lunettes (dunes). The national topographic data from Geoscience Australia (Dataset 2) were used to define floodplains in SA as lands that are subject to inundation, marine swamps, swamps or saline coastal flats. This division allows broad classification of the landscape components that might be influenced by flooding regimes that are more likely to support water-dependent biota.

The next division is based on landform and is at ANAE level 3 (system). Polygons were divided into ‘wetland’ and ‘non-wetland’. Wetlands were classified as either ‘estuarine’, ‘lacustrine’, ‘palustrine’ or ‘riverine’ based on the wetland class field in the Queensland wetland mapping (DSITIA, Dataset 3) and in the SA GDE classification (SA Department for Water, Dataset 4).

The remainder of the classification was based on habitat variables also at level 3 of the ANAE structure. These variables were water type, water availability and groundwater source, specifically:

- water source (groundwater/non-groundwater dependent)
- water type (brackish or saline/fresh)
- water availability (permanent/near-permanent (wet greater than 80% of time)/intermittent or ephemeral).

Water availability and water type were inferred from Queensland wetland and GDE mapping datasets. Water type was determined from Queensland wetland mapping for wetlands and from GDE mapping for non-wetlands. Attribution of water source is based on the predominant water source (e.g. if predominantly groundwater, it is classified as such). Combined categories were not used.

In addition to the five elements of the classification derived from the ANAE, an additional variable was used that identified a polygon as either remnant or non-remnant vegetation. This distinction is based on the Queensland remnant Regional Ecosystem (RE) mapping from 2013 (Queensland Herbarium, Dataset 1). This approach separates relatively intact landscapes from 'human-modified' landscapes. This distinction has important consequences for defining where important habitats and biota may occur when considering assets and their likely distribution.

Table 3 Summary of the seven steps undertaken to develop and refine a classification and then a typology of landscape classes in the Galilee preliminary assessment extent (PAE)

Step	Description	Comment
1	Review existing classifications.	
2	Develop 5-element ANAE-based classification following expert input (3 workshops, Adelaide and Brisbane).	A typology of 180 potential landscape classes was developed.
3	Apply classification to Galilee datasets followed by initial lumping of some elements (e.g. 'Landform' was reduced from five categories to two, specifically: 'wetland' (including estuarine, riverine, lacustrine, palustrine) and 'non-wetland').	A typology with 27 landscape classes was developed.
4	Apply 'Broad Habitat' element to each of the landscape classes where applicable. Thus each existing class can be 'remnant' or 'non-remnant'.	Typology was modified to include 50 potential landscape classes.
5	Seek expert feedback on the modified typology.	Typology undergoes minor refinement.
6	Further reduce typology by lumping of categories within some elements. Specifically, 'near-permanent' and 'intermittent' lumped for 'Water Availability'. 'Water Type' only considered for disconnected wetlands.	Final typology is established.
7	Lump 'artesian' groundwater and 'non-artesian' groundwater in the 'Water source' element.	Based on reviewer comments.

The rule sets applied to the databases to undertake these tasks are summarised in Table 4.

A spatially complete layer of all classed polygons was produced by running a topological overlay of the datasets such that a new polygon dataset was produced, which retained the features of all the input layers. Landscape classes were defined using the five elements from the ANAE structure (Table 5) with their nomenclature reflecting key water-dependency attributes. For example, an area classified as 'remnant', 'non-floodplain', 'wetland', 'disconnected, 'saline' has the landscape class: 'Non-floodplain disconnected saline wetland, remnant vegetation'. In other words, this area is not on a floodplain and is surface water dependent and associated with a saline wetland.

Table 4 Landscape classification rule sets used for the landscape elements (polygons) in the Queensland portion of the Galilee preliminary assessment extent (PAE)

Classification	Class	Dataset	Dataset (field)	Query
Broad habitat	Remnant	Queensland Herbarium (Dataset 1)	Qld_RE_13 (RE)	IF RE IS NOT = non-rem THEN Broad habitat = Remnant
	Non-remnant	Queensland Herbarium (Dataset 1)	Qld_RE_13 (RE)	IF RE = non-rem THEN Broad habitat = Non - remnant
Topography	Floodplain	DSITIA (Dataset 3)	QLD_WETLAND_SYSTEM_100K_A (FLOODPLAIN)	IF FLOODPLAIN = F THEN Topography = Floodplain
	Floodplain	Geoscience Australia (Dataset 2)	Hydrography: Flats (FEATURETYPE)	IF FEATURETYPE = Land Subject to Inundation OR Marine Swamp OR Swamp OR Saline Coastal Flats THEN Topography = Floodplain
	Non-floodplain	DSITIA (Dataset 3)	QLD_WETLAND_SYSTEM_100K_A (FLOODPLAIN)	IF FLOODPLAIN IS NOT = F THEN Topography = Non-floodplain
Landform	L (lacustrine)	DSITIA (Dataset 3)	QLD_WETLAND_SYSTEM_100K_A (WETCLASS)	IF WETCLASS = L THEN Landform = L
	L (lacustrine)	SA Department for Water (Dataset 4)	Wetlands_GDE_Classification (WETLANDSYS)	IF WETLANDSYS = LAC THEN Landform = L
	R (riverine)	DSITIA (Dataset 3)	QLD_WETLAND_SYSTEM_100K_A (WETCLASS)	IF WETCLASS = R THEN Landform = R
	R (riverine)	SA Department for Water (Dataset 4)	Wetlands_GDE_Classification (WETLANDSYS)	IF WETLANDSYS = RIV THEN Landform = R
	P (palustrine)	DSITIA (Dataset 3)	QLD_WETLAND_SYSTEM_100K_A (WETCLASS)	IF WETCLASS = P THEN Landform = P
	P (palustrine)	SA Department for Water (Dataset 4)	Wetlands_GDE_Classification (WETLANDSYS)	IF WETLANDSYS = PAL THEN Landform = P
	E (estuarine)	DSITIA (Dataset 3)	QLD_WETLAND_SYSTEM_100K_A (WETCLASS)	IF WETCLASS = E THEN Landform = E
	E (estuarine)	SA Department for Water (Dataset 4)	Wetlands_GDE_Classification (WETLANDSYS)	IF WETLANDSYS = EST THEN Landform = E

Classification	Class	Dataset	Dataset (field)	Query
	D (dryland)	DSITIA (Dataset 3)	QLD_WETLAND_SYSTEM_100K_A (WETCLASS)	IF WETCLASS = '-' THEN Landform = D
	D (dryland)	SA Department for Water (Dataset 4)	Wetlands_GDE_Classification (WETLANDSYS)	IF WETLANDSYS = ' ' THEN Landform = D
Water type	Brackish or saline	DSITIA (Dataset 3)	Queensland wetland data version 3 - wetland areas (SALINMOD)	IF SALINMOD = S2 OR S3 OR T1 THEN Water type = saline
	Brackish or saline	Queensland Herbarium (Dataset 5)	GDE_v01_3: GDE_Terrestrial_Areas_v01_3 (GW_SALINTY);	IF GW_SALINTY >= 3000 mg/L TDS THEN Water type = saline
	Fresh	Queensland Herbarium (Dataset 5)	GDE_v01_3: GDE_Surface_Areas_v01_3 (GW_SALINTY);	IF GW_SALINITY < 3000 mg/L TDS THEN Water type = fresh
	Fresh	DSITIA (Dataset 3)	Queensland wetland data version 3 - wetland areas (SALINMOD)	IF SALINMOD IS NOT = S2 OR S3 OR T1 THEN Water type = fresh
Water regime	Near-permanent	DSITIA (Dataset 3)	Queensland wetland data version 3 - wetland areas (WTRREGIME)	IF WTRREGIME = WR3 THEN Water regime = Near-permanent
	Temporary	DSITIA (Dataset 3)	Queensland wetland data version 3 - wetland areas (WTRREGIME)	IF WTRREGIME IS NOT = WR3 THEN Water regime = Temporary

2.3.3.1.1.2 Classification and typology of the stream network

Streams in the PAE were classified based on their catchment position, water regime and association with GDEs (Table 5). Catchment position (i.e. upland *versus* lowland) is a potential strong influence on stream morphology and flow patterns. Rivers and streams can also receive significant baseflow inputs from local and regional groundwater systems and act as recharge sources to support GDEs. Water regime is critical in determining suitable habitat for biota and physical features of the channel and riparian zone.

The stream network had not previously been classified in the Galilee PAE, which meant that the Assessment team completed this part of the landscape classification. The stream network data were based on the Geofabric v2 cartographic mapping of river channels derived from 1:250,000 topographic maps (Bureau of Meteorology, Dataset 7). The Geofabric is a purpose-built geographic information system (GIS) that maps Australian rivers and streams and identifies how stream features are hydrologically connected. The water regime of these stream networks was also defined ('near-permanent' or 'temporary') using the Queensland pre-clearing and remnant ecosystems mapping data (Queensland Herbarium, Dataset 1). Mapping data of valley bottom flatness (MrVBF) (CSIRO, Dataset 8) was used to classify streams as either 'upland' or 'lowland' following methods outlined in Brooks et al. (2014). To determine estuarine stream systems, the term 'tidal' was added to the groundwater source as this identifies areas that are under a tidal influence and hence should be considered estuarine.

Table 5 Landscape classification rule sets used for the stream network polylines

Classification	Class	Dataset citation	Dataset (field)	Query
Catchment position	Upland	CSIRO (Dataset 8)	MrVBF_3s (Value)	IF Value < 2.5 THEN Catchment position = upland
	Lowland	CSIRO (Dataset 8)	MrVBF_3s (Value)	IF Value ≥ 2.5 THEN Catchment position = lowland
Water regime	Temporary	Bureau of Meteorology (Dataset 7)	Geofabric Surface Cartography (Water regime)	IF Water regime = Periodically inundated THEN Water regime = temporary
	Near-permanent	Bureau of Meteorology (Dataset 7)	Geofabric Surface Cartography (Water regime)	IF Water regime IS NOT = Periodically inundated THEN Water regime = near-permanent
Water source	Non-groundwater	Queensland Herbarium (Dataset 5)	GDE_v01_3: GDE_Surface_Lines_v01_3 (C_Model)	IF C_Model is null THEN Water source = non-GDE

2.3.3.1.1.3 Classification of springs

Springs and springs complexes were not classified further.

The logic of the landscape classification rule sets used in the Galilee subregion is shown in Figure 19. Landscape classes belonging to the same landscape group have the same colour.

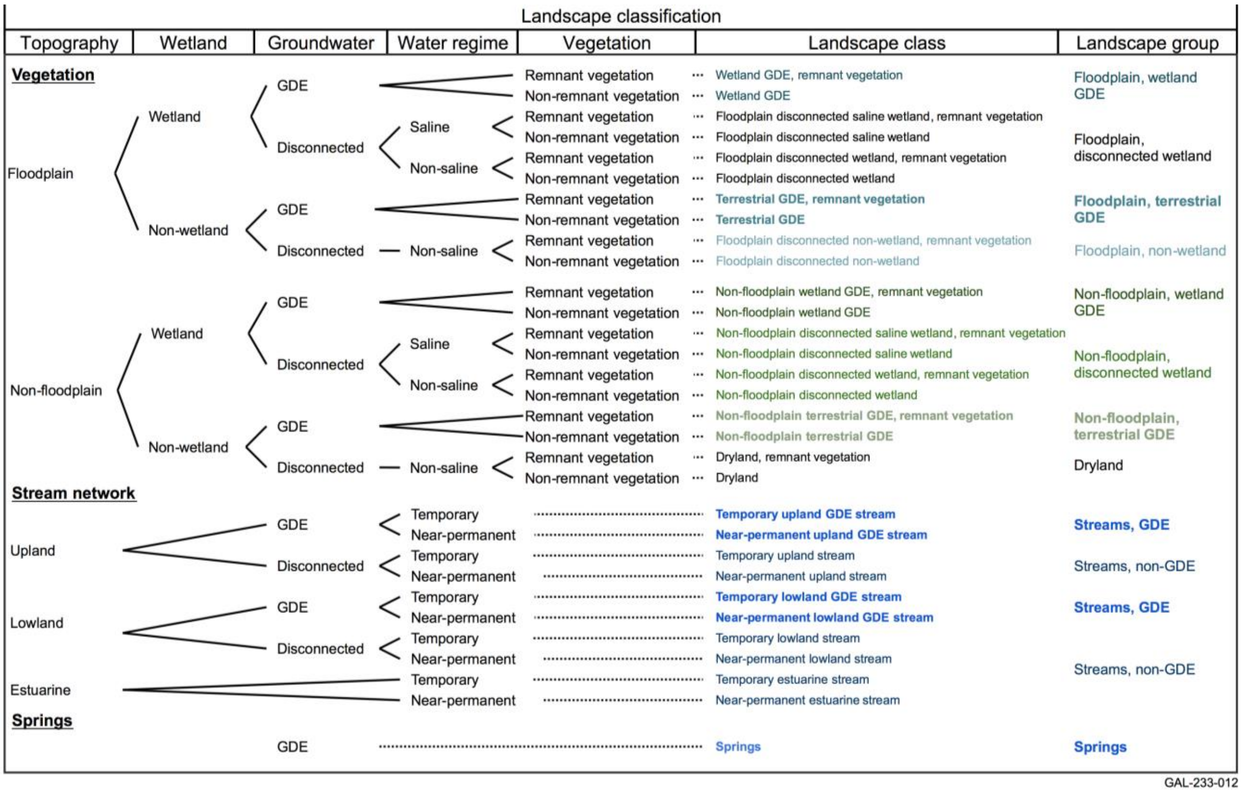

Figure 19 Schematic of the landscape classification for the Galilee assessment extent

Refer to Table 7 and Table 8 for a full description of landscape groups and landscape classes.

2.3.3.1.2 Landscape classification

2.3.3.1.2.1 Typology of landscape classes

The Assessment team defined a set of landscape classes that represent the main biophysical and human systems in the Galilee subregion. This typology consists of 20 landscape classes derived from polygons, 10 landscape classes from lines (streams) and 1 landscape class from points (springs).

Landscape classes were classified into 11 landscape groups. Each landscape group consists of one or more landscape classes. Among polygons, landscape classes were first sorted on the basis of topography (i.e. whether an area is on a floodplain or not). Below the level of topography, the landscape classes were grouped on the basis of water source and whether they are a wetland or non-wetland. Wetlands were divided into groundwater and disconnected (reliant on surface water). The non-wetlands are either terrestrial GDEs (i.e. groundwater dependent) or surface water-dependent areas of the landscape. In summary, in each of the two topographical categories (floodplain, non-floodplain), there were potentially four landscape groups. The landscape groups contained landscape classes that were either (i) wetland GDEs, (ii) disconnected (surface water dependent) wetland, (iii) terrestrial (non-wetland) GDEs or (iv) surface water-dependent non-wetlands (referred to in the 'Floodplain, non-wetland' landscape group for floodplains and the 'Dryland' landscape group for non-floodplains).

For streams, landscape classes were divided into two landscape groups on the basis of whether they were GDE or non-GDE.

The typology developed by the Assessment team includes aspects of existing wetland models such as those developed for Queensland that form part of the Queensland Government's Wetland*Info* website (DEHP, 2015). Similar wetland models are available for wetlands in other areas of the Galilee PAE. These include models intended to cover the entire Lake Eyre Basin (Imgraben and McNeil, 2015), NSW including arid regions (Claus et al., 2011) and the semi-arid (northern) section of the Murray–Darling Basin (Price and Gawne, 2009). Each suite of models was consulted in the development of the Bioregional Assessment Programme typology of landscape classes for the Galilee PAE (Table 3, step 1); however, each has strengths and weaknesses and no model covers the entire geographical area or environmental heterogeneity of the Galilee PAE. Therefore, no existing approach was considered suitable to adapt in its entirety for this Assessment. For example, the concordance of the Galilee PAE typology with that from Queensland Wetland*Info* is summarised in Table 6.

Table 6 Concordance of landscape classes and landscape groups from the Galilee preliminary assessment extent classification and typology with the Queensland Wetland*Info* models

Landscape group	Landscape class	Queensland Wetland*Info* models	Comments
Dryland	Dryland	Not applicable	No comment
Floodplain, non-wetland	Floodplain disconnected non-wetland	Not applicable	No comment
Floodplain, wetland GDE	Wetland GDE	GDEs: alluvia – lower catchment GDEs: alluvia – closed drainage systems GDEs: sedimentary rocks (GAB)	No comment
Floodplain, disconnected wetland	Floodplain disconnected wetland	Arid and semi-arid floodplain lake Arid and semi-arid tree swamp Arid and semi-arid lignum swamp Arid and semi-arid grass, sedge, herb swamp	Models do not separate disconnected wetlands from GDEs. Swamp models do not separate floodplain from non-floodplain.
	Floodplain disconnected saline wetland	Arid and semi-arid saline lake Arid and semi-arid saline swamp	No comment
Floodplain, terrestrial GDE	Terrestrial GDE	GDEs: alluvia – lower catchment GDEs: alluvia – closed drainage systems	No comment
Non-floodplain, wetland GDE	Non-floodplain wetland GDE	GDEs: alluvia – upper/mid catchment GDEs: wind-blown inland sand dunefields GDEs: sedimentary rocks (GAB)	No comment
Non-floodplain, disconnected wetland	Non-floodplain disconnected wetland	Arid and semi-arid non-floodplain lake Arid and semi-arid tree swamp Arid and semi-arid lignum swamp Arid and semi-arid grass, sedge, herb swamp	Models do not separate disconnected wetlands from GDEs. Swamp models do not separate floodplain from non-floodplain.
	Non-floodplain disconnected saline wetland	Arid and semi-arid saline lake Arid and semi-arid saline swamp	No comment
Non-floodplain, terrestrial GDE	Non-floodplain, terrestrial GDE	GDEs: alluvia – upper/mid catchment GDEs: wind-blown inland sand dunefields	No comment

GDE = groundwater-dependent ecosystem

2.3.3.1.2.2 Naming conventions for landscape classes

Landscape classes were named on the basis of the classification systems used for the landscape classification (refer to Table 4 and Table 5). Colloquial terminology was avoided to minimise confusion. Rather, a standard naming convention was adopted. The naming convention for polygon landscape classes (Table 7) is detailed below.

1. *Floodplain/non-floodplain*. Of the 10 landscape classes that are non-floodplain, all but two non-floodplain landscape classes have 'non-floodplain' as the first word of the landscape class name. The exceptions are the two landscape classes (which are non-floodplain, non-wetlands) in the 'Dryland' landscape group. 'Floodplain' is used in the name of the six floodplain landscape classes that are 'disconnected' (surface water dependent); these are in the 'Floodplain, non-wetland' and 'Floodplain, disconnected wetland' landscape groups.
2. *Wetland/non-wetland*. The next word in the name of each landscape class indicates if it is a wetland or not. If it is a wetland, it will either be a groundwater-dependent ecosystem ('wetland GDE') or surface water-dependent ecosystem ('disconnected wetland'). If the landscape class is not a wetland, the term 'terrestrial' appears for GDEs and 'non-wetland' for surface water-dependent ecosystems.
3. *Salinity*. Saline disconnected wetlands are indicated as 'disconnected saline wetland'. Salinity is indicated only for disconnected wetlands.
4. *Remnant/non-remnant*. The broad habitat separation of 'remnant' or 'non-remnant' is indicated last in the landscape class name. Only the term 'remnant vegetation' is included in the name of the landscape class. If this does not appear, then the landscape class is 'non-remnant vegetation'.

The stream network was defined from a smaller set of criteria. The naming conventions for streams (Table 8) follows this order: 'temporary' or 'near-permanent', then 'lowland', 'upland' or 'estuarine' and lastly, 'GDE' if groundwater dependent. .

2.3.3.1.2.3 Area of landscape classes

The typology of landscape classes included two landscape classes that are non-water dependent (i.e. they support terrestrial vegetation that is not groundwater dependent; rather, it relies predominantly on surface water including direct precipitation, flood flows from rainfall and local runoff). Together, these two landscape classes occupy 68.54% of the Galilee PAE (Figure 20). The predominance of these non-water dependent categories is apparent in the map of landscape classes in the Lagoon Creek and Native Companion Creek, a series of temporary lowland drainages north of Alpha (Figure 21). Here, most of the landscape is in the 'Dryland, remnant vegetation' and 'Dryland' landscape classes with large areas of the floodplain being in the 'Floodplain disconnected non-wetland' and 'Floodplain disconnected non-wetland, remnant vegetation' landscape classes.

Of the remaining landscape classes, 26.52% of the area of the PAE consists of floodplain landscape classes, with the remaining 4.87% of the area occupied by non-floodplain, water-dependent landscape classes (Table 7).

Table 7 Typology of landscape classes in the Galilee preliminary assessment extent (PAE) based on polygons with land area and percentage of the PAE

Landscape group	Landscape class number	Landscape class	Total land area (ha)	Percentage of PAE (%)
Dryland	1	Dryland	5,414,087	8.84%
	2	Dryland, remnant vegetation	36,551,613	59.70%
		Total	**41,965,700**	**68.54%**
Floodplain, non-wetland	3	Floodplain disconnected non-wetland	1,235,696	2.02%
	4	Floodplain disconnected non-wetland, remnant vegetation	5,965,894	9.74%
		Total	**7,201,590**	**11.76%**
Floodplain, wetland GDE	5	Wetland GDE	9,324	0.02%
	6	Wetland GDE, remnant vegetation	485,548	0.79%
		Total	**494,872**	**0.81%**
Floodplain, disconnected wetland	7	Floodplain disconnected wetland	35,802	0.06%
	8	Floodplain disconnected wetland, remnant vegetation	579,012	0.95%
	9	Floodplain disconnected saline wetland	20,722	0.03%
	10	Floodplain disconnected saline wetland, remnant vegetation	20,282	0.03%
		Total	**655,818**	**1.07%**
Floodplain, terrestrial GDE	11	Terrestrial GDE	74,955	0.12%
	12	Terrestrial GDE, remnant vegetation	7,847,936	12.82%
		Total	**7,922,891**	**12.94%**
Non-floodplain, wetland GDE	13	Non-floodplain wetland GDE	9,765	0.02%
	14	Non-floodplain wetland GDE, remnant vegetation	16,072	0.03%
		Total	**25,837**	**0.05%**

Landscape group	Landscape class number	Landscape class	Total land area (ha)	Percentage of PAE (%)
Non-floodplain disconnected wetland	15	Non-floodplain disconnected wetland	54,104	0.09%
	16	Non-floodplain disconnected wetland, remnant vegetation	52,031	0.08%
	17	Non-floodplain disconnected saline wetland	766,561	1.25%
	18	Non-floodplain disconnected saline wetland, remnant vegetation	5,704	0.01%
		Total	**878,400**	**1.43%**
Non-floodplain, terrestrial GDE	19	Non-floodplain, terrestrial GDE	26,807	0.04%
	20	Non-floodplain, terrestrial GDE, remnant vegetation	2,053,195	3.35%
		Total	**2,080,002**	**3.39%**
Total			**61,225,110**	**99.99%**

GDE = groundwater-dependent ecosystem

Table 8 Typology of stream network classes in the Galilee preliminary assessment extent (PAE) with total length and percentage of total stream network in the PAE

Landscape group	Landscape class number	Landscape class	Total length (km)	Percentage of total stream network (%)
Streams, GDE	21	Near-permanent, lowland GDE stream	408	0.10%
	22	Near-permanent, upland GDE stream	52	0.01%
	23	Temporary, lowland GDE stream	40,785	10.37%
	24	Temporary, upland GDE stream	7,284	1.85%
		Total	**48,529**	**12.33%**
Streams, non-GDE	25	Near-permanent, estuarine stream	142	0.04%
	26	Near-permanent, lowland stream	116	0.03%
	27	Near-permanent, upland stream	100	0.03%
	28	Temporary, estuarine stream	149	0.04%
	29	Temporary, lowland stream	327,094	83.12%
	30	Temporary, upland stream	17,361	4.41%
		Total	**344,962**	**87.67%**
Total			**393,491**	**100%**

GDE = groundwater-dependent ecosystem

Table 9 Number of springs in the Galilee preliminary assessment extent

Landscape group	Landscape class number	Landscape class	Total count
Springs	31	Springs	3358

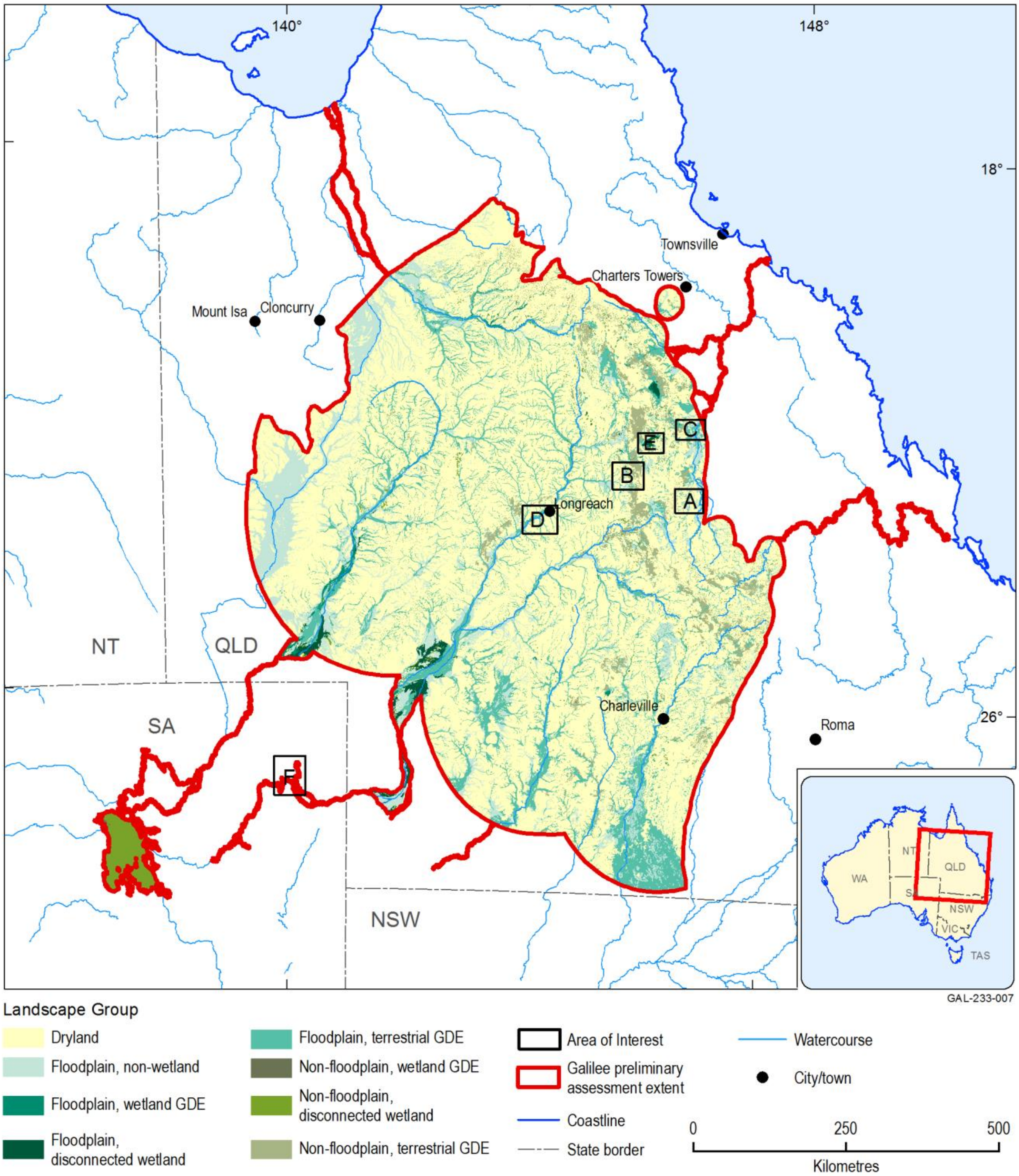

Figure 20 Distribution of landscape groups in the Galilee preliminary assessment extent

Inset boxes A to F show the location of Lagoon Creek and Native Companion Creek, north of Alpha, Queensland (Figure 21); Edgbaston Springs complex, north-east of Aramac, Queensland (Figure 22); Carmichael River from near Doongmabulla Springs to its confluence with the Belyando River, Queensland (Figure 23); Thomson River at Longreach, Queensland (Figure 24); Lake Galilee, Queensland (Figure 25); and Cooper Creek and Coongie Lakes, north-west of Innamincka, SA (Figure 26) respectively.
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 10)

2.3.3.1.3 Description of landscape groups

This section provides a description of the landscape groups in the classification. Eleven landscape groups are recognised. The floodplain and non-floodplain landscape groups are detailed in this section.

2.3.3.1.3.1 Floodplains

A floodplain can be broadly defined as that area of a landscape that occurs between a river system and the enclosing valley walls and is exposed to inundation or flooding during periods of high discharge (Rogers, 2011). For the Lake Eyre Basin, floodplains are considered to be alluvial plains that have an average recurrence interval of 50 years or less for channelled or overbank streamflow (Aquatic Ecosystems Task Group, 2012b). Floodplain and lowland riverine areas derived from Quaternary alluvial deposits are widely distributed across the Galilee PAE and include eight river systems including major catchments such as the Burdekin, Fitzroy, Flinders, Diamantina and Cooper river basins. The floodplains of the south-westerly flowing river systems are extremely wide; for example, in some areas the floodplain of the Cooper Creek exceeds 60 km.

‘Floodplain, non-wetland’ landscape group

Floodplains within the Galilee PAE consist of a significant area that is classified as ‘non-wetland’. These areas of the floodplain support terrestrial vegetation that is not groundwater dependent; rather it relies predominantly on surface water including direct precipitation, flood flows from rainfall and local runoff. This landscape group is widespread across the Galilee PAE (Figure 20 and Figure 21).

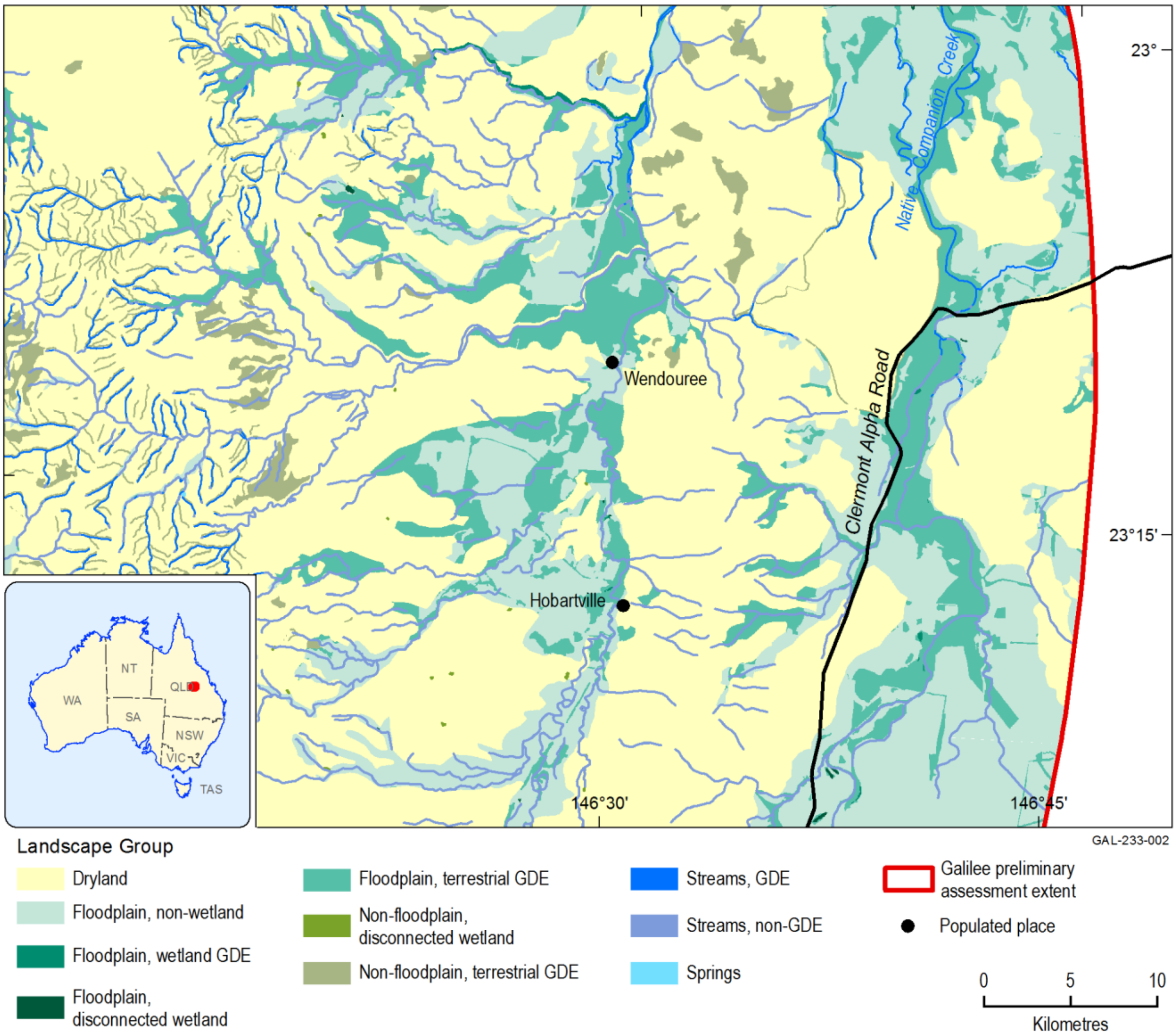

Figure 21 Landscape groups in the catchments of Lagoon Creek and Native Companion Creek, north of Alpha, Queensland

GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 10)

'Floodplain, wetland GDE' landscape group

Wetland GDEs occupy a small part of the PAE; 0.81% of the area is covered by polygons. This landscape group includes palustrine and lacustrine wetlands around discharge springs. A map of the landscape classes in the vicinity of Edgbaston Springs north-east of Aramac (Figure 22) illustrates the spatial distribution of wetland GDEs within the eastern portion of the PAE. Similarly, wetland GDEs occur along Carmichael River, near Doongmabulla Springs (Figure 23) in the north-west portion of the landscape.

Wetland GDEs are of extremely high importance in terms of biodiversity values. The biodiversity values for this landscape group are covered in detail under the 'Springs' landscape group.

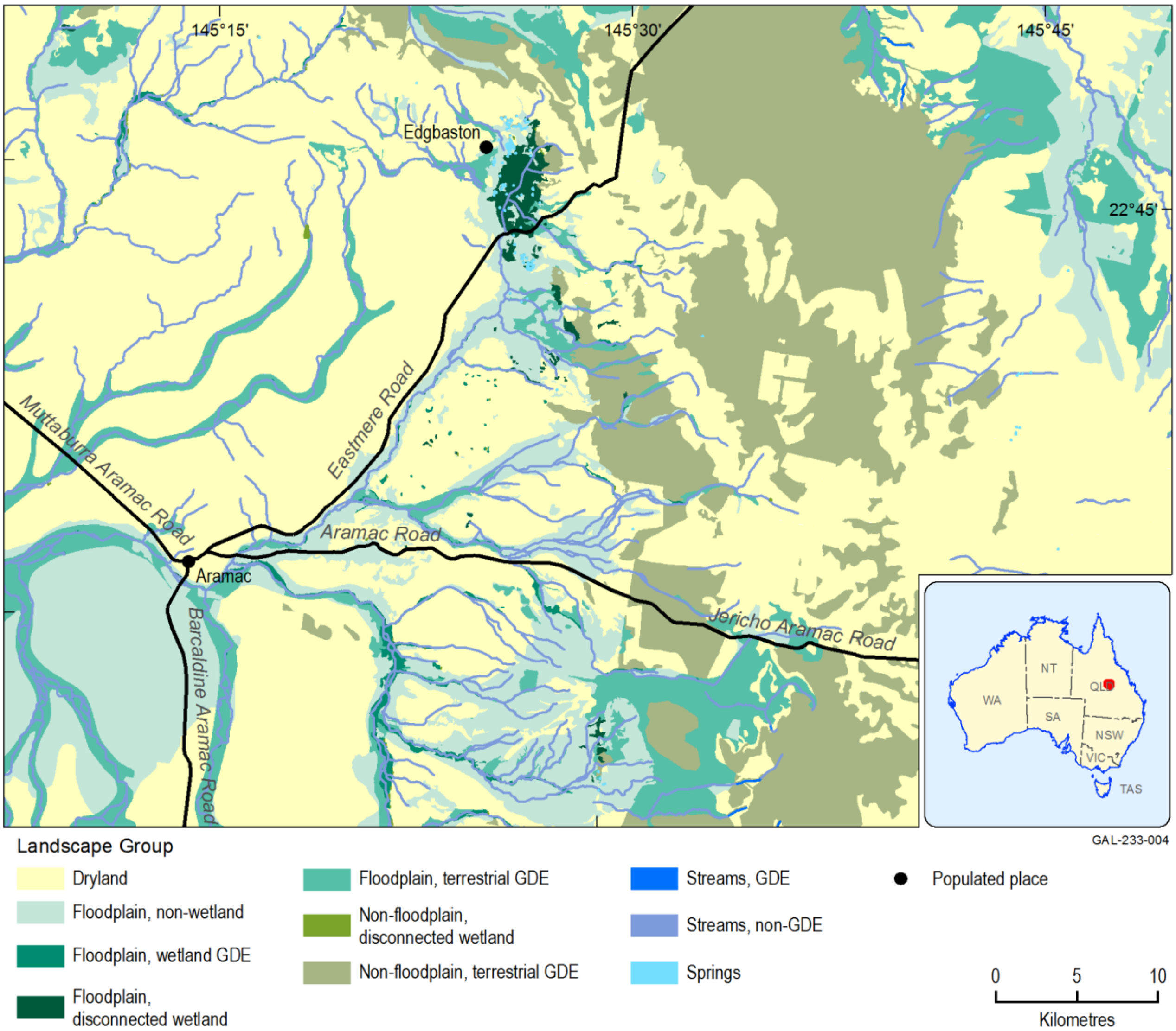

Figure 22 Landscape groups in the vicinity of the Edgbaston Springs complex, north-east of Aramac, Queensland

GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 10)

'Floodplain, terrestrial GDE' landscape group

The 'Floodplain, terrestrial GDE' landscape group contains landscape classes that have a subsurface reliance on groundwater. Landscape classes in the 'Floodplain, terrestrial GDE' landscape group occupy a significant portion of the Galilee PAE (12.94%) and are widespread throughout the PAE. Particular concentrations occur close to major river systems in the south and south-west (Figure 20).

Terrestrial GDEs typically consist of terrestrial vegetation of various types (open forest, woodland, shrubland, grassland) that require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements. The plants in these landscape classes are dependent on the subsurface presence of groundwater, which is accessed via their roots at depth. Examples of terrestrial GDEs in the PAE include riparian vegetation such as river red gum (*Eucalyptus camaldulensis*) open forest and coolibah (*Eucalyptus coolabah*) woodland.

Floodplain terrestrial GDEs in the Galilee PAE differ on the basis of water availability. The majority access intermittent subsurface groundwater.

Landscapes dominated by terrestrial GDEs are shown in the vicinity of Carmichael River and the Belyando River (Figure 23) in the east of the PAE and in the vicinity of the Thomson River (Figure 24), an inland draining system south-east of Longreach. .

Terrestrial GDEs on floodplains possibly support three threatened ecological communities listed in the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). These threatened ecological communities are:

- Brigalow (*Acacia harpophylla* dominant and co-dominant)
- Natural Grasslands of the Queensland Central Highlands and the northern Fitzroy Basin
- Weeping Myall Woodlands.

Groundwater dependency of these communities is yet to be established but they have been included based on the expectation that where these communities occupy floodplains interception of groundwater will occur.

Terrestrial GDEs on floodplains are likely to provide habitat for two EPBC Act-listed threatened species that occur within the Galilee PAE. These species are:

- squatter pigeon (southern) (*Geophaps scripta scripta*), vulnerable
- waxy cabbage palm (*Livistona lanuginosa*), vulnerable.

The waxy cabbage palm is part of the riparian vegetation along river channels and on floodplains on alluvial duplex soils in a small area of the Burdekin river basin that includes Doongmabulla on Carmichael River. It relies on subsurface availability of groundwater (Pettit and Dowe, 2004; Department of Environment, 2015). The squatter pigeon feeds and breeds in woodland that is both groundwater and surface water dependent.

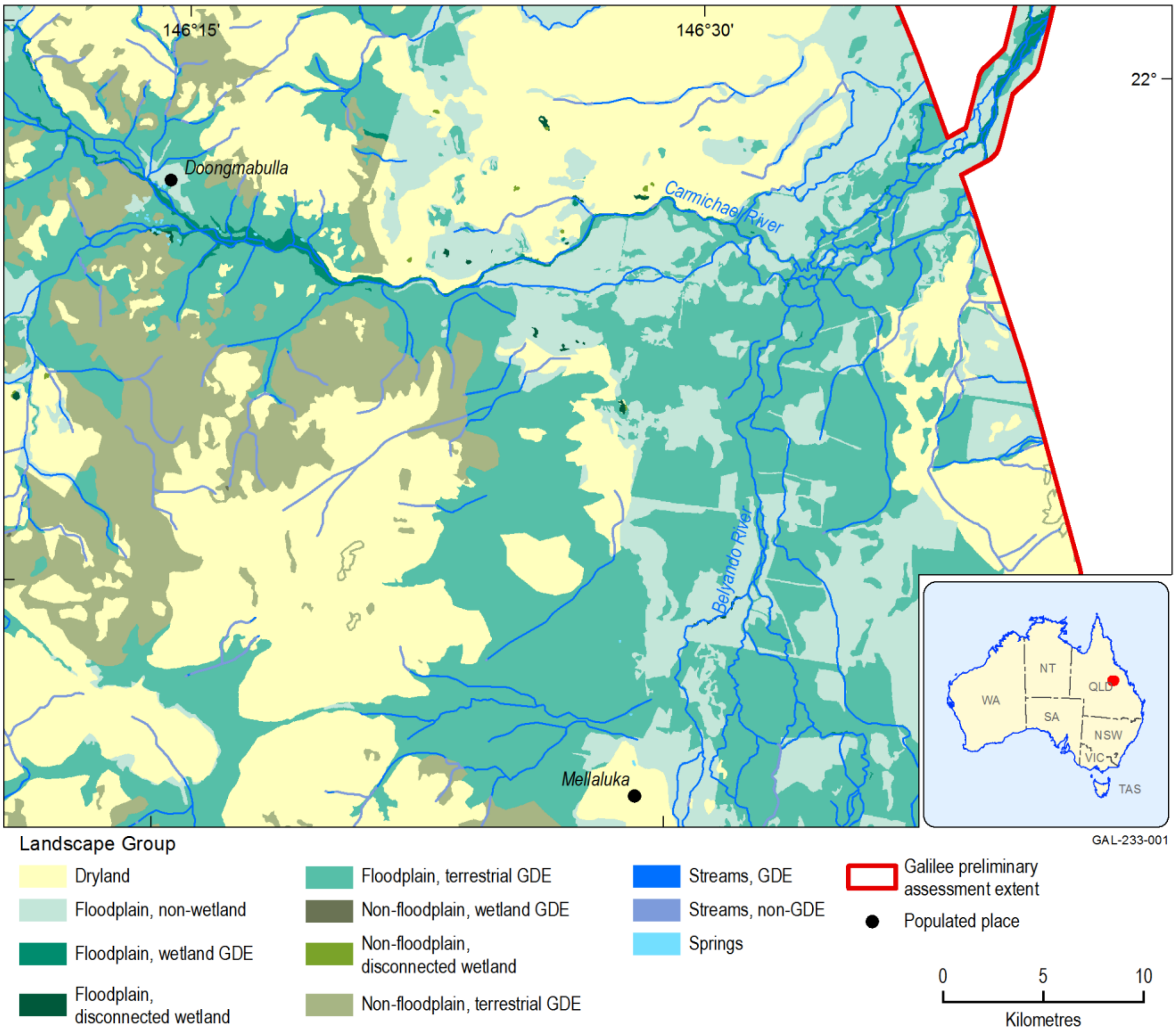

Figure 23 Landscape groups in the vicinity of Carmichael River, from near Doongmabulla Springs to its confluence with the Belyando River, Queensland

GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 10)

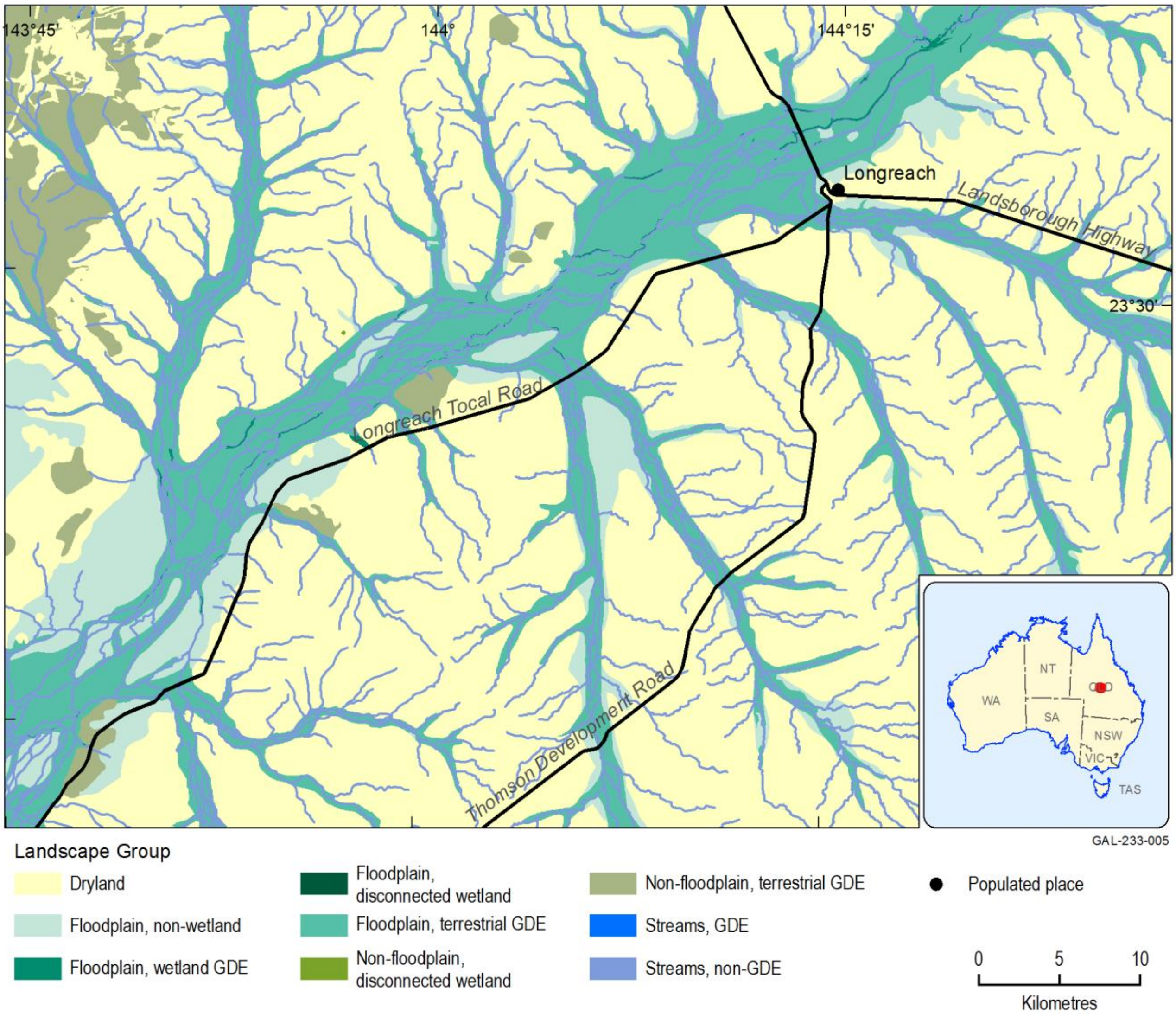

Figure 24 Landscape groups in the vicinity of the Thomson River at Longreach, Queensland

Data: Bioregional Assessment Programme (Dataset 10)

'Floodplain, disconnected wetland' landscape group

The 'Floodplain, disconnected wetland' landscape group includes all floodplain wetland landscape classes that depend predominantly on surface water such as flood flows from rainfall events, direct precipitation and local runoff. These wetlands are usually separated from the underlying groundwater system by an unsaturated zone; if groundwater seepage does occur it is not the main source of water. Because most of the Galilee PAE is within regions of low and unpredictable rainfall, most of these wetlands are temporary. This landscape group includes both saline (here referring to both brackish and saline, >3000 mg/L total dissolved solids) and freshwater landscape classes. Landforms included are lacustrine and palustrine. Saline disconnected wetlands include lakes and swamps. Saline swamps commonly form on the fringing dunes of saline claypans. These saline systems are closed hydrologically – a lack of regular freshwater flushing can lead to very high salinity.

A landscape dominated by the 'Floodplain, disconnected wetland' landscape group is Lake Galilee (Figure 25), a terminal wetland fed by about 20 temporary lowland streams in the east of the PAE.

The area consists of a mixture of saline and freshwater disconnected wetlands. Another floodplain landscape that is dominated by disconnected wetlands is Cooper Creek in the vicinity of Coongie Lakes (Figure 26), in the arid zone of SA. This dominance of disconnected wetland in the lower reaches of the Cooper system contrasts with the terrestrial GDEs that dominate upstream at the Thomson River immediately south-east of Longreach (Figure 24) and the easterly flowing Carmichael River and Belyando River (Figure 23).

Remnant vegetation associated with disconnected wetlands includes woodland of river red gum, coolibah or river cooba (*Acacia stenophylla*); and shrubland of lignum (*Muehlenbeckia florulenta*) and northern bluebush (*Chenopodium auricomum*). Chenopod shrublands are common on some saline disconnected wetlands and include samphire (*Halosarcia* spp.), saltbushes and bluebushes.

Waterholes are included in this landscape group. Waterholes are of considerable importance because they continue to hold water once flow in river channels ceases. Thus waterholes act as refuges for aquatic biota when natural fragmentation occurs during dry periods and play a key role in sustaining assemblage dynamics (Arthington et al., 2010; Arthington and Balcombe, 2011). Waterholes may or may not interact with groundwater depending on the level of substrate permeability and on depth to groundwater. Most waterholes in the Diamantina and Cooper river systems are not groundwater dependent (Fensham et al., 2011). Although surface water-dependent waterholes lose water through evaporation, suspended clays that settle out after flow events form a bottom seal that minimises seepage losses.

This landscape group supports an EPBC Act-listed threatened ecological community, 'Coolibah – Black Box Woodlands of the Darling Riverine Plains and the Brigalow Belt South Bioregions' (TSSC, 2010). The threatened ecological community is classified as surface water dependent and occurs on floodplains in the south-east portion of the Galilee subregion.

The 'Floodplain, disconnected wetland' landscape group is likely to provide habitat for four EPBC Act-listed threatened species that occur within the Galilee PAE. These species are:

- Australian painted snipe (*Rostratula australis*), endangered
- ornamental snake (*Denisonia maculata*), vulnerable
- squatter pigeon (southern), vulnerable
- star finch (eastern) (*Neochmia ruficauda ruficauda*), endangered.

The Australian painted snipe depends on shallow freshwater wetlands, including floodplain lakes and swamps, in which to feed and breed. The squatter pigeon feeds and breeds in woodland that is both surface water and groundwater dependent and depends on a daily uptake of water — most of which is likely to come from disconnected wetlands on floodplains. The star finch occupies swamps and other wetlands on floodplains. The ornamental snake occupies river channels and adjacent floodplains with cracking clay soils and feeds on frogs in and around wetlands.

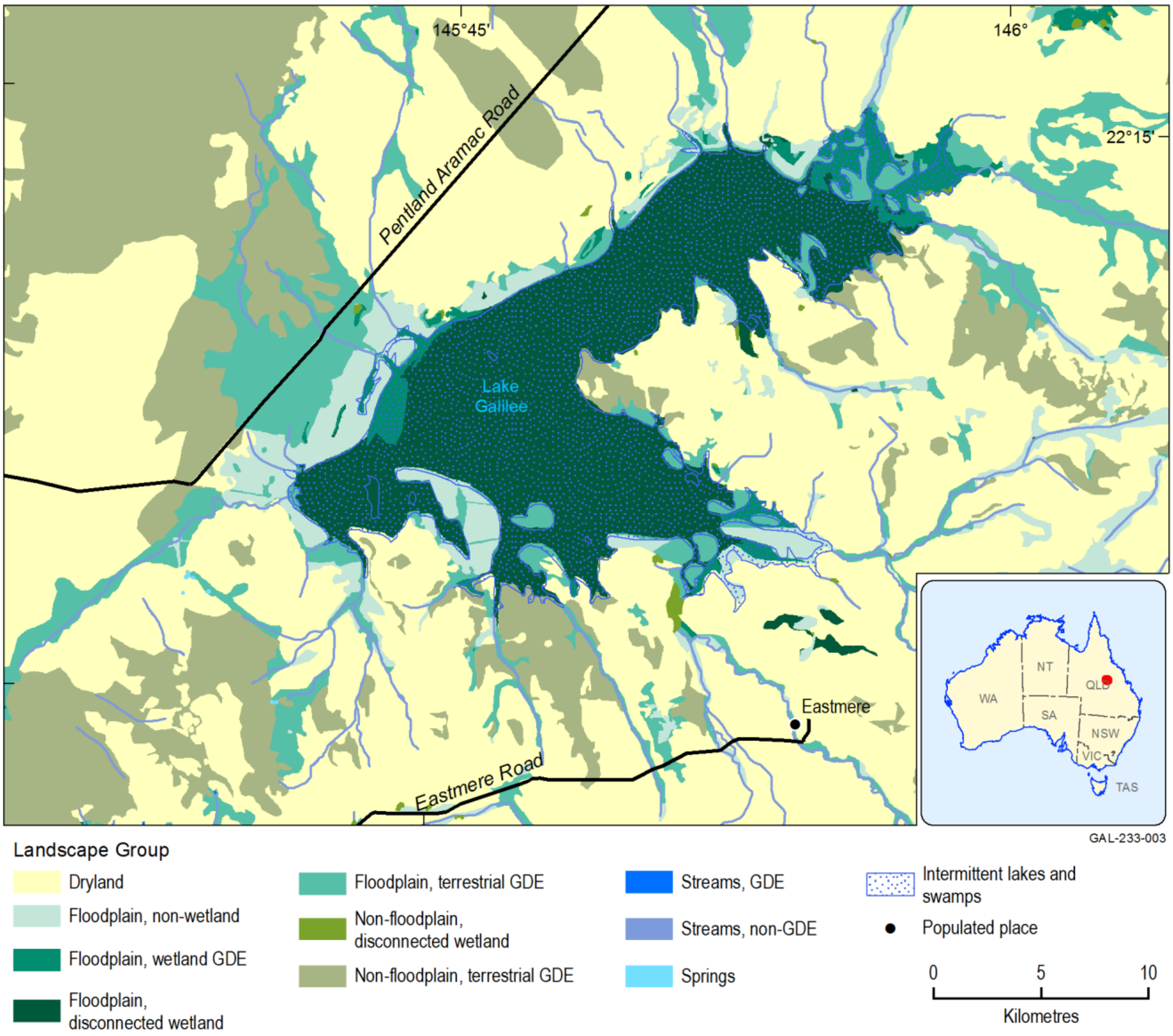

Figure 25 Landscape groups in the vicinity of Lake Galilee, Queensland

Data: Bioregional Assessment Programme (Dataset 10)

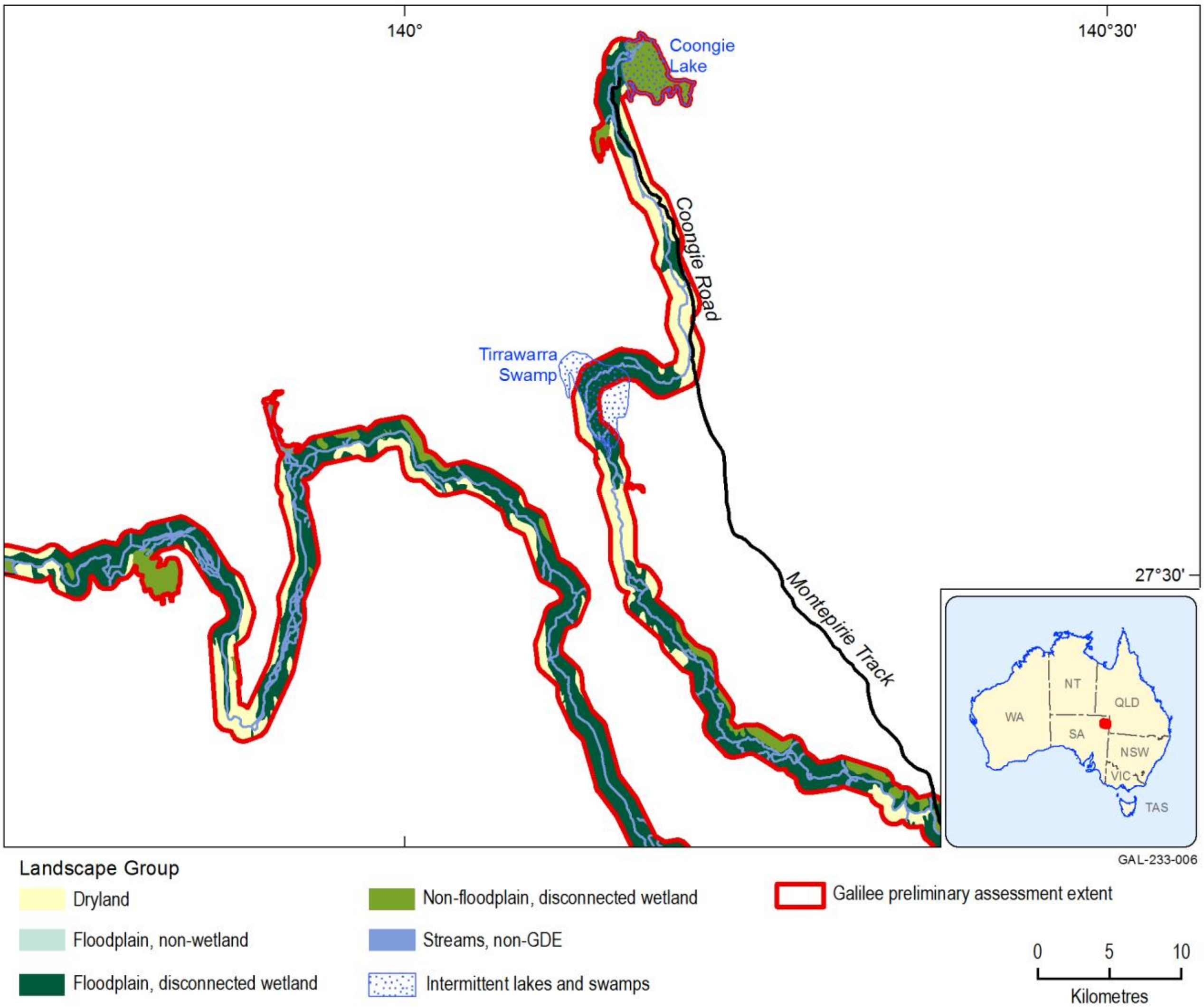

Figure 26 Landscape groups in the vicinity of Cooper Creek and Coongie Lakes, north-west of Innamincka, South Australia

Data: Bioregional Assessment Programme (Dataset 10)

2.3.3.1.3.2 Non-floodplains

A further four landscape groups are water dependent but do not occur on floodplains (Table 7). The land zones that support these landscape groups include clay plains, loamy and sandy plains, inland dunefields, and fine-grained and coarse-grained sedimentary rocks. The occurrence of these non-floodplain land zones is variable across the PAE. Extensive areas of duricrusts (Land Zone 7) occur throughout the Galilee PAE with concentrations along the eastern margins and in the south-west corner. In the north-east and central eastern parts of the PAE the geology mainly comprises intrusive igneous rock and sedimentary rock. In contrast, inland dunefields (Land Zone 6) are confined to the extreme south-west of the PAE.

'Dryland' landscape group

Drylands are those areas of the landscape that are not on the floodplain and are not wetlands. Water comes from rainfall and local runoff and its availability is unpredictable. Most of the Galilee PAE is semi-arid or arid, with a mean annual rainfall of less than 500 mm (companion product 1.1 for the Galilee subregion (Evans et al., 2014, Figure 11)). It is only the eastern margin of the PAE that receives greater than 500 mm of rainfall on average annually. Rainfall within the PAE and throughout arid and semi-arid northern Australia is highly unpredictable (van Etten, 2010) and occurs in discrete pulses. As a consequence, land systems such as drylands, which depend on rainfall and local runoff for water availability, experience irruptive pulses in primary productivity and support a biota that undergoes boom-bust population dynamics.

Most of the Galilee PAE is dryland and most of this area supports remnant vegetation. A wide range of vegetation types occur including Mitchell grass (*Astrebla*) tussock grassland, spinifex (*Triodia*) hummock grassland, Eucalyptus open forest and woodland, and Acacia (including Mulga and Brigalow) open woodland and shrubland.

The 'Dryland, remnant vegetation' landscape class provides habitat for EPBC Act-listed threatened ecological communities including 'Brigalow (*Acacia harpophylla* dominant and co-dominant)' and 'Weeping Myall Woodlands'.

'Non-floodplain, wetland GDE' landscape group

The two landscape classes in the 'Non-floodplain, wetland GDE' landscape group occupy a very small area of the PAE. Non-floodplain wetland GDEs occur where sedimentary layers outcrop at or near the surface especially where there are sandstone ranges.

In the central and western regions of the Galilee PAE, sand dunefields (sand ridges) are an important source of groundwater, which supports non-floodplain wetland GDEs. These dunefields can store groundwater in local, intermediate or regional groundwater flow systems and also in perched aquifers formed by layers of relatively impermeable clay-dominated material. Palustrine, lacustrine and riverine wetlands on the edge of inland sand dunefields may be present because of the surface expression of this groundwater.

'Non-floodplain, terrestrial GDE' landscape group

The details of landscape classes in the 'Non-floodplain, terrestrial GDE' landscape group are similar to the landscape classes in the 'Floodplain, terrestrial GDE' landscape group; however, the former landscape group occupies a smaller area of the PAE (3.39%) (Table 7). Terrestrial GDEs are typically terrestrial vegetation of various types (open-forest, woodland, shrubland, grassland) that require access to groundwater on a permanent or intermittent basis to meet all or some of their water requirements. In the case of non-floodplain environments, terrestrial GDEs tend to be on loamy or sandy plains or inland sand dunefields (sand ridges), which are largely composed of unconsolidated sand deposited by aeolian processes (wind). These landscape classes are dependent on the subsurface presence of groundwater, which is accessed via their roots at depth. On inland sand dunefields, groundwater is available from unconsolidated sedimentary aquifers from which terrestrial vegetation typically accesses water through the capillary zone above the watertable.

'Non-floodplain, disconnected wetland' landscape group

The 'Non-floodplain disconnected wetland' landscape group includes all non-floodplain landscape classes that depend on surface water such as flood flows from rainfall events. Landforms included are lacustrine and palustrine. Also included are riverine elements such as waterholes. This landscape group includes saline/brackish and freshwater wetlands with water availability being usually non-permanent or near-permanent, with rare examples of permanency. Landscape classes in the 'Non-floodplain, disconnected wetland' landscape group make up 1.43% of the PAE, with the most common landscape class being 'Non-floodplain disconnected saline wetland' (1.25% of the PAE) (Table 7).

Landscapes that include small areas of 'Non-floodplain disconnected wetland' are shown in Figure 25 and Figure 26. Non-floodplain disconnected wetlands are present south of Lake Galilee (Figure 25).

Rockholes are a type of wetland only present in the 'Non-floodplain, disconnected wetland' landscape group. Rockholes are natural hollows in rocky landscapes that form by fracturing and weathering of rock and which store water from local runoff (Fensham et al., 2011). Typically, rockholes occur in sandstone and granite ranges within the Galilee PAE. As with other wetlands in this landscape group, most rockholes are non-permanent; however, a small number are known to be permanent, replenished by small rainfall events (Fensham et al., 2011).

Gilgai is another type of non-floodplain, disconnected wetland. Gilgais occur within the clay plains land zone and consist of shrink-swell and cracking clay soils that form depressions. Gilgai microrelief occurs when the layers of clay soil shrink and swell during alternate drying and wetting cycles. Gilgai depressions fill with water during and after rain resulting in a landscape containing several shallow wetlands.

Landscapes in the 'Non-floodplain, disconnected wetland' landscape group potentially provide habitat for four EPBC Act-listed threatened species that occur within the Galilee PAE. These species are:

- Australian painted snipe, endangered
- squatter pigeon (southern), vulnerable
- star finch (eastern), endangered
- *Lawrencia buchananensis*, vulnerable.

Lawrencia buchananensis grows only on the fringes of Lake Buchanan and Lake Constant. The species may be surface water dependent but this is not known for sure.

2.3.3.1.3.3 Streams

The streams within the PAE are divided into two landscape groups: 'Streams, GDE' and 'Streams, non-GDE' (Table 8).

'Streams, GDE' landscape group

Riverine GDEs occur in both lowland and upland streams. The most common landscape class in this group is 'Temporary, lowland GDE stream'. Stream GDEs may occur in streams with gaining or variable gaining/losing aquifer connectivity. These streams receive baseflow from upward leakage from sandstone aquifers such as the Hooray Sandstone, Clematis-Warang Sandstone and Ronlow beds (companion product 1.1 for the Galilee subregion (Evans et al., 2014, p. 113)). This groundwater – surface water connectivity is highest where Galilee Basin strata outcrop along the eastern margin of the Galilee subregion and involve rivers such as the Belyando River.

'Streams, non-GDE' landscape group

Streams in the 'Streams, non-GDE' landscape group occur in both upland and lowland areas. The low and unpredictable rainfall across most of the Galilee PAE has resulted in this landscape group being dominated by streams that are temporary. Specifically, the 'Temporary, lowland stream' landscape class makes up 83.12% of the total stream network, whereas the 'Near-permanent, lowland stream' landscape class is only 0.03%.

2.3.3.1.3.4 Springs

'Springs' landscape group

The 'Springs' landscape group (Table 9) includes both discharge springs and recharge springs. Discharge springs occur where groundwater escapes to the surface under hydrostatic pressure from cracks and faults in the confining bedrock. Discharge spring wetlands in the Galilee PAE occur on recently deposited alluvia and fine-grained sedimentary rocks (shales). The area of discharge spring wetlands is generally small, mostly less than 0.05 ha, but with a small number of more than 1 ha wetlands (Fensham and Fairfax, 2003). Vegetation varies from site to site depending on moisture, but generally supports a ground layer of grasses, sedges and/or a mat of herbs.

This landscape group supports a threatened ecological community listed in the EPBC Act, 'The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin'. This threatened ecological community occurs in parts of NSW, elsewhere in Queensland and within the Galilee PAE in Queensland and SA (Fensham et al., 2010). It includes three species of EPBC Act-listed threatened freshwater fish: the redfin blue eye (*Scaturiginichthys vermeilipinnis*), Edgbaston goby (*Chlamydogobius squamigenus*) and Elizabeth Springs goby (*Chlamydogobius micropterus*). The redfin blue eye is endangered and the Edgbaston goby is vulnerable. Both occur, often together, in springs within the Barcaldine supergroup at Edgbaston Station and, in the case of the Edgbaston goby, Crossmoor Station on the Thomson River. The range of the redfin blue eye is four springs – approximately 0.3 ha, whereas the Edgbaston Goby occupies 11 springs. The Elizabeth Springs goby is endangered and occurs within the Galilee PAE at the Elizabeth Springs complex and Spring Creek (Fensham et al., 2010).

The endangered mat-forming herb, salt pipewort (*Eriocaulon carsonii*), also occurs within discharge springs of the Galilee PAE in Queensland and SA. Another endangered herb, blue devil (*Eryngium fontanum*), is confined to two spring complexes within this landscape group (Fensham et al., 2010).

Recharge springs occur in upland areas within the PAE. An example is recharge springs from sandstone aquifers. These springs and associated wetlands are dependent on groundwater and occur where sediments that form an aquifer are outcropping (Fensham et al., 2011).

2.3.3.1.3.5 Modified landscapes

As mentioned in Section 2.3.3.1, very little of the PAE includes modified landscapes. In this respect, the Galilee subregion differs from most of the other subregions being assessed by the Bioregional Assessment Programme. The PAE does not include any dryland cropping or horticulture, irrigated cropping or horticulture, grazing of modified pastures or intensive horticulture or animal production. The main impact on water-dependent ecosystems from human activity is the placement of bores to provide water at the surface for livestock. Bores rely on groundwater and in the past have had a significant negative impact on springs within the PAE (Fensham and Fairfax, 2003; Fensham et al., 2011). Urban settlement is very limited in extent and the towns that exist have a low population size. These towns rely on groundwater and surface water via bores and river offtakes.

2.3.3.2 Gaps

Wetlands in large areas of the Galilee PAE are not yet adequately mapped. However, a significant amount of work targeting gaps in mapping has been undertaken as part of the Lake Eyre Basin Springs Assessment project. Specifically, this task is being done for groundwater (DSITI, 2015) with a related project focusing on springs (Fensham et al., 2016).

The separation between groundwater-dependent and surface water-dependent wetlands may not always be accurate. In many areas there is little knowledge of groundwater – surface water interactions. There is also a significant data gap in the understanding of water thresholds for ecosystems associated with springs and other water assets. In part, this results from a lack of bores to provide meaningful groundwater level data time series. Some examples of these data gaps appear in the discussion of the functioning of springs in the Doongmabulla Springs complex in the Galilee subregion, particularly in identifying the source aquifer (Fensham et al., 2016).

Subsurface GDEs have not been adequately surveyed within the PAE and are not adequately represented in this landscape classification. This is known to be a widespread issue (e.g. Tomlinson and Boulton, 2010). A consequence of these gaps is uncertainty in the understanding of water dependency.

Further discussion on gaps and opportunities is also outlined in Section 3.7 in companion product 3-4 (Lewis et al., 2018).

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2.3.4 Baseline and coal resource development pathway

Summary

Coal seams were first discovered in the geological Galilee Basin more than 100 years ago, and there are now about 20 identified coal resources within the Galilee subregion. Most deposits contain high volatile, low rank black coal hosted in Permian-age strata. However, although many world-class thermal coal deposits occur in the Galilee subregion, as of mid-2016 no commercially producing coal mines have ever operated there. Likewise, there has been no commercial-scale coal seam gas (CSG) production, although several pilot projects have confirmed that CSG does occur in the Permian coal layers and can be recovered. The geographic isolation and lack of mine-enabling infrastructure have long hampered exploration and development of the massive coal deposits of the Galilee Basin, although a number of large-scale coal mine proposals were submitted for regulatory approval between 2008 and 2014.

For the purposes of the bioregional assessment (BA) for the Galilee subregion, the absence of commercially producing coal mines and CSG fields in the Galilee subregion means that there are no coal resource developments being quantitatively modelled in the baseline. This is an important point, as it means that the focus of hydrological modelling and impact and risk analysis will be on the subregion's additional coal resource development, that is, the combination of proposed coal mine and CSG developments that the Assessment team has evaluated as most likely to progress to commercial production at some time in the future (post the baseline date of December 2012).

The coal resource development pathway (CRDP) for the Galilee subregion includes 17 proposed new coal resource developments. Most of these are for large-scale thermal coal mines, with associated on-site mining development and coal processing infrastructure covering many thousands of hectares. There are 14 proposed new coal mines in the Galilee CRDP comprising: 3 open-cut coal mines (Alpha, Hyde Park and Blackall); 2 underground coal mines (Alpha West and Hughenden); 5 combined open-cut and underground coal mining operations (Carmichael, China First, China Stone, Kevin's Corner and South Galilee); and 4 coal mines of currently unknown type (Clyde Park, Milray, Pentland and West Pentland). The CRDP for the Galilee subregion also includes three early-stage CSG projects, namely the Galilee Gas Project, Gunn pilot site and Blue Energy operations, focused in the central zone of the Galilee Basin, where a recognised CSG resource fairway exists.

Of the total number of proposed developments in the CRDP for the Galilee subregion, there is sufficient information publicly available to include seven coal mines in the numerical modelling for the Galilee subregion. Thus, the modelled CRDP for the BA for the Galilee subregion, which is focused on the central-eastern margin of the subregion, includes the proposed coal mines at Alpha, Carmichael, China First, China Stone, Hyde Park, Kevin's Corner and South Galilee. These are the most advanced mining proposals in terms of the various environmental and mining-related approvals processes required prior to the start of commercial production. The other coal mine (Alpha West, Blackall, Clyde Park, Hughenden, Milray, Pentland and West Pentland) and CSG developments (Galilee Gas, Gunn and Blue

Energy) in the CRDP will not be assessed by hydrological modelling in this iteration of the BA. However, qualitative analysis of potential development-related impacts to water resources and water-dependent assets for the non-modelled CRDP will be reported in companion product 3-4 (impact and risk analysis) for the Galilee subregion.

Detailed information on water management is only available for the six coal mine developments which have thus far submitted their environmental impact statements (excludes Hyde Park from those listed in the modelled CRDP). There are many common elements to the proposed water management strategies for these large mining complexes, including surface water is diverted around the mine and infrastructure areas (where possible), and any water retained in the mine area will be used for mining or related purposes (this includes groundwater pumped to dewater the mines). Also, there will be progressive rehabilitation of mined-out areas as mining operations advance over time. Thus, the amount of surface area that is disconnected from part of a river basin due to mining may vary during life of mine.

2.3.4.1 Developing the coal resource development pathway

2.3.4.1.1 Introduction

The coal resource development pathway (CRDP) is a fundamental concept in bioregional assessments (BA), and an important initial step in the model-data analysis component of any BA. It defines the most likely future that includes all coal mines and coal seam gas (CSG) fields commercially producing as of December 2012 (known as the *baseline*), as well as those expected to commence production post-2012. The difference in results between the baseline and the CRDP is the change that is primarily reported in a BA, and this is due to the *additional coal resource development*. The additional coal resource development is defined as all coal mines and CSG fields, including expansions of baseline operations, which are considered most likely to begin commercial production after December 2012.

The general input data and analysis required to develop the CRDP are outlined in companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014). This section explains the specific application of this BA submethodology to the Galilee subregion, and builds upon the coal and CSG resource assessment provided in companion product 1.2 for the Galilee subregion (Lewis et al., 2014). In particular, the catalogue of potential coal resource developments (Section 1.2.4 in companion product 1.2) provides the starting inventory for assessment of the CRDP. This catalogue lists 20 identified coal resources from the Galilee subregion with a combined thermal coal tonnage of about 36 billion tonnes, as well as three CSG projects with contingent (2C and 3C) resources.

The CRDP for the Galilee subregion is based on the Assessment team’s analysis of relevant coal resource information for each project in the catalogue of potential coal resource developments. The data and information used to inform this analysis comprised publicly available material as of December 2014. An important step in finalising the CRDP for the Galilee subregion was the critical discussion and expert input received at an external participant workshop held in Brisbane in October 2014. Representatives from the Australian Government Department of the Environment, CSIRO, Geoscience Australia, and the Queensland Government, as well as the Queensland Resources Council (QRC) and various coal and CSG development companies with interests in the Galilee subregion, all participated in this CRDP workshop. Following the discussion and information-sharing that occurred at this event, the Assessment team was able to finalise the CRDP in December 2014 and 'lock it in' as the basis for the future hydrological modelling in the BA (as reported in the surface water modelling (companion product 2.6.1 (Karim et al., 2018)) and groundwater modelling (companion product 2.6.2 (Peeters et al., 2018) for the Galilee subregion)).

2.3.4.1.2 Coal resource development pathway for the Galilee subregion

As documented in companion product 1.2 for the Galilee subregion (Lewis et al., 2014) there were no coal mines or CSG fields in commercial production as of December 2012. Consequently, for the purposes of the BA, the modelled baseline does not include any coal resource developments.

In contrast to the baseline, the CRDP for the Galilee subregion consists of 17 proposed new coal and CSG resource developments (Table 10). Most of the developments in the CRDP are for new large-scale coal mines that target thermal coal resources hosted within upper Permian strata, such as the Betts Creek beds (companion product 1.1 for the Galilee subregion (Evans et al., 2014)). These proposed coal mines mainly occur close to the northern and eastern margins of the geological Galilee Basin (Figure 27), where the coal-bearing Permian rocks are relatively close to the surface (i.e. generally within several hundred metres), and thus amenable to future mining development.

On the basis of information available as of December 2014, the proposed coal mining operations included in the CRDP consist of:

- three open-cut coal mines (Alpha, Hyde Park and Blackall[1])
- two underground coal mines (Alpha West and Hughenden)
- five combined open-cut and underground coal mining operations (Carmichael, China First, China Stone, Kevin's Corner and South Galilee)
- four coal mines of currently unknown type (Clyde Park, Milray, Pentland and West Pentland).

There are also three early-stage CSG projects included in the CRDP (Galilee Gas Project, focused on the Glenaras pilot site; Gunn pilot site; and Blue Energy's CSG project in Exploration Permit for Petroleum (EPP) 812). The locations of the proposed coal mines and CSG developments in the CRDP are shown in Figure 27. Summary information about each development listed in the CRDP is provided in Table 10, including company name, total identified resources and expected start year and duration of mining. Further details about each of these proposed operations, including plans of several mine sites, are available in companion product 1.2 for the Galilee subregion (Lewis et al., 2014).

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[1] As explained in companion product 1.2 for the Galilee subregion (Lewis et al., 2014), the coal resources at Blackall differ from those at other sites in the CRDP, as they are significantly younger and of lower coal rank. This is because the Blackall coal deposit is hosted in the Upper Cretaceous Winton Formation, a unit of the geological Eromanga Basin which stratigraphically overlies the Permian Galilee Basin.

Section 2.3.4.1.2.1 and Section 2.3.4.1.2.2 respectively provide details on coal resource developments in the CRDP that are included in the quantitative or qualitative assessment of hydrological changes.

Table 10 Coal resource development pathway for the Galilee subregion as determined at December 2014

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 – all coal mines and CSG fields, including expansions of baseline operations, which are expected to begin commercial production after December 2012.

Name of existing operation or proposed development	Coal mine or coal seam gas (CSG) operation	Company	Included in the baseline?	Included in the coal resource development pathway (CRDP)? (modelled or commentary)	Start of mining operations or estimated project start	Expected duration of commercial operations	Total coal resources (Mt) (for coal mining) or gas resources (PJ) (for CSG)	Comments
Alpha Coal Project	Open-cut coal mine	GVK Hancock Coal	No	Yes – modelled	2018	30 years	1821 Mt	Total coal resource is 821 Mt measured, 700 Mt indicated and 300 Mt inferred, and is mostly from the C and D coal seams of the Betts Creek beds. Geology and coal resource information in Hancock Prospecting (2010)
Carmichael Coal Mine and Rail Project	Combined open-cut and underground coal mine	Adani Mining Pty Ltd	No	Yes – modelled	2019	60 years	7800 Mt	Total coal resource is 500 Mt indicated and 7300 Mt inferred, and is mostly in AB and D coal seams. Coal resource information in Adani Mining (2012)
China First Coal Project	Combined open-cut and underground coal mine	Waratah Coal Pty Ltd	No	Yes – modelled	2021	30 years	3680 Mt	Total coal resource is 1975 Mt measured, 565 Mt indicated and 1140 Mt inferred. Coal resource information in Waratah Coal (2011)
China Stone Coal Project	Combined open-cut and underground coal mine	Macmines Austasia Pty Ltd	No	Yes – modelled	2022	50 years	5590 Mt	Total coal resource is 830 Mt measured, 1230 Mt indicated and 3530 Mt inferred. Coal resource and geology information in Hansen Bailey (2015)

Name of existing operation or proposed development	Coal mine or coal seam gas (CSG) operation	Company	Included in the baseline?	Included in the coal resource development pathway (CRDP)? (modelled or commentary)	Start of mining operations or estimated project start	Expected duration of commercial operations	Total coal resources (Mt) (for coal mining) or gas resources (PJ) (for CSG)	Comments
Hyde Park Coal Project	Open-cut coal mine	Resolve Coal Pty Ltd	No	Yes – modelled	2022	30+ years	1625 Mt	Pre-feasibility study underway as of 2016. Total coal resource is 315 Mt indicated and 1310 Mt inferred, and is mostly in A and B, and C and D coal seams. Coal resource and geology information at Resolve Coal (2016)
Kevin's Corner Coal Project	Combined open-cut and underground mine	GVK Hancock Coal	No	Yes – modelled	2020	30 years	4269 Mt	Total coal resource is 229 Mt measured, 1040 Mt indicated and 3000 Mt inferred, to be mined from the A, B, C and D coal seams. Geology and coal resource data in Hancock Galilee (2011)
South Galilee Coal Project	Combined open-cut and underground coal mine	Alpha Coal Management Pty Ltd, on behalf of AMCI and Alpha Coal Pty Ltd	No	Yes – modelled	2021	33 years	1179 Mt	Total coal resource is 167 Mt measured, 206 Mt indicated and 806 Mt inferred, within the D1 and D2 coal seams. Coal resource and geology information in Alpha Coal (2012)
Alpha West Coal Project	Underground coal mine	GVK Hancock Coal	No	Yes – commentary	Unknown	Unknown	1800 Mt	Not able to be modelled for this iteration of Galilee subregion. Total coal resource is 500 Mt indicated and 1300 Mt inferred. Located immediately west of Alpha, initial concept plan indicates an underground longwall mining operation (Mulder, 2013)

Name of existing operation or proposed development	Coal mine or coal seam gas (CSG) operation	Company	Included in the baseline?	Included in the coal resource development pathway (CRDP)? (modelled or commentary)	Start of mining operations or estimated project start	Expected duration of commercial operations	Total coal resources (Mt) (for coal mining) or gas resources (PJ) (for CSG)	Comments
Blackall Coal Project	Open-cut coal mine	East Energy Resources Limited	No	Yes – commentary	Unknown	Unknown	3445 Mt	Not able to be modelled for this iteration for the Galilee subregion. Total coal resource hosted in Cretaceous Winton Formation (Eromanga Basin) is 628 Mt indicated and 2817 Mt inferred. Coal resource information in EER (2014)
Clyde Park Coal Project	Coal mine of unknown type	TerraCom Limited (formerly Guildford Coal Limited)	No	Yes – commentary	Unknown	Unknown	728 Mt	Total coal resource is 51 Mt indicated and 677 Mt inferred. There is also a 40 to 815 Mt exploration target in adjacent tenement. Not able to be modelled for this iteration for the Galilee subregion. Coal resource information at TerraCom (2016)
Hughenden Project	Underground coal mine	TerraCom Limited (formerly Guildford Coal Limited)	No	Yes – commentary	Unknown	Unknown	1209 Mt	Total coal resource is 133 Mt indicated and 1076 Mt inferred. Not able to be modelled for this iteration for the Galilee subregion. Coal resource information at TerraCom (2016)
Pentland Coal Project	Coal mine of unknown type	Glencore Coal Queensland Pty Ltd	No	Yes – commentary	Unknown	Unknown	100 Mt	Total coal resource is 65 Mt measured, 15 Mt indicated and 20 Mt inferred. Not able to be modelled for this iteration for the Galilee subregion. Coal resource information in GA and BREE (2013)
Milray	Coal mine of unknown type	Glencore Coal Queensland Pty Ltd	No	Yes – commentary	Unknown	Unknown	610 Mt	Inferred resource defined only. Not able to be modelled for this iteration of Galilee subregion

Name of existing operation or proposed development	Coal mine or coal seam gas (CSG) operation	Company	Included in the baseline?	Included in the coal resource development pathway (CRDP)? (modelled or commentary)	Start of mining operations or estimated project start	Expected duration of commercial operations	Total coal resources (Mt) (for coal mining) or gas resources (PJ) (for CSG)	Comments
West Pentland Coal Project	Possibly open-cut coal mine, but no development plans as yet	United Queensland Resources Pty Limited (previously owned by New Emerald Coal Ltd)	No	Yes – commentary	Unknown	Unknown	266 Mt	Total coal resource is 176 Mt indicated and 90 Mt inferred, contained in five mineable seams. United Queensland Resources Pty Ltd gained ownership of New Emerald Coal Ltd in May 2015. Not able to be modelled for this iteration for the Galilee subregion. Coal resource information in Xenith (2013)
Galilee Gas Project (Glenaras site)	CSG	Galilee Energy Limited	No	Yes – commentary	Unknown	Unknown	2C resource of 2508 PJ and 3C resource of 5314 PJ	CSG resource is in part of exploration permit for petroleum (EPP) 529, and focused on the Glenaras production pilot which has a number of test wells. Not able to be modelled for this iteration for the Galilee subregion. CSG resource information at Galilee Energy (2016)
Gunn Project	CSG	Comet Ridge Limited	No	Yes – commentary	Unknown	Unknown	2C resource of 67 PJ and 3C resource of 1870 PJ	CSG resource is in part of EPP 744, in which there is also an identified 597 PJ of prospective resources. CSG production test well and exploration site. Not able to be modelled for this iteration for the Galilee subregion. CSG resource information at Comet Ridge (2016)

Name of existing operation or proposed development	Coal mine or coal seam gas (CSG) operation	Company	Included in the baseline?	Included in the coal resource development pathway (CRDP)? (modelled or commentary)	Start of mining operations or estimated project start	Expected duration of commercial operations	Total coal resources (Mt) (for coal mining) or gas resources (PJ) (for CSG)	Comments
Blue Energy's CSG exploration project EPP 813	CSG	Blue Energy Limited	No	Yes – commentary	Unknown	Unknown	2C resources of 62 PJ and 3C resource of 838 PJ	Resource is in part of CSG exploration project in EPP 813 in central Galilee Basin, in which there is also an identified 1142 PJ of prospective CSG resource. Not able to be modelled for this iteration for the Galilee subregion. CSG resource information at Blue Energy (2016)

Some coal and CSG resource figures for projects in this table differ from the resource figures previously published in companion product 1.2 for the Galilee subregion (Lewis et al., 2014). Examples include the China Stone Coal Project, Galilee Gas Project and Blue Energy’s CSG exploration project. These differences reflect updated coal and CSG resource data published by the project owners since the October 2014 release of companion product 1.2 for the Galilee subregion (Lewis et al., 2014). As far as possible, the most recent coal and CSG resource figures publicly available for each development project have been included in this table.

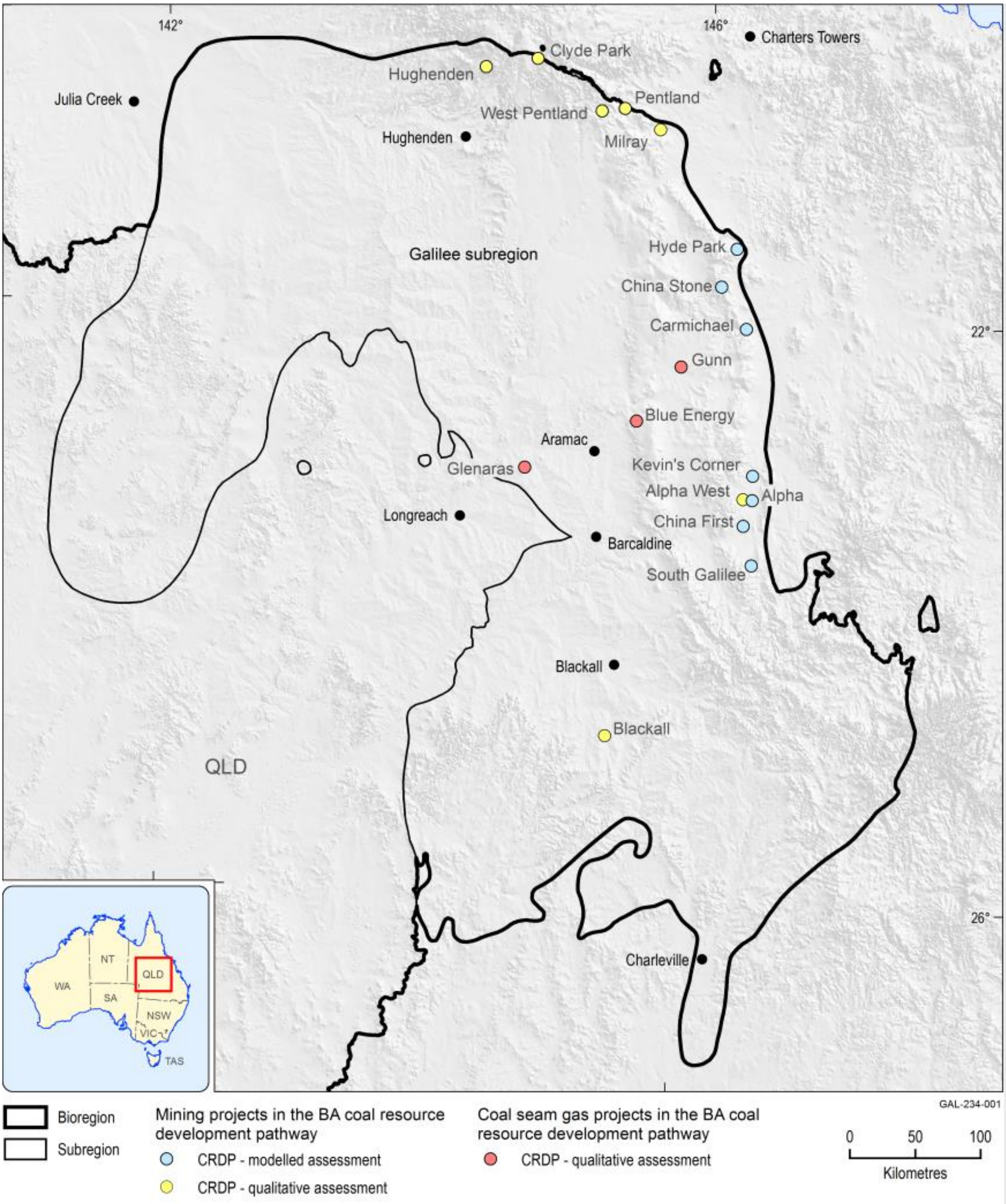

Figure 27 Proposed coal mines and coal seam gas operations in the coal resource development pathway for the Galilee subregion

The coal mine and CSG developments in the CRDP are the sum of those in the baseline and in the additional coal resource development. Because there are no coal resource developments in the baseline for the Galilee subregion, the CRDP only includes the proposed coal mine and CSG developments.
Data: Geoscience Australia (Dataset 1)

2.3.4.1.2.1 Quantitative assessment of hydrological changes of the coal resource development pathway

The CRDP for the Galilee subregion describes the most likely future (post 2012) for coal resource development, based on the Assessment team's analysis of publicly available information and expert consultation undertaken in late 2014 (and 'locked-in' as of December 2014). This CRDP then forms the basis for the subsequent hydrological modelling for the BA (of both surface water and groundwater), which attempts to quantify the hydrological changes of the expected coal resource development. However, in order to undertake the type of numerical hydrological modelling specified for the BAs (see companion submethodology M06 for surface water modelling (Viney, 2016) and companion submethodology M07 for groundwater modelling (Crosbie et al., 2016) as listed in Table 1), there are minimum levels of data and information required for each of the coal resource developments in the CRDP.

The data requirements for both surface water and groundwater modelling in BAs are outlined in companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (refer to Table 9 in Lewis, 2014). Important information required for hydrological modelling in BAs includes details of the type of coal resource extraction operation (e.g. open-cut, underground or combined development mine), time-series of the progression of mining and associated infrastructure areas (both in area and with depth), and the nature of the mine-site stratigraphy and depth to watertable.

Of the 17 coal resource developments in the CRDP, there are seven coal mines that are considered by the Assessment team to have sufficient information available to be quantitatively assessed through hydrological modelling. These proposed coal mines are: Alpha, Carmichael, China First, China Stone, Hyde Park, Kevin's Corner and South Galilee (Figure 27). These seven coal mines are the most advanced mining developments in the Galilee subregion in terms of progressing through the various environmental and mining-related approvals processes that apply under relevant Queensland and Australian Government legislation. Most of these mines have previously undertaken very detailed planning and development studies to determine optimal mining and production methods. Importantly, much of the required information for BA modelling purposes has been made publicly available as part of environmental impact statements (EISs) for the individual mines (DSD, 2016).

The expected mine life and production rates for the seven mines that will be modelled in the BA are shown in Table 11. A simplified mine development schedule for the modelled CRDP has also been compiled based on available information. This is shown in Figure 28 and includes major stages such as the initial construction period, open-cut and/or underground mining operations, and the final rehabilitation and closure phase. These seven coal mines will be the focus for the later-stage quantitative assessment components of the BA including surface water modelling (companion product 2.6.1), groundwater modelling (companion product 2.6.2), receptor impact modelling (product 2.7), and impact and risk analysis (product 3-4).

Table 11 Production rates for coal mines in the coal resource development pathway that will be quantitatively assessed for the Galilee subregion

Proposed coal mine	Estimated annual production rate for run-of-mine coal[a] (Mt/y)	Estimated production rate for product coal[b] (Mt/y)	Estimated life of mine (years)
Alpha	42 (maximum)	30 (maximum)	30
Carmichael	74 (maximum)	60 (maximum)	60
China First	56 (maximum)	40 (maximum)	30
China Stone	55 (target)	38 (target)	50
Hyde Park	11[c]	10[c]	30+
Kevin's Corner	40	26–27 (maximum)	30
South Galilee	17 (target)	15 (target)	33

[a]Run-of-mine (ROM) coal refers to the tonnage of coal delivered from the mining area to the coal handling and preparation plant (CHPP). This is essentially the raw mining material prior to processing and, in addition to coal, may include other rock types, minerals or contaminants.
[b]Product coal refers to the tonnage of coal produced following processing at a coal handling and preparation plant. Coal processing may involve crushing, screening and washing to separate any non-coal materials that may have been present in the ROM coal stockpile (prior to processing).
[c]Pre-feasibility study is underway for Hyde Park, so the estimated production rates and mine life is less certain than for the other six coal mines in the modelled coal resource development pathway.

2.3.4.1.2.2 Qualitative assessment of hydrological changes of the coal resource development pathway

Of the 14 proposed coal mines in the CRDP, 7 are currently much less advanced in their development mine planning and assessment studies under the relevant regulatory approvals processes. These seven coal mines are: Alpha West, Blackall, Clyde Park, Hughenden, Milray, Pentland and West Pentland. They have all been included in the CRDP, consistent with the methods outlined in companion submethodology M04 (as listed in Table 1) for developing the coal resource development pathway (Lewis, 2014), and aided by additional information provided at or immediately after the Galilee external CRDP workshop held in October 2014. However, as there is scant information publicly available about the nature and time frame of future development plans at these proposed mining sites, it is not possible to include these seven mines specifically in the hydrological modelling for the BA. Thus, the assessment of the impacts of these CRDP mines will be limited to qualitative assessment in companion product 3-4 (impact and risk analysis) for the Galilee subregion.

The three CSG projects in the Galilee subregion all have current estimates for contingent gas resources (2C and 3C resources defined, based on the guideline from the Society of Petroleum Engineers Petroleum Resources Management System, SPE, 2011). There are no proved, probable or possible CSG reserves defined in the Galilee Basin, and the most advanced CSG projects at Glenaras and Gunn are at the stage of initial pilot well testing and appraisal. There are currently no publicly available plans to progress any CSG projects to full-scale commercial operation in the Galilee subregion. Consequently, although the Assessment team has included the three CSG projects in the CRDP, the projects are not sufficiently mature to be able to provide the type of data required for inclusion in hydrological modelling. Instead, assessment of CSG development impacts in this iteration of the BA will be restricted to qualitative assessment and commentary.

Finally, it is worthwhile to note that not all of the projects listed in the catalogue of potential coal resource developments (see Figure 12 and Table 12 in Section 1.2.4 of companion product 1.2 for the Galilee subregion (Lewis et al., 2014)) have been included in the CRDP. This mainly reflects that for some coal resources in the Galilee subregion, mine development planning may not yet have been undertaken, and there remains a high level of uncertainty around the likelihood, scope and nature of any future operations. This may be due to various reasons, such as the coal resource having only been recently discovered and thus requiring significant further appraisal of the magnitude, quality and suitability for mining. In other cases, there may be compelling economic or company-specific evidence that has been used by the Assessment team to help determine that the project should not be included in the CRDP.

In these cases, the Assessment team has considered that, on the basis of available information, it is not likely that future commercial production from these coal resources will occur within the next 10 to 15 years. Of course, this does not imply that these resources will not be mined at some later stage in the future, particularly if further assessment studies are undertaken to better understand the geology of the deposit and the economic feasibility of extraction. A summary of salient information used by the Assessment team to develop and justify the CRDP for the Galilee subregion is provided in Table 12. This table provides information that may have been used to exclude some proposed projects from the CRDP, as well as information relevant to decisions to include the project in future hydrological modelling for the BA.

Table 12 Rationale for including or not including projects in the coal resource development pathway (CRDP) for the Galilee subregion

Coal resource project	Company	Included in CRDP?	Rationale for including or not including in CRDP
Alpha Coal Project	GVK Hancock Coal	Yes – modelled	Alpha Coal Project has passed EIS and Environment Protection and Biodiversity Conservation (EPBC) Act approvals, and has also been granted the required Environmental Authority to proceed. A mining lease remains to be granted. As one of the front-running coal mine projects in the Galilee Basin, Alpha has also been subject to several legal challenges. Sufficient information is considered available about the proposed Alpha Coal Mine development to enable inclusion in the Galilee CRDP and hydrological modelling. For example, required mine development plans and scheduling data for Alpha are available to the Assessment team from information and datasets publicly released as part of the Alpha EIS and SEIS documentation.
Alpha North Coal Project	Waratah Coal Pty Ltd	No	An inferred coal resource is currently defined for Alpha North, but there is no economically demonstrated resource (EDR) yet available. This probably reflects that the main focus currently (and into the foreseeable future) for Waratah Coal Pty Ltd (Waratah Coal) is their front-running China First Coal Project. There is a mining lease application and a mineral development licence for Alpha North; however, given the current focus of the company and the non-approval of their proposed rail line to the main export port, it is considered unlikely that Alpha North will be developed within at least a 10–15 year time frame. Request for additional data and information from Waratah Coal on the nature and scale of expected future mining development at Alpha North has not met with success. The only relevant data that the Assessment team has been available to obtain is a final mine design concept plan, although the Assessment team has not been able to verify this as current or accurate with Waratah Coal. Consequently, there is insufficient evidence available to the Assessment team on the likely mine development time frame, scale, type and sequencing for Alpha North for it to be realistically included in the current hydrological modelling for the Galilee subregion. Due to its greenfield development status and uncertain future, Alpha North will not be included in the Galilee CRDP.

Coal resource project	Company	Included in CRDP?	Rationale for including or not including in CRDP
Alpha West Coal Project	GVK Hancock Coal	Yes – commentary	There is good understanding of the coal resources at Alpha West, and its development is considered likely to proceed at some future stage. This reflects that it is covered by a mining lease application and has had initial concept mine plans developed. Importantly, it will essentially target the down-dip coals west of the Alpha open-cut mine, and will most likely be developed as a future underground mining stage associated with the larger Alpha open-cut mine complex. Consequently, the Alpha West Coal Project is included in the Galilee CRDP. Feedback provided to the Assessment team by the project owner suggests that development plans for Alpha West are not sufficiently progressed to provide the type of required information needed as input for groundwater modelling. This includes no clear indication as yet about the timing or progression of expected development, or any detail on the mine development plans. Consequently, although Alpha West is included in the Galilee CRDP, there is insufficient data currently available for it to be considered for modelling in the Assessment.
Blackall Coal Project	East Energy Resources Limited	Yes – commentary	Blackall has an economically demonstrated resource (EDR) for coal and is the most advanced of the known sub-bituminous coal deposits in the Eromanga Basin strata that occur in the Galilee subregion. Information provided by East Energy Resources Limited (EER) to the Assessment team indicates that the Blackall deposit is largely a greenfield development site. Although there is some basic information available on the nature of the coal resources and the likely mining method (open-cut), the development company (EER) still requires a significant amount of further work to understand the type of detailed mine planning, temporal sequencing and water management information that is needed for the hydrological modelling to be undertaken. Consequently, the Blackall deposit is in the Galilee CRDP, but is not able to be included in the current phase of numerical modelling work for this iteration for the Galilee subregion.
Carmichael Coal Mine and Rail Project	Adani Mining Pty Ltd	Yes – modelled	Carmichael has passed EIS and EPBC Act approvals[a], and has more recently also been granted its requisite mining lease and Queensland Government Environmental Authority (EA). Thus, all of the required environmental and mining-related authorisations have now been secured for Carmichael to proceed to mine construction phase. Sufficient data and information is known to exist about proposed mining plans for Carmichael to allow for its inclusion in Galilee CRDP and the BA modelling process. In particular, the required mine development plans and scheduling data for Carmichael mine is available to the Assessment team from information and datasets publicly released as part of the Carmichael EIS and SEIS documentation.

Coal resource project	Company	Included in CRDP?	Rationale for including or not including in CRDP
Carmichael East Coal Project	Waratah Coal Pty Ltd	No	No coal resource is yet defined in accordance with the JORC Code for the Carmichael East coal deposit – only an exploration target figure is publicly available. Consequently, due to lack of current geological understanding about the deposit and its economic and geological suitability for mining operations to occur, Carmichael East is not included in the Galilee CRDP.
China First Coal Project	Waratah Coal Pty Ltd	Yes – modelled	The China First Coal Project has passed EIS and EPBC Act approvals, and (from an approvals viewpoint) now needs a mining lease to be granted and final Queensland Government Environmental Authority (EA) until construction can commence. Sufficient data and information is known to exist about proposed mining development to allow for inclusion of China First in the Galilee CRDP, as well as for it to be included in the BA hydrological modelling. Most of the required mine development plans and scheduling data for China First mine is available to the Assessment team from information and datasets publicly released as part of the China First EIS and SEIS documentation.
China Stone Coal Project	Macmines Austasia Pty Ltd	Yes – modelled	China Stone Coal Project has recently submitted an EIS to the Queensland Coordinator-General, and this is currently being assessed prior to determination being made. There is a good understanding of the coal resources at China Stone (i.e. an economically demonstrated resource (EDR) is well defined) and advanced plans for mining and processing operations were included as part of the EIS documentation. Consequently, China Stone is included in the Galilee CRDP, and there is also sufficient data available as part of the current EIS documentation for it to be part of the Galilee hydrological modelling process. Discussions with Macmines Austasia following the external Galilee CRDP workshop in Brisbane have indicated that they agree to allow the Assessment team to use any of the publicly available information provided in the China Stone EIS as part of the modelling for the Galilee subregion.
Clyde Park Coal Project	TerraCom Limited (formerly Guildford Coal Limited)	Yes – commentary	The Clyde Park Coal Project is included in the Galilee CRDP as it has an economically demonstrated resource (EDR) and is part of a larger tenement and coal resource position held by TerraCom Ltd in the northern Galilee Basin. This broader portfolio of assets suggests likely future development at some stage. However, there is insufficient information available about the nature of any future development at the Clyde Park coal resource, and the type, timing, schedule, and life span of possible development is currently uncertain. Thus, while it is appropriate to include Clyde Park in the Galilee CRDP, it will not be possible to quantitatively assess its impacts via hydrological modelling in this iteration for the Galilee subregion.

Coal resource project	Company	Included in CRDP?	Rationale for including or not including in CRDP
Degulla Coal Project	Vale Coal Exploration Pty Ltd	No	There is scant information available about the current plans for development of the Degulla coal deposits. Some media reports have indicated that the owners (Vale) are actively trying to sell the Degulla resource, rather than develop it. No current mineral development licences (MDL) or mining lease applications exist, and there is only an exploration permit covering the resource. Also, as there is no known economically demonstrated resource (EDR) figure publicly available for Degulla, the Assessment team considers that the future development of Degulla is very uncertain, and thus it is not included in the Galilee CRDP.
EPP 813 – CSG project	Blue Energy Limited	Yes – commentary	Blue Energy's Galilee Basin CSG exploration project in EPP 813 has a defined contingent CSG resource of 838 PJ (3C). Given this resource and its prospective tenement position, about midway between the more advanced pilot projects at Glenaras and Gunn, it is considered likely that future gasfield development may occur in EPP 813 if operations at Gunn/Glenaras go ahead, and the required infrastructure is built to facilitate CSG delivery and operations. Thus, it is recommended to include EPP 813 in the Galilee CRDP, although it will not be assessed as part of the BA hydrological modelling due to the lack of maturity around the likely scale, location and magnitude of production operations.
Galilee Gas Project (Glenaras site)	Galilee Energy Limited	Yes – commentary	The Glenaras CSG pilot site has had successful pilot production testing done and has defined 2C and 3C contingent gas resources. This suggests that future development of the field is likely, although this may be a decade or more away, and the magnitude and location of any commercial CSG production operations here are currently unknown. However, despite these limitations, it is recommended to include Glenaras in the Galilee CRDP. Discussions with previous joint venture operators AGL Energy following the external Galilee CRDP workshop clearly indicated that there are no firm data or information currently available to indicate if/when/how commercial CSG production will occur at the Glenaras Project area. Following AGL's pull-out from the Galilee joint venture in August 2015, Galilee Energy Limited have now taken 100% interest in the Galilee Gas Project. Due to the uncertainty that exists about the nature, timing and scale of any commercial CSG production at Glenaras, the Assessment team is unable to include Glenaras in the current round of Galilee hydrological modelling. Thus, although Glenaras can be retained in the Galilee CRDP, there are insufficient data for it to be part of the modelled developments.

Coal resource project	Company	Included in CRDP?	Rationale for including or not including in CRDP
Gunn Project	Comet Ridge Limited	Yes – commentary	The Gunn CSG site has had pilot production testing done and has defined 2C and 3C gas contingent resources. This suggests that future development of the CSG resources is likely, although this may be a decade or more away, and the magnitude and location of any commercial CSG production operations here is currently unknown. Discussions with Comet Ridge following the external Galilee CRDP workshop have clearly indicated that there are insufficient data or information currently available to indicate if/when/how commercial CSG production will occur at Gunn Project area. Comet Ridge has undertaken pilot production testing operations for CSG at Gunn, although there are no clear investment decisions to proceed to commercialisation. Given the greenfield nature of current operations, and the uncertainty that exists about the nature, timing and scale of any CSG production at Gunn, the Assessment team is unable to include Gunn in the current round of Galilee hydrological modelling. Although Gunn is included in the Galilee CRDP, there are insufficient data for it to be modelled, and assessment will be limited to qualitative analysis for this BA.
Hughenden Project	TerraCom Limited (formerly Guildford Coal Limited)	Yes – commentary	The Hughenden Coal Project is included in Galilee CRDP as it has an economically demonstrated coal resource (EDR) associated with it and is part of the larger tenement position held by TerraCom Ltd in the northern Galilee Basin. This evidence suggests that future underground mining development of the Hughenden deposit is likely. However, there is currently insufficient specific information available about the nature of the development at Hughenden, including the details of mine timing, schedule and life span, for it to be included in the Galilee hydrological modelling component of this BA.
Hyde Park Coal Project	Resolve Coal Pty Ltd	Yes – modelled	Hyde Park is included in the Galilee CRDP as it has an economically demonstrated coal resource (EDR) defined, and there is considerable evidence available publicly about the expected manner in which the resource development project is likely to occur. At this stage, there has been no application for an EIS, or for a mining lease or mineral development licence, although Hyde Park was granted 'project status' by the Queensland Government in April 2016. Discussions with Resolve Coal have proven encouraging since the external Galilee CRDP workshop, and Resolve Coal have agreed to provide to the Assessment team the required data and information on the proposed Hyde Park Coal Project development for it to be included in the hydrological modelling for the Galilee subregion.

Coal resource project	Company	Included in CRDP?	Rationale for including or not including in CRDP
Inverness	Coalbank Limited	No	The Inverness coal deposit only has an inferred 1300 Mt coal resource recently defined, i.e. there is no economically demonstrated resource (EDR) at present. There are also no mining leases or mineral development licence applications as yet, only the original coal exploration permit covers the deposit. Consequently, it is uncertain if future development at Inverness will proceed, and the deposit needs considerable further work to improve geological understanding and determine potential for economic development. Thus, it is not included in the Galilee CRDP.
Kevin’s Corner Coal Project	GVK Hancock Coal	Yes – modelled	The Kevin's Corner Coal Project has passed EIS and EPBC Act approvals, and now only needs a mining lease to be granted and Queensland Government Environmental Authority (EA) to proceed. Sufficient information is considered to be available about the proposed mine development to enable inclusion in modelling. For example, the required mine development plans, scheduling data and water management plans for Kevin's Corner Mine are available to the Assessment team from information and datasets publicly released as part of the Kevin's Corner EIS and SEIS documentation. The resource owners (GVK Hancock) have formally agreed to permit the Assessment team to use such data in the hydrological modelling for the Galilee subregion.
Milray	Glencore Coal Queensland Pty Ltd	Yes – commentary	The Milray deposit has an inferred coal resource, i.e. no economically demonstrated resource (EDR) is known to be publicly defined at present. There are also no mining lease or mineral development licence applications for Milray, only the original coal exploration tenement. The deposit probably needs considerable further work to improve geological understanding and determine potential for economic development, although there is very little relevant information publicly available to test this idea at present. Following the external Galilee CRDP workshop, Glencore Coal Queensland has provided additional information relevant to the CRDP decision for Milray. Glencore Coal Queensland owns both the Milray and nearby Pentland deposits, in the northern Galilee Basin. Development of these two deposits is viewed by Glencore Coal Queensland as likely to proceed at a similar time, and both are considered viable resources for future extraction, especially to fulfil supply contracts if Glencore Coal Queensland’s Bowen Basin coal operations begin to exhaust supplies in future. For these reasons Milray is included in the Galilee CRDP; although there is insufficient information to numerically model it for the Galilee subregion.

Coal resource project	Company	Included in CRDP?	Rationale for including or not including in CRDP
Pentland Coal Project	Glencore Coal Queensland Pty Ltd	Yes – commentary	The Pentland coal deposit has a well-defined economically demonstrated resource (EDR) for coal and has been known about for several decades. Pentland is a relatively small (at least for Galilee standards) coal resource in northern part of the Galilee subregion. As mentioned above, the Pentland deposit occurs near Milray, and both coal resources are currently owned by Glencore Coal Queensland. Thus, Pentland is included in the Galilee CRDP as a likely joint future development target along with Milray. However, there are currently insufficient data or information to assess development options with any certainty, so it is not included in the hydrological modelling for the Galilee subregion.
South Galilee Coal Project	Alpha Coal Management Pty Ltd, on behalf of AMCI and Alpha Coal Pty Ltd	Yes – modelled	South Galilee has an economically demonstrated resource (EDR) and the project has received EIS approval from the Queensland Coordinator-General, as well as Australian Government approvals under the EPBC Act. The project requires granting of the mining lease and Queensland Environmental Authority prior to mining commencing. However, the Assessment team considers that mining is considered likely to proceed in the proposed mining lease area, and consequently South Galilee is included in the Galilee CRDP. There is sufficient data and information available about the proposed mine operations at South Galilee from the EIS and AEIS documentation to allow it to be modelled. The Assessment team has also received formal agreement from AMCI to use such data for the Galilee subregion.
South Pentland Project	Cockatoo Coal Limited	No	South Pentland only has an inferred resource recently defined (i.e. no economically demonstrated resource (EDR) at present). The deposit is not covered by applications for a mining lease or mineral development licence at present, only the original coal exploration permit exists. The coal resource at South Pentland likely requires considerable work to improve geological understanding and determine potential for economic development. Thus, it is not at a current state of knowledge to include in the CRDP for the Galilee subregion.
West Pentland Coal Project	United Queensland Resources Pty Limited (previously owned by New Emerald Coal Ltd)	Yes – commentary	The West Pentland coal deposit has an economically demonstrated resource (EDR) associated with it, and has had some preliminary assessment of possible mining concept plans, and, on this basis, it is included in the Galilee CRDP. However, there is insufficient feasibility and planning work reported publicly thus far to provide the required information and data to feed into the modelling process for the Galilee subregion. Consequently, West Pentland is in the Galilee CRDP, but is not able to be modelled. United Queensland Resources Pty Ltd gained ownership of New Emerald Coal Ltd in May 2015 and now owns the West Pentland coal deposit.

Coal resource project	Company	Included in CRDP?	Rationale for including or not including in CRDP
Yellow Jacket Project	Cuesta Coal Limited	No	The Yellow Jacket coal deposit is a relatively recent exploration discovery, and the coal resource is not yet an economically demonstrated resource (EDR) (only an inferred resource known at present). There are also no mining lease or mineral development licence applications that yet apply for Yellow Jacket. Thus, the Yellow Jacket deposit requires considerable further work to improve geological understanding and determine potential for economic development. It is not in the CRDP for the Galilee subregion.

[a]On 5 August 2015 the Federal Court overturned the Australian Government's approval of the Carmichael Coal Mine, requiring it to be reassessed. The mine is included in the CRDP as it is based on information available as of December 2014. On 14 October 2015 Carmichael Coal Mine was re-approved by the Federal Environment Minister with 36 conditions.
AEIS = additional environmental impact statement, BA = bioregional assessment, EDR = economic demonstrated resource, EIS = environmental impact statement, EPBC Act = Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*, EPP = exploration permit for petroleum, MDL = mineral development licence, ML = mining lease, SEIS = supplementary environmental impact statement

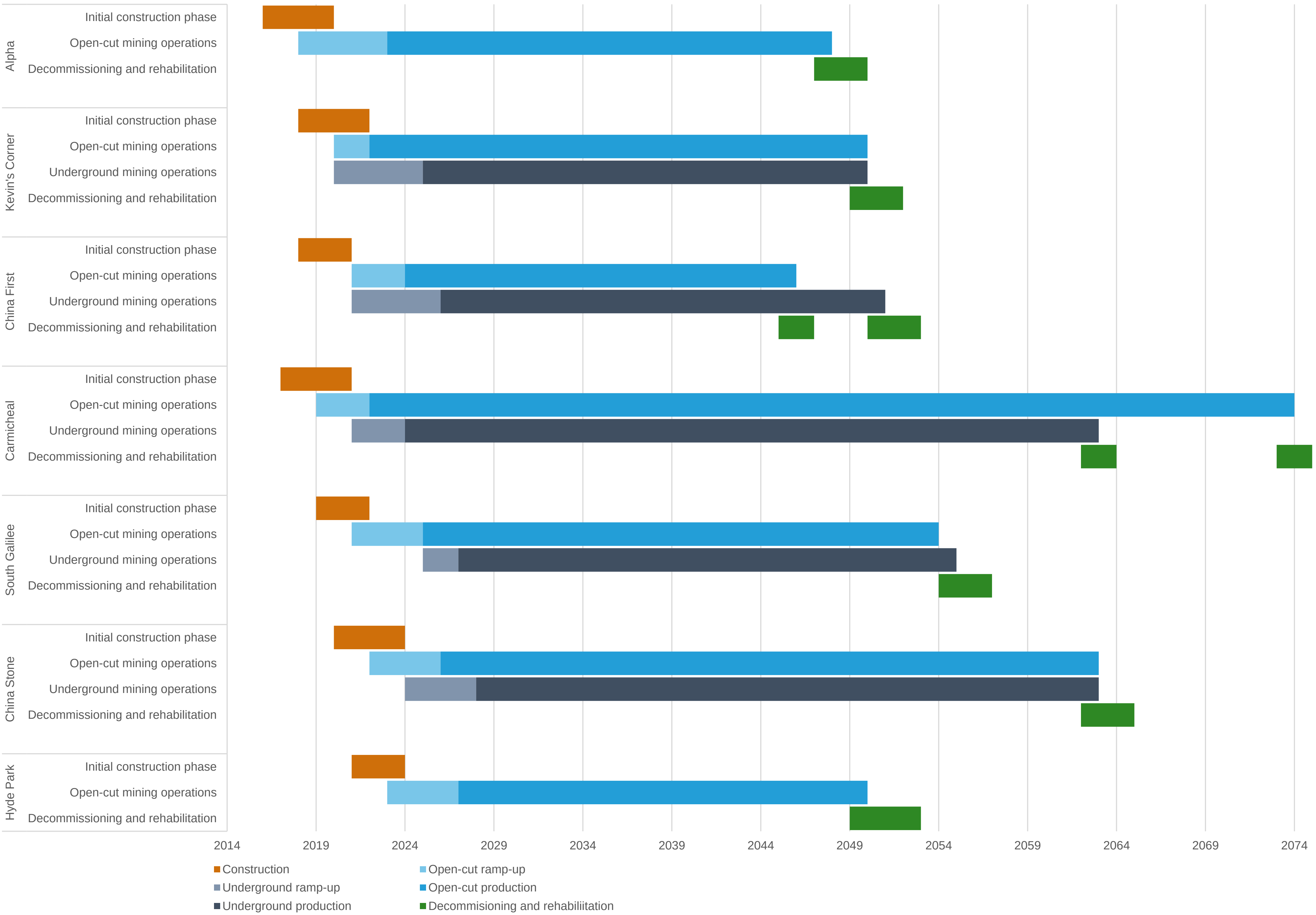

Figure 28 Estimated scheduling of proposed coal mine developments to be quantitatively assessed in the bioregional assessment for the Galilee subregion

Dates as shown on Figure 26 represent best available estimates as at December 2014. Actual operational start and end dates and production time frames may change due to various factors.
This figure has been optimised for printing on A3 paper (297 mm x 420 mm).

2.3.4.2 Water management for coal resource developments

As noted in companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014), the proposed water management strategies at each modelled coal mine in the CRDP are important to inform the hydrological modelling in the BA. Specific rules or assumptions that may relate to modelling the coal mines in the CRDP are outlined in the surface water modelling (companion product 2.6.1 (Karim et al., 2018)) and the groundwater modelling (companion product 2.6.2 (Peeters et al., 2018)) for the Galilee subregion.

There are no coal or CSG developments in the baseline for the Galilee subregion. Six of the seven coal mines in the modelled CRDP are either at an EIS stage in development approval, or have an approved environmental authority. The six coal mine development proposals at these advanced stages of approval are: China Stone, Carmichael, Kevin's Corner, Alpha, China First and South Galilee. As of February 2016, only the proposed Carmichael Mine has been granted a mining lease by the Queensland Government. The only modelled CRDP development at pre-EIS approval stage is Hyde Park. There are no CSG projects in the Galilee subregion that are currently at the EIS approval stage.

Information is available on water management for the six most advanced coal development projects in the Galilee subregion. A more detailed description of these water management plans is in Section 2.1.6 of companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018). The common elements to all the water management plans as outlined in the various EIS documents are:

- Mines and associated infrastructure areas are isolated from parts of the larger surface water river basins in which they occur by diversion drains at an early stage in the development process.
- Any rain that falls within the mine area is kept on site and used for mine and coal processing water requirements as much as possible.
- Any groundwater pumped out from mine workings is kept on site and used for mine and coal processing water requirements.
- There will be progressive rehabilitation of mined-out areas as mining advances, so that the amount of surface area disconnected from a river basin due to mining may vary during life of mine.

There may be some provision for each of the mines to discharge excess mine water off site during surface water high-flow periods. However, details about the water management regime, monitoring and permitting conditions for each mine in the modelled CRDP are still being finalised and were not available as of February 2016.

2.3.4.3 Gaps

As previously stated, the CRDP for the Galilee subregion was confirmed and 'locked-in' for this BA as of December 2014, so any significant project-related changes since then have not altered the CRDP presented here.

Many of the most advanced mining proposals in the Galilee subregion may still be undertaking pre-mine planning and optimisation studies, so mine scheduling and production rates provided in this product are estimates only. Even mines past the EIS approvals stage require further environmental and mining-related authorisations, so the estimated commencement dates reported (e.g. in Figure 28) may vary from actual start-up time. Additionally, there remains significant uncertainty around the most likely commencement dates for the front-running mining proposals in the Galilee subregion due to various legal challenges that are underway, and the continuation of a protracted downturn in coal prices that may affect the economic viability of some mines.

Other current knowledge gaps relating to mining operations include the likelihood that actual mine production rates will vary over the life of operations due to various factors, including changes in mine sequencing rates and schedules, variability in ground conditions encountered during mining, or other unforeseen events such as those caused by inclement weather or natural hazards. Mine lifetimes will depend on a number of factors not directly known before mining commences, including fluctuations in commodity markets.

Water management strategies need to be finalised and conditions set as part of the approvals process for each proposed coal mine. Thus, there may be variations in water management plans from what is reported here and in companion product 2.1-2.2 (Evans et al., 2018) for the Galilee subregion.

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2.3.5 Conceptual model of causal pathways

Summary

This section presents the possible causal pathways that may link hazards and water-dependent assets in the Galilee subregion. Hazards that have potential for cumulative impacts for coal mines include dewatering and depressurisation around coal mines, fracturing and subsidence that can occur above underground coal mine longwall panels, and effects of mine infrastructure and mine water discharge on surface water systems. For coal seam gas (CSG) operations, these include depressurisation of coal seams, well integrity, and co-produced water management related issues.

A hazard analysis is used to systematically identify activities that occur as part of coal resource development in the Galilee subregion and which may initiate *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). Several hazards are identified; some of these are beyond the scope of bioregional assessments (BAs), such as accidents, and others are adequately addressed by site-based risk management processes and regulation. Hazards associated with CSG operations and coal mines that are considered to be in scope for BA in the Galilee subregion are grouped into four causal pathway groups: (i) ‘Subsurface depressurisation and dewatering’, (ii) ‘Subsurface physical flow paths’, (iii) ‘Surface water drainage’, and (iv) ‘Operational water management’.

A systematic analysis of the potential hazards associated with coal resource development was conducted for the Galilee subregion and underpinned by discussions with relevant experts during a formal workshop. A total of 274 and 260 activities were identified for the Galilee subregion that related to various life cycles of coal mines and CSG operations, respectively. The 30 highest ranking hazards and impact modes were subsequently identified. These 30 top-ranking hazards were then grouped according to their impact modes.

Subsurface depressurisation and dewatering associated with the coal resource development pathway (CRDP) have the potential to directly affect groundwater systems through removal of groundwater. There are a number of geological factors that may either impede or enhance groundwater depressurisation and dewatering. Subsurface physical flow paths can be affected by hydraulic fracturing (CSG only), sub-surface fracturing above underground longwall panels (underground coal mines only), or changes to well integrity. For the Glenaras pilot wellfield, the drilling of horizontal CSG wells along target coal seams is considered to be a more applicable technology for increasing gas flow to CSG wells rather than hydraulic fracturing. Fracturing above longwall panels will occur if longwall mining takes place, but will be confined to areas where underground coal mining has occurred. Detrimental changes to well integrity may result in inter-aquifer groundwater flow that utilises the well as a pathway.

‘Surface water drainage’ causal pathway group refers to changes to the surface drainage network and may lead to a loss or redirection of runoff, which can have long-term cumulative effects on downstream watercourses. Subsidence, diverting site drain lines, rainwater and runoff diversion, levee bunds and creek crossings can change, or disrupt, surface water

drainage. 'Operational water management' causal pathway group relates to possible impacts derived from on-site water storage usage and disposal methods.

A schematic demonstrating the relationships between coal mine operations, CSG and Great Artesian Basin (GAB) in the Galilee subregion is presented in Figure 29. The most advanced underground and open-cut coal mine developments are situated near the eastern margin of the Galilee subregion. Here, coal will be extracted from the upper Permian coal measures. CSG resource developments occur to the west of the Great Dividing Range and will extract gas from coal seams in the upper Permian coal measures. West of the Great Dividing Range the main source of groundwater are the GAB aquifers, which for the most part are separated from the upper Permian coal measures by the Rewan Group, Clematis Group and Moolayember Formation. Some areas do exist, however, where Clematis Group aquifer or the upper Permian coal measures are in contact with Hutton Sandstone aquifer (refer to companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018)). The most utilised aquifer in the Galilee Basin is the Clematis Group aquifer. Some groundwater is also drawn from alluvial aquifers.

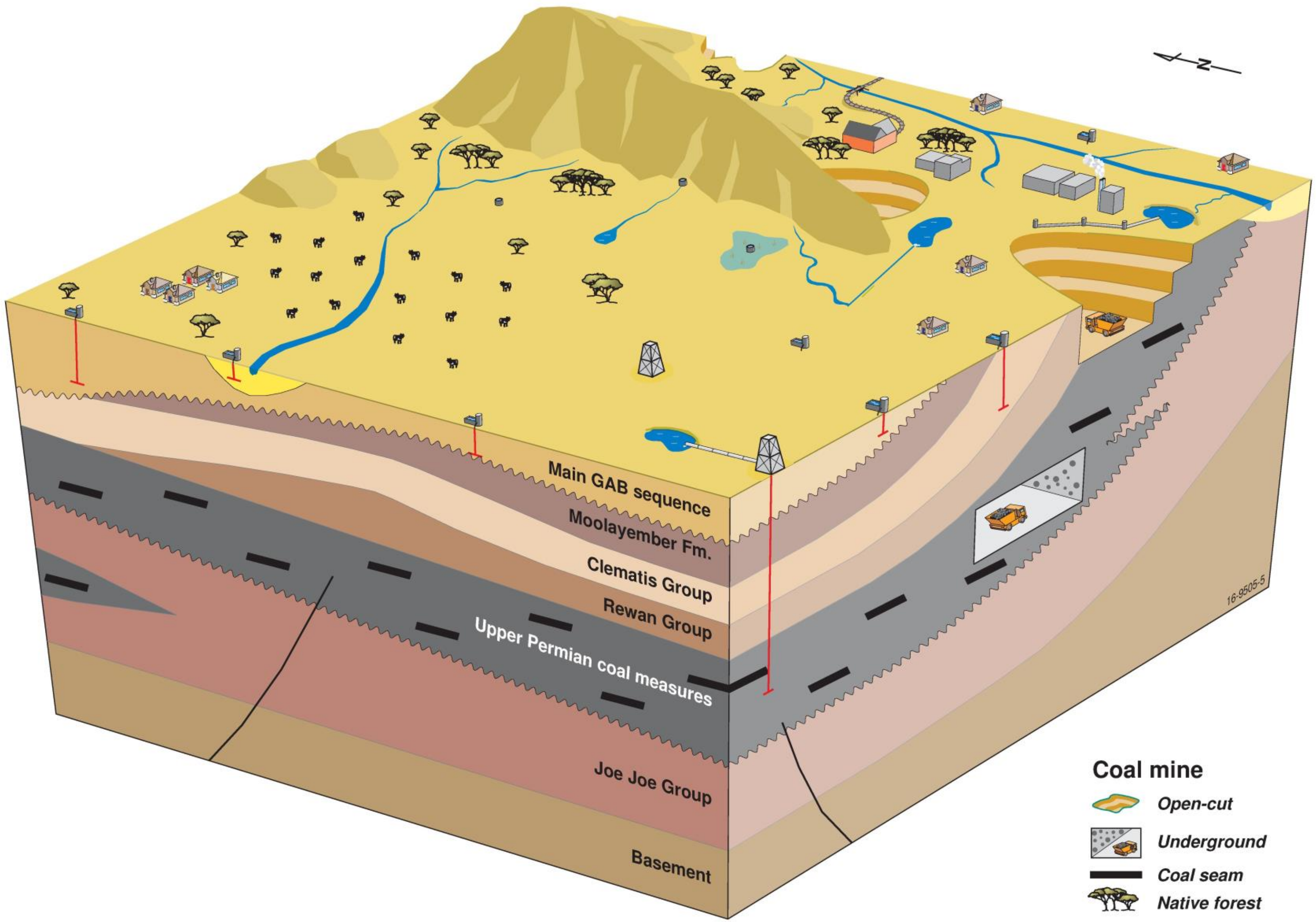

Figure 29 Schematic showing open-cut and underground coal mine operations in the Galilee subregion

GAB = Great Artesian Basin; Fm = formation.

2.3.5.1 Methodology

Conceptual models of causal pathways are a specific type of conceptual model that characterises the *causal pathways*, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water 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 Galilee subregion has leveraged existing state-based resources and knowledge of geological, surface water and groundwater conceptual models. The Assessment team summarised the key system components, processes and interactions for the geology, hydrogeology and surface water of the subregion at the 'Conceptual modelling of causal pathways' workshop held in Brisbane in August 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 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 Galilee subregion 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 and underground 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 a more beneficial effect (such as reinjection of treated co-produced water to restore groundwater pressure in a heavily utilised aquifer).

An *impact mode* 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 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 Galilee subregion 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 2.3.5.2.3 and Section 2.3.5.3 present specific results for the Galilee subregion.

Hazards are grouped for the Galilee subregion 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 classes of receptors will *not* be affected. Throughout the BA, areas of the preliminary assessment extent (PAE) 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

Hazard analysis is a critical part of the BA as it rigorously and systematically identifies the potential impacts (hazards) on water-dependent assets arising from whole-of-life-cycle CSG and coal mine activities. Only hazards identified through this process are considered further in a BA.

A hazard analysis conducted for the Galilee subregion (Bioregional Assessment Programme, Dataset 1) was based on the proposed CSG operations and coal mines (as outlined Section 2.3.4.1) and their water management (Section 2.3.4.2). The hazard analysis for the Galilee subregion was completed during a one-day workshop in March 2015 with experts from CSIRO, Geoscience Australia and the Department of the Environment.

2.3.5.2.1 Coal seam gas operations

The hazard analysis identified some 260 activities associated with CSG projects. However, not all of the activities listed were applicable to the Galilee subregion or had potential to impact water. Further information on hazards that are within scope for the Assessment is outlined in Section 2.3.5.2.3.

The hazard scores from the IMEA help to pinpoint what would potentially be the more serious hazards. The top 30 hazards and their associated activities and impact modes are outlined in Figure 30 and identify the following potential effects to aquifers including:

- hydrostatic depressurisation of the aquifer (target coal seam and non-target aquifers)
- fault-mediated depressurisation caused by faults opening or closing due to CSG operations
- aquitard-mediated depressurisation (i.e. an aquitard is absent or the integrity of the aquitard is compromised in some parts of the subregion)
- connection of previously disconnected aquifers by hydraulic fracturing, incomplete casing of wells or incomplete seal integrity
- disruption to natural surface drainage.

After impacts on aquifers, the potential impacts associated with storage, processing and disposal of treated water were all identified as potentially important in this context.

Although a number of hazards have been identified, hazards for CSG operations were not included in groundwater and surface water modelling undertaken for the CRDP (Section 2.3.4.1) as the potential for development of CSG projects to full production in the Galilee subregion may be still be some years into the future.

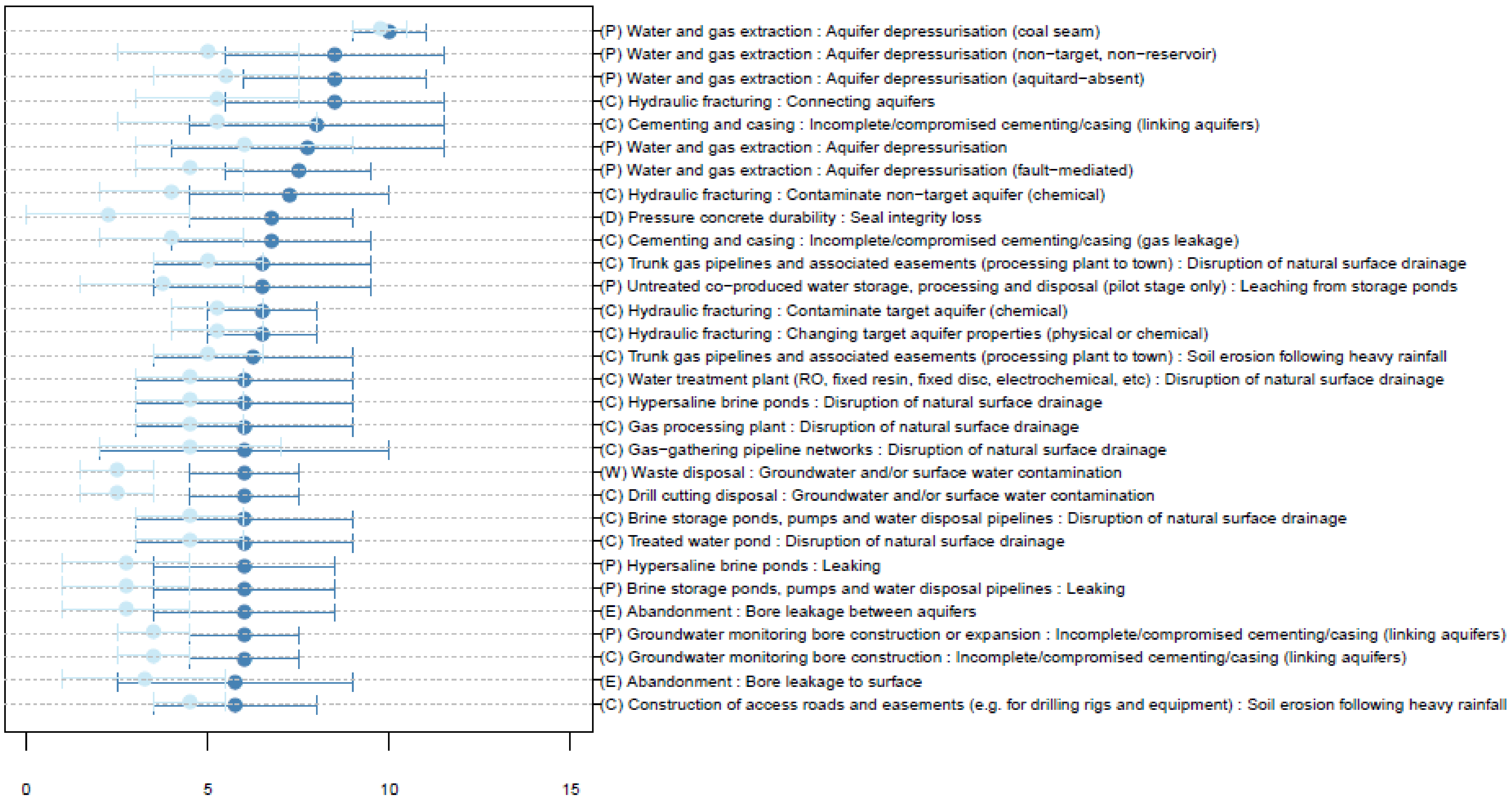

Figure 30 Highest ranked hazards (and their associated activities and impact modes) for coal seam gas operations, ranked by midpoint of the hazard priority number

The x-axis shows the hazard priority number and hazard score for potential hazards. The intervals between the highest and lowest hazard priority number are shown in dark blue; the intervals for hazard score are shown in light blue. The same hazard may appear multiple times, as it may arise from a number of different life-cycle stages and activities. Hazards are listed with the syntax [Life-cycle stage][Activity]:[Impact mode], where life-cycle stages are indicated by (E) for exploration and appraisal, (C) for construction, (P) for production and (D) for decommissioning.
Typology and punctuation are consistent with Dataset 1.
Data: Bioregional Assessment Programme (Dataset 1)

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

2.3.5.2.2 Open-cut and underground coal mines

The hazard analysis identified some 274 activities associated with open-cut and underground mines. However, not all of the activities listed were applicable to the Galilee subregion or had potential to impact water. Further information on hazards that are within scope for the Assessment is outlined in Section 2.3.5.2.3.

The hazard priority number scores from IMEA help to pinpoint what would potentially be the more serious hazards. The top 30 hazards and their associated activities and impact modes are outlined in Figure 31. Issues associated with underground longwall mining such as fracturing and subsidence and disruption to surface drainage were some of the highest ranked hazards.

The potential impacts of leaching is associated with 8 of the 30 highest ranked hazards, including leaching from:

- in-pit waste rock dumps and backfill
- waste rock dumps outside of the pit
- coal stockpiles (in and out of the pit)
- run-of-mine (ROM) plants
- tailings decant water dams.

Leaching ranks fairly high due to difficulties in detecting whether leaching of mine or coal-related materials is taking place and if leachate changed quality of the nearby groundwater.

The following are identified as having the potential to link, or cause leakage between, aquifers:

- incomplete or compromised cementing of groundwater supply and monitoring bores
- mine expansion too close to a water body
- abandoned exploration and appraisal bores.

These – together with dewatering and enhanced aquifer interconnectivity caused by post-closure water filling the open-cut and underground mine workings – are identified as potentially important hazards. The remaining 30 highest ranked hazards include:

- soil erosion caused by heavy rainfall or failure to successfully rehabilitate abandoned mines
- artificial groundwater recharge (following pit abandonment).

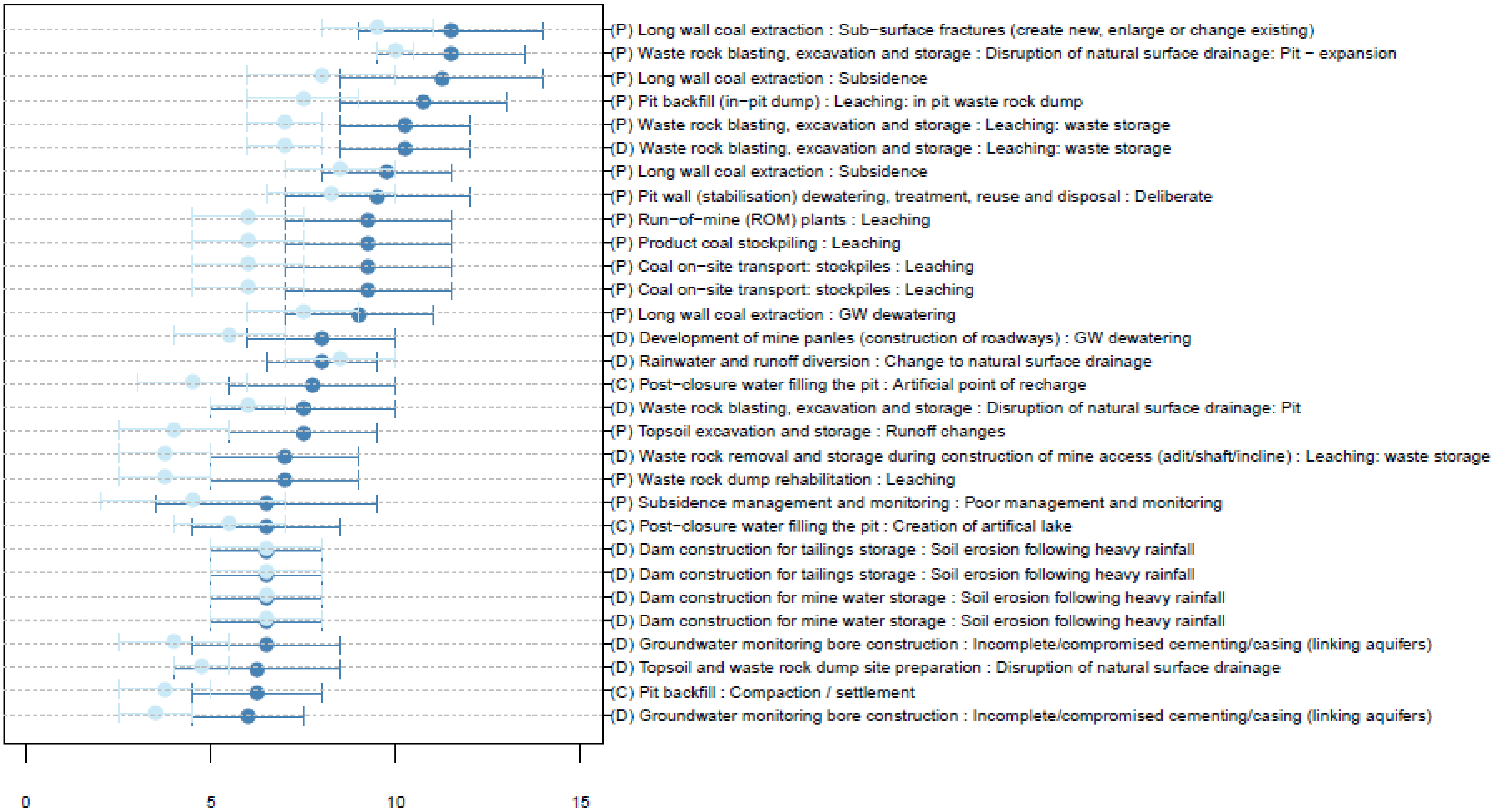

Figure 31 Highest ranked hazards (and their associated activities and impact modes) for coal operations, ranked by midpoint of the hazard priority number

The x-axis shows the hazard priority number and hazard score for potential hazards. The intervals between the highest and lowest hazard priority number are shown in dark blue; the intervals for hazard score are shown in light blue. The same hazard may appear multiple times, as it may arise from a number of different life-cycle stages and activities. Hazards are listed with the syntax [Life-cycle stage][Activity]:[Impact mode], where life-cycle stages are indicated by (E) for exploration and appraisal, (C) for construction, (P) for production and (D) for decommissioning.
Typology and punctuation are consistent with Dataset 1.
Data: Bioregional Assessment Programme (Dataset 1)

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

2.3.5.2.3 Hazard handling and scope

A full list of hazards (Bioregional Assessment Programme, Dataset 1) has been generated for both CSG operations and coal mines, as described in Section 2.3.5.2.1 and Section 2.3.5.2.2. 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, as these are consistent with the regional focus of BA, and are where BAs will add greater 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, and so hazards such as dust, fire or noise are deemed 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 deemed 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 Galilee subregion because they are deemed to be covered by site-based risk management and regulation:

- abandonment practice
- hazards addressed by site management, no water-mediated pathway (dust, fire or noise)
- containment failure due to poor construction or design
- equipment/infrastructure failure (e.g. pipeline failures)
- leaching/leaking from storage ponds and stockpiles
- spillages and disposals (diesel, mud, cuttings, fluid recovery)
- vegetation clearance and subsequent soil erosion following heavy rainfall.

Hydrological effects associated with CSG operations that are considered to be in scope are detailed in companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016) and listed below:

- surface water quality
- surface water direction
- surface water flow
- aquifer properties
- groundwater composition

- groundwater flow (reduction)
- groundwater level
- groundwater pressure.

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) affects '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)

Activities, impact modes and hydrological effects are assigned to a specific series of causal pathways (Table 13, Table 14). A causal pathway describes the logical chain of events – planned or unplanned– that link coal resource development to changes in groundwater or surface water, and then to impacts on water-dependent assets. The various combinations of activities, impact modes and effects have common themes relating to causal pathways. Hence causal pathways can be grouped further into four main causal pathway groups (Table 13, Table 14). The companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al. 2016) provides further detail on causal pathways and causal pathway groups that were utilised for BAs.

CSG projects are included in the CRDP but have not been modelled (Section 2.3.4.1). Although cumulative hazards and potential causal pathways by CSG operations are recognised (as noted in Section 2.3.4.1), the timing and nature of future CSG production (beyond small-scale pilot operations) is currently unknown, but unlikely to occur within the next 10 to 15 years.

Table 13 Top 30 coal seam gas (CSG) activities, associated impact modes and causal pathway groups for the Galilee subregion

Component	Life cycle	Activity	Impact mode	Hydrological effect	Causal pathway group	Causal pathway
Wells	C	Hydraulic fracturing	Connecting aquifers	GW composition, GW quality	Subsurface physical flow paths	Hydraulic fracturing
Wells	C	Cementing and casing	Incomplete/compromised cementing/casing (linking aquifers)	GW quality	Subsurface physical flow paths	Failure of well integrity
Wells	C	Cementing and casing	Incomplete/compromised cementing/casing (gas leak)	GW quality	Subsurface physical flow paths	Failure of well integrity
Wells	C	Hydraulic fracturing	Contaminate target aquifer (chemical)	GW quality	Subsurface physical flow paths	Hydraulic fracturing
Wells	C	Hydraulic fracturing	Changing target aquifer properties (physical or chemical)	Aquifer properties	Subsurface physical flow paths	Hydraulic fracturing
Wells	C	Groundwater monitoring bore construction	Incomplete/compromised cementing/casing (linking aquifers)	GW composition, GW quality	Subsurface physical flow paths	Failure of well integrity
Wells	C	Drill cutting disposal	Groundwater and/or surface water contamination	SW quality, GW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Wells	C	Hydraulic fracturing	Contaminate non-target aquifer (chemical)	GW quality	Subsurface physical flow paths	Hydraulic fracturing
Wells	D	Pressure concrete durability	Seal integrity loss	GW quality	Subsurface physical flow paths	Failure of well integrity
Wells	E	Abandonment	Bore leakage between aquifers	GW composition, GW quality	Subsurface physical flow paths	Failure of well integrity
Wells	E	Abandonment	Bore leakage to surface	SW quality	Subsurface physical flow paths	Failure of well integrity
Wells	P	Groundwater monitoring bore construction or expansion	Incomplete/compromised cementing/casing (linking aquifers)	GW composition, GW quality	Subsurface physical flow paths	Failure of well integrity

Component	Life cycle	Activity	Impact mode	Hydrological effect	Causal pathway group	Causal pathway
Wells	P	Water and gas extraction	Aquifer depressurisation (coal seam)	GW pressure	Subsurface depressurisation and dewatering	Groundwater pumping enabling coal seam gas extraction
Wells	P	Water and gas extraction	Aquifer depressurisation (non-target, non-reservoir)	GW pressure	Subsurface depressurisation and dewatering	Unplanned groundwater changes in non-target aquifers
Wells	P	Water and gas extraction	Aquifer depressurisation (aquitard-absent)	GW pressure	Subsurface depressurisation and dewatering	Unplanned groundwater changes in non-target aquifers
Wells	P	Water and gas extraction	Aquifer depressurisation	GW flow (reduction)	Subsurface depressurisation and dewatering	Unplanned groundwater changes in non-target aquifers
Wells	P	Water and gas extraction	Aquifer depressurisation (fault mediated)	GW pressure	Subsurface depressurisation and dewatering	Unplanned groundwater changes in non-target aquifers
Wells	C	Waste disposal	Groundwater and/or surface water contamination	SW quality, GW quality	No specific causal pathway in bioregional assessments	Addressed by site-based risk management procedures
Roads and infrastructure	C	Construction of access roads and easements (e.g. for drilling rigs and equipment)	Soil erosion following heavy rainfall	SW quality	Surface water drainage	Altering surface water system
Processing facilities	C	Hypersaline brine ponds	Disruption of natural surface drainage	SW volume, SW quality	Surface water drainage	Altering surface water system
Processing facilities	C	Gas processing plant	Disruption of natural surface drainage	SW volume, SW quality	Surface water drainage	Altering surface water system
Processing facilities	C	Gas-gathering pipeline networks	Disruption of natural surface drainage	SW volume, SW quality	Surface water drainage	Altering surface water system
Processing facilities	C	Brine storage ponds, pumps and water disposal pipelines	Disruption of natural surface drainage	Surface water flow	Surface water drainage	Intercepting surface water runoff

Component	Life cycle	Activity	Impact mode	Hydrological effect	Causal pathway group	Causal pathway
Processing facilities	C	Treated water pond	Disruption of natural surface drainage	Surface water flow	Surface water drainage	Altering surface water system
Processing facilities	C	Water treatment plant (RO, fixed resin, fixed disc, electrochemical etc.)	Disruption of natural surface drainage	SW volume, SW quality	Surface water drainage	Altering surface water system
Processing facilities	P	Untreated co-produced water storage, processing and disposal (pilot stage only)	Leaching from storage ponds	GW quality	Operational water management	Storing extracted water
Processing facilities	P	Hypersaline brine ponds	Leaking	SW quality, GW quality	Operational water management	Storing extracted water
Processing facilities	P	Brine storage ponds, pumps and water disposal pipelines	Leaking	SW quality, GW quality	Operational water management	Storing extracted water
Pipelines facilities	C	Trunk gas pipelines and associated easements (processing plant to town)	Disruption of natural surface drainage	SW volume, SW quality, GW quantity	Surface water drainage	Intercepting surface water runoff
Pipelines facilities	C	Trunk gas pipelines and associated easements (processing plant to town)	Soil erosion following heavy rainfall	SW quality	Surface water drainage	Altering surface water system

[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]Table rows are ordered according to component and life cycle.
GW = groundwater, SW = surface water, RO = reverse osmosis
The full list of identified hazards is available from Bioregional Assessment Programme (Dataset 1). Typology and punctuation are consistent with this dataset.
Data: Bioregional Assessment Programme (Dataset 1)

For open-cut and underground coal mines, the following hazards are considered out of scope for the Galilee subregion because they are deemed to be covered by site-based risk management and regulation and do not have cumulative effects on water in the subregion:

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

Of those hazards that are in scope, some will be addressed by the BA numerical modelling, while for others (e.g. water quality hazards) it will only be possible through informed narrative. In the full list of hazards (Bioregional Assessment Programme, Dataset 1), the hazard priority number or hazard score indicates the relative importance of the hazard. Hazards with low scores are of lower priority.

Hydrological effects associated with coal mines that are considered to be in scope for the Galilee subregion are listed below:

- surface water quality
- surface water direction
- surface water flow
- surface water volume
- change to zero flow days
- groundwater quality
- groundwater direction
- groundwater flow (reduction)
- groundwater quantity/volume
- groundwater pressure.

Activities, impact modes and hydrological effects for open-cut and underground coal mines are assigned to causal pathways that can be aggregated into causal pathway groups (Table 14). The companion submethodology M05 (as listed in Table 1) for developing a coal resource development pathway (Henderson et al., 2016) provides further detail on causal pathways and their groupings that were utilised for BAs.

Table 14 Top 30 open-cut and underground mine activities, associated impact modes and causal pathway groups for the Galilee subregion

Component	Life cycle	Activities	Impact mode	Hydrological effects	Causal pathway group	Causal pathway
Open pit	D	Post-closure water filling the pit	Artificial point of recharge	GW quantity/volume, GW quality	Surface water drainage	Altering surface water systems
Open pit	D	Post-closure water filling the pit	Creation of artificial lake	SW quality	Surface water drainage	Altering surface water systems
Open pit	D	Pit backfill	Compaction/settlement	SW directional characteristics, GW directional characteristics	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Open pit	D	Waste rock blasting, excavation and storage	Leaching: waste storage	GW quality, SW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Open pit	D	Rainwater runoff diversion	Change to natural surface drainage	SW volume/quantity, SW quality, GW quantity/volume	Surface water drainage	Intercepting surface water runoff
Open pit	D	Waste rock blasting, excavation and storage	Disruption of natural surface drainage	SW directional characteristics, SW volume/quantity, SW quality, GW directional characteristics, GW quantity/volume, GW quality	Surface water drainage	Altering surface water systems
Open pit	D	Dam construction for tailings storage	Soil erosion following heavy rainfall	SW quality	Surface water drainage	Altering surface water systems
Open pit	D	Dam construction for mine water storage	Soil erosion following heavy rainfall	SW quality	Surface water drainage	Altering surface water systems
Open pit	D	Topsoil and waste rock dump site preparation	Disruption of natural surface drainage	SW volume/quantity, SW quality, GW quantity/volume	Surface water drainage	Altering surface water systems
Open pit	P	Waste rock blasting, excavation and storage	Disruption of natural surface drainage	SW directional characteristics, SW volume/quantity, SW quality, GW directional characteristics, GW quantity/volume, GW quality	Surface water drainage	Altering surface water systems

Component	Life cycle	Activities	Impact mode	Hydrological effects	Causal pathway group	Causal pathway
Open pit	P	Pit backfill	Leaching: in-pit waste rock dump	GW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Open pit	P	Waste rock blasting, excavation and storage	Leaching: waste storage	GW quality, SW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Open pit	P	Pit wall (stabilisation) dewatering, treatment, reuse, and disposal	Deliberate	GW flow, GW directional characteristics, GW quantity/volume, GW pressure, SW flow	Subsurface depressurisation and dewatering	Groundwater pumping enabling open-cut coal mining
Open pit	P	Coal onsite transport: stockpiles	Leaching	GW quality, SW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Open pit	P	Topsoil excavation and storage	Runoff changes	GW quantity/volume (changed recharge), SW flow	Surface water drainage	Altering surface water systems
Open pit	P	Waste rock dump rehabilitation	Leaching	GW quality, SW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Surface facilities	P	Run-of-mine plants	Leaching	GW quality, SW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Surface facilities	P	Product coal stockpiling	Leaching	GW quality, SW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Underground mining	D	Development of mine panels (construction of roadways)	GW dewatering	GW level	Subsurface depressurisation and dewatering	Groundwater pumping enabling underground coal mining

Component	Life cycle	Activities	Impact mode	Hydrological effects	Causal pathway group	Causal pathway
Underground mining	D	Waste rock removal and storage during construction of mine access (adit/shaft/incline)	Leaching	GW quality, SW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Underground mining	D	Groundwater monitoring bore construction	Incomplete/compromised cementing/casing (linking aquifers)	GW composition, GW quality	No specific causal pathway in BAs	Addressed by site-based risk management procedures
Underground mining	P	Longwall coal extraction	Subsurface fractures	GW pressure, GW flow, GW quality, GW quantity/volume, SW flow, SW volume/quantity	Subsurface physical flow paths	Subsurface fracturing above underground longwall panels
Underground mining	P	Longwall coal extraction	Subsidence	SW directional characteristics	Surface water drainage	Subsidence of land surface
Underground mining	P	Longwall coal extraction	GW dewatering	GW level	Subsurface depressurisation and dewatering	Groundwater pumping enabling underground coal mining
Underground mining	P	Subsidence management and monitoring	Poor management and monitoring	SW flow, SW directional characteristics, SW quality, GW flow, GW level, GW directional characteristics	Surface water drainage	Subsidence of land surface
Underground mining	P	Longwall coal extraction	Subsidence	GW quantity/volume, GW quantity/volume (changed recharge), GW connectivity	Surface water drainage	Subsidence of land surface

[a]Life-cycle stages are indicated by (C) for construction, (E) for exploration and appraisal, (P) for production and (D) for decommissioning.
[b]Table rows are ordered according to component and life cycle.
BA = bioregional assessment, GW = groundwater, SW = surface water
The full list of identified hazards is included in Bioregional Assessment Programme (Dataset 1). Typology and punctuation are consistent with this dataset.
Data: Bioregional Assessment Programme (Dataset 1)

2.3.5.3 Causal pathways

Although there is a long history of exploration for coal-related resources in the Galilee subregion, it is considered to be a greenfields development area as there is no history of commercial coal or CSG production. Hence there are no coal resource developments in the baseline for the Galilee subregion – a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012. The causal pathways introduced in Table 13 and Table 14 are described in further detail and relate to the CRDP – 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. Hydrological changes due to any of the causal pathways described in the following sections will contribute to differences that may occur between the CRDP and the baseline (See Section 2.3.1.1 and Section 2.3.5.3.3).

2.3.5.3.1 Coal seam gas operations

Hazards associated with CSG operations that are considered to be in scope for the Assessment are aggregated into four primary causal pathway groups (refer to companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016)). 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 subregion-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.

As noted in Section 2.3.5.2.1, CSG projects in the Galilee subregion are not as advanced in their development nor permitting as many of the coal mine developments. The most advanced CSG project in the Galilee subregion is the Glenaras Project (refer to companion product 1.2 for the Galilee subregion (Lewis et al., 2014)). As of December 2015, Galilee Energy Limited had refined the CSG well design for the Glenaras pilot wellfield and were utilising the updated well design to conduct an extended pump test to assess CSG flow rates to surface (Galilee Energy Ltd, 2015; Lansom, 2015).

Depending on results, the next steps could include applications to regulatory authorities for the necessary permits required for the Glenaras Project to proceed towards a production phase. It is possible that the potential for cumulative impacts from CSG may only become significant once multiple developments are commercially producing.

2.3.5.3.1.1 'Subsurface depressurisation and dewatering' causal pathway group

The suite of causal pathways in the 'Subsurface depressurisation and dewatering' causal pathway group is outlined in companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016). Relevant causal pathways in this causal pathway group for CSG operations in the Galilee subregion are 'Groundwater pumping enabling coal seam gas extraction' and 'Unplanned groundwater changes in non-target aquifers'.

In most cases, the confining hydrostatic pressure of groundwater within coal seams is a significant controlling factor on gas migration. Thus for CSG to be produced to the surface there is commonly a need to decrease groundwater pressures in the coal seams. Coal seams do not need to be completely dewatered in order for CSG to flow; groundwater pressures only need to be decreased below a critical pressure so that CSG can flow to the surface. This critical pressure (the desorption pressure) is a factor that is unique to each project and one of the many parameters that must be determined prior to a CSG project proceeding towards commercial operations.

In the Galilee subregion, the primary target seams for CSG development are in the upper Permian coal measures (Figure 32). If present, the Aramac Coal Meaures, which are situated stratigraphically below the upper Permian coal measures, can be a secondary target.

Coal seams will need to be depressurised in order for CSG to flow to the surface. Factors that can affect the extent to which depressurisation occurs and propagates around CSG projects include:

- local geological architecture (e.g. lithological variation, geological structures such as faults and fold hinges)
- configuration and characteristics of groundwater flow systems (e.g. aquifers, aquitards, flow direction)
- hydraulic properties, connectivity of aquifer systems and CSG reservoirs
- rate and duration of pumping (extent of depressurisation is time dependent)
- desorption pressure and depth of coal seams
- overburden thickness.

Due to the various complexities mentioned above, the degree of depressurisation that can occur at depth in a coal seam will not occur near the surface. Depressurisation in coal seams will propagate laterally through the coal measures at a certain rate and usually to a lesser extent, vertically through the overlying geological sequence. Propagation of the depressurisation cone may be impeded or enhanced by faults (fault mediated), the presence or absence of aquitard sequences such as the Rewan Group, or the distribution of lower permeability shaley sequences within the coal measures. Shaley units that could impede propagation of depressurisation both vertically and laterally are recognised in the upper Permian coal measures (Lansom, 2015), as are regional aquitards such as the Rewan Group and Moolayember Formation (Figure 32).

If an aquitard is thin or absent, then this may enhance propagation of a depressurisation cone laterally or vertically. The Rewan Group does vary in thickness and thins and pinches out towards the western margin of the Galilee Basin (Figure 32). Along the western margin of the Galilee subregion, some parts of the upper Permian coal measures can be in direct contact with overlying aquifers such as the Hutton Sandstone (Section 2.3.2.2.2). If propagation of a depressurisation cone were to extend this far west, then there is potential for impact on groundwater pressures in overlying aquifers. If pressures decreased along the western margins of the upper Permian coal measures to such a point where groundwater flow reversal may potentially occur (i.e. groundwater were to flow from Hutton Sandstone into the upper Permian coal measures), then this may potentially result in changes to groundwater pressures in the Hutton Sandstone aquifer.

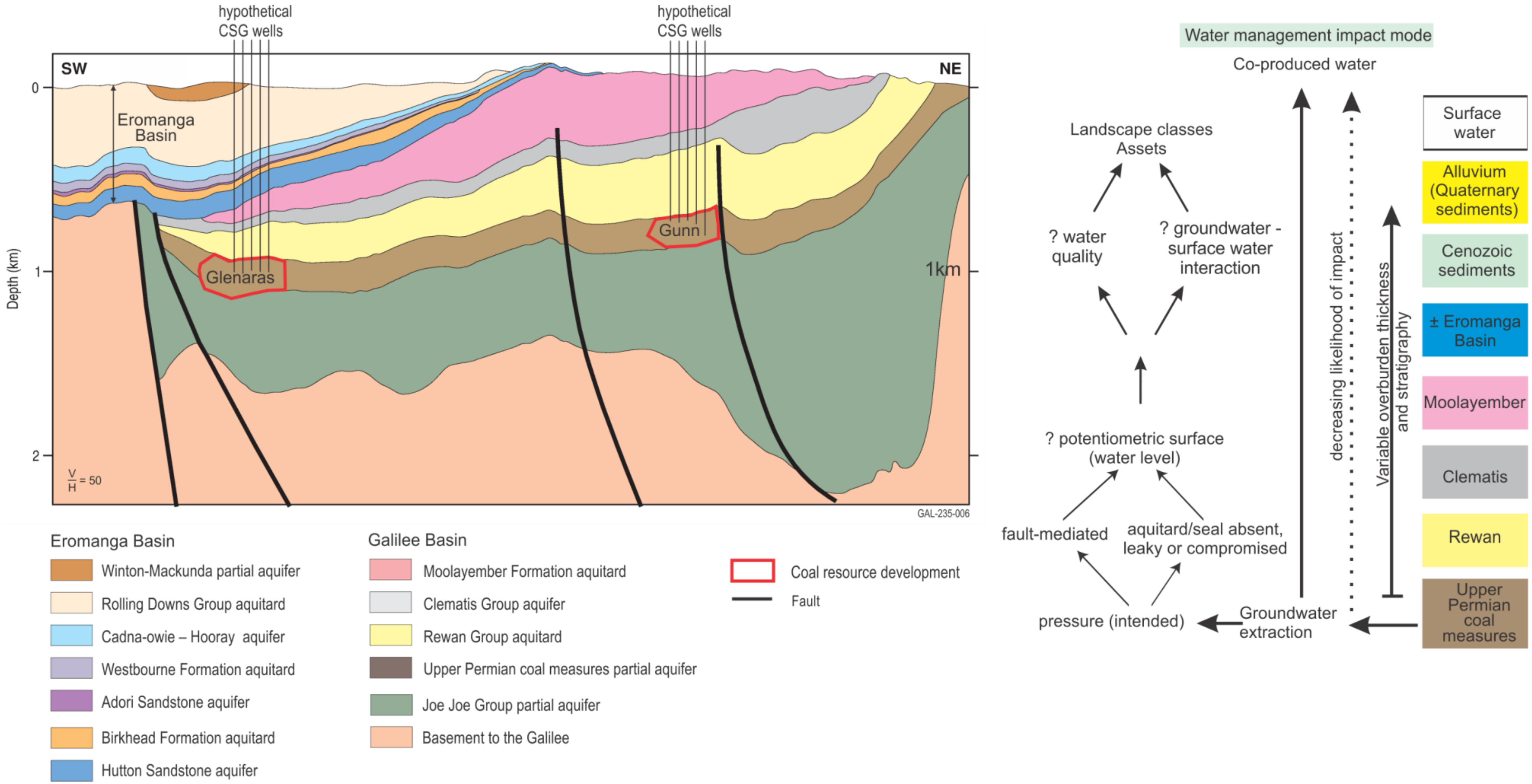

Figure 32 'Subsurface depressurisation and dewatering' causal pathway group for coal seam gas operations in the Galilee subregion

Causal pathways in this group that are relevant for coal seam gas in the Galilee subregion are 'Groundwater pumping enabling coal seam gas extraction' and 'Unplanned groundwater changes in non-target aquifers'. Refer to Table 13 for further details.
Cross-section is a stylised equivalent of Figure 6 in Section 2.3.2.
Arrows in diagram highlight direction of potential causal pathways.
Question marks next to text in figure suggest that change may or may not occur. It depends on site-specific circumstances.

2.3.5.3.1.2 'Subsurface physical flow paths' causal pathway group

The companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016) outlines the suite of causal pathways in this group. According to the hazard analysis presented in Table 13, the causal pathways of specific interest to the Galilee subregion are 'Failure of well integrity' and 'Hydraulic fracturing' (Figure 33).

CSG well integrity is important because it prevents connectivity between aquifers and reservoirs via the path of the well. Wells are drilled during the exploration and appraisal phase to evaluate the potential commercial viability of the prospective CSG operations, and during the production phase to extract commercial quantities of identified gas. 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 prevents the inter-aquifer mixing of fluids (liquid or gas) and pressures, as well as preventing the escape of fluids to the surface. Incomplete and/or compromised casing and seals could introduce preferential pathways for groundwater flow between aquifers. Well design and control measures include the selection of the right grade of casing and cement that are suitable for well conditions, as well as the proper installation of well casing and proper completion of cementing operations.

The impacts associated with compromised well integrity are more likely to be of a local scale; that is, they are likely to be restricted to within the vicinity of the compromised well. These impacts, however, will continue until remedial action is taken. These impacts include the escape of gas from the coal seams to the overlying geological layers and potentially to the atmosphere. In addition, inter-aquifer mixing could potentially locally compromise the water quality of some aquifers such as the Hutton Sandstone. Adverse impacts on surface water systems are thought to be minimal due to the limited spatial scale of the impact.

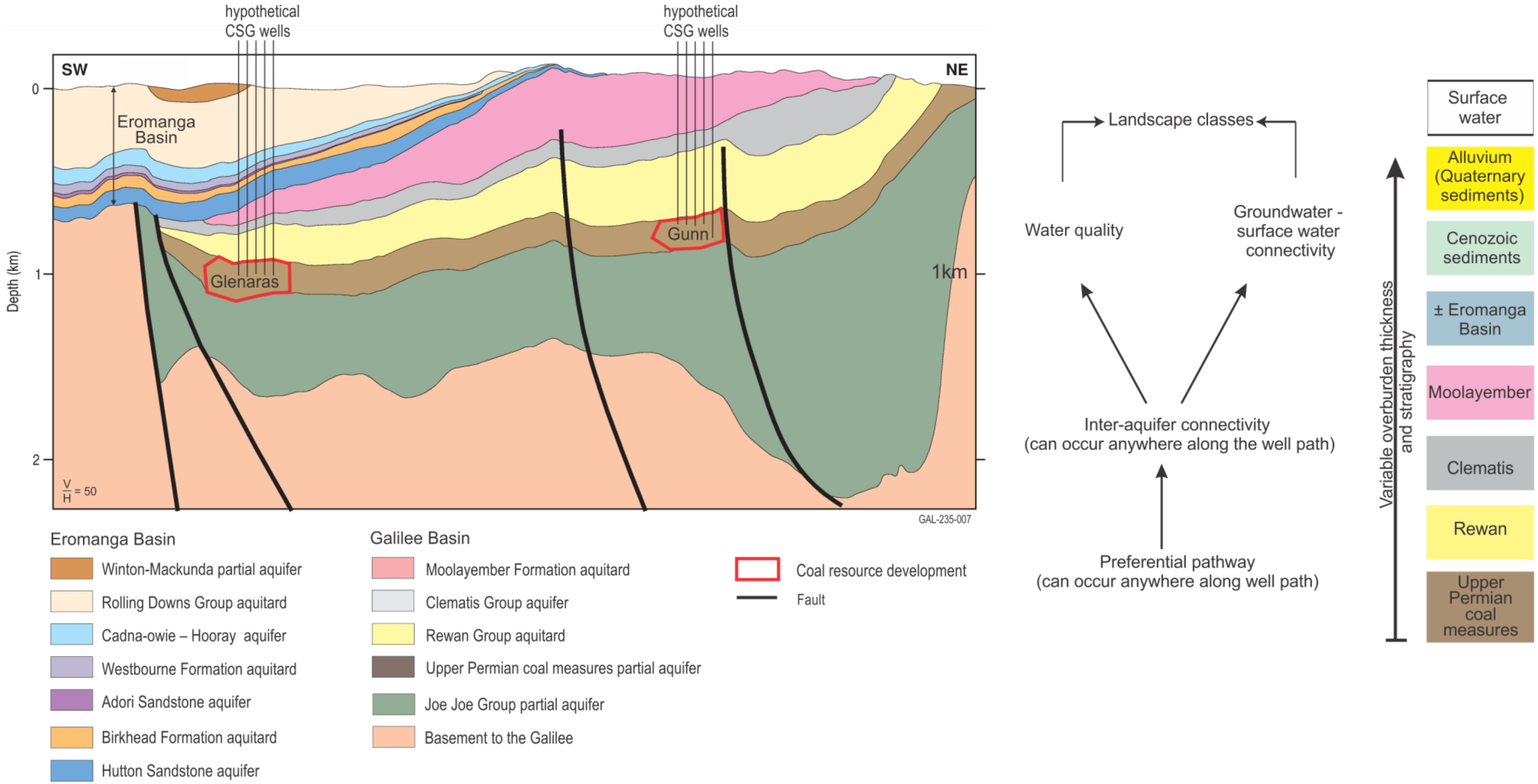

Figure 33 'Subsurface physical flow paths' causal pathway group for coal seam gas operations in the Galilee subregion

Causal pathways in this group that are relevant for coal seam gas operations in the Galilee subregion are: 'Failure of well integrity' and 'Hydraulic fracturing'. Refer to Table 13 for further details.
Cross-section is a stylised equivalent of Figure 6 in Section 2.3.2.
Arrows in diagram highlight direction of potential causal pathways.

Hydraulic fracturing is one of a suite of reservoir stimulation techniques that can be used to enhance gas flow from a CSG reservoir to a well. Due to the CSG fields being at a relatively early phase of development, it is uncertain whether hydraulic fracturing will become a technique that is readily applied across the Galilee Basin. For the Glenaras pilot wellfield, the drilling of horizontal CSG wells along target coal seams is considered to be a more applicable technology for increasing gas flow to CSG wells rather than hydraulic fracturing (Galilee Energy Ltd, 2016; Lansom, 2016). It is unknown whether this will be the case for other CSG projects in the Galilee subregion.

2.3.5.3.1.3 'Surface water drainage' causal pathway group

The companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016) outlines the suite of causal pathways included in this causal pathway group. According to the hazard analysis presented in Table 13, the causal pathways of specific interest to the Galilee subregion include 'Altering the surface water system' and 'Intercepting surface water runoff'.

Disruption of the surface drainage network may lead to a loss or redirection of runoff, which can have long-term cumulative effects on downstream watercourses. Some of steps in the development of physical infrastructure for CSG operations may include land clearing, land levelling, the construction of hard-packed areas such as roads and tracks, pipelines and plant for collection and transport of gas, can all disrupt natural surface flows and pathways by redirecting and concentrating flows. Water flow and landscape topography co-evolve in natural systems such that the areas of most concentrated flow tend to be the most resistant to erosion. Changes in flow regime and catastrophic events can alter flows and pathways either temporarily before returning to the previous state, or semi-permanently until the next event. In the same way, anthropogenic structures and earth works associated with CSG exploration and production may divert and concentrate surface flow. This may lead to erosion of the land surface, stream banks or streambeds, and alter water quality in streams if new material is mobilised and washed into them.

The CSG projects outlined in Section 2.3.4 are located west of the Great Dividing Range, in the Cooper Creek – Bulloo river basin (see Figure 17 in Section 2.3.2.2). In particular, the Thomson river basin is a major river basin situated in the headwaters of the Cooper Creek–Bulloo river basin.

As part of the Bioregional Assessment Programme, Wakelin-King (2015) presented an overview of the fluvial geomorphology of the Thomson river basin and, in particular, focused on river reaches that lie within the Galilee subregion. Some of the findings of Wakelin-King (2015) are:

- Landforms in the upland areas of the Thomson river basin, despite relatively high riverbed gradients, relate to low-energy fluvial processes. The stability of the fluvial landforms are likely to relate to low discharge flow regimes
- Geomorphology of the upper parts of the Thomson river basin is significantly different to what is found downstream. Therefore, conclusions drawn from studies in better understood areas of the Cooper Creek – Bulloo river basin (e.g. Cooper Creek) may not be applicable to the upper reaches of the Thomson river basin.

Wakelin-King (2015) suggested that more detailed fluvial geomorphological studies be undertaken if there are industry development proposals that have the potential to alter the streamflow regime.

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, water is also produced during the production stage and needs to be effectively and appropriately managed (Figure 34). The water needed for CSG activities could be sourced from either surface water or groundwater systems. If direct extraction from surface water features such as rivers were to occur, this could result in some impact to their flow regime depending on the volume of extraction relative to streamflow. Extraction from surface water streamflow would only be possible if permits allow and, in the Galilee subregion, it occurs during wetter months of the year when streams are flowing.

Co-produced water from groundwater pumping, as mentioned in Table 13, may be disposed of via various methods. These may include:

- storage tanks or ponds. This is currently the case for Glenaras Project (Lewis et al., 2014)
- reinjection (managed aquifer recharge) to a groundwater system. This may have potential impacts on groundwater quality for aquifers that would need to be addressed as part of any management plan. It may also have a positive impact on groundwater pressures in an aquifer
- reuse for other purposes such as for agricultural purposes after adequate treatment and amendment. Water quality should be such that it does not have any adverse impacts on soil properties and the water resource
- discharge of treated water to surface water systems. This may result in potential impacts to flow regime, fluvial geomorphology (Wakelin-King, 2015) or water quality. Impacts could be positive or negative
- reuse in a project as part of CSG development or production activities. This would be dependent on water quality.

Hazards relating directly to the 'Operational water management' causal pathway group are not included in the top 30 hazards as outlined in Table 13. This may, in part, reflect the current stages that CSG projects are at in the Galilee subregion. More detail is required on which treatment options would be applicable for water disposal in the Galilee subregion. Any water treatment and disposal options would be subject to regulatory oversight and approval by Queensland state agencies. The findings of Wakelin-King (2015) may be pertinent, depending on the pathway taken for treatment of co-produced water.

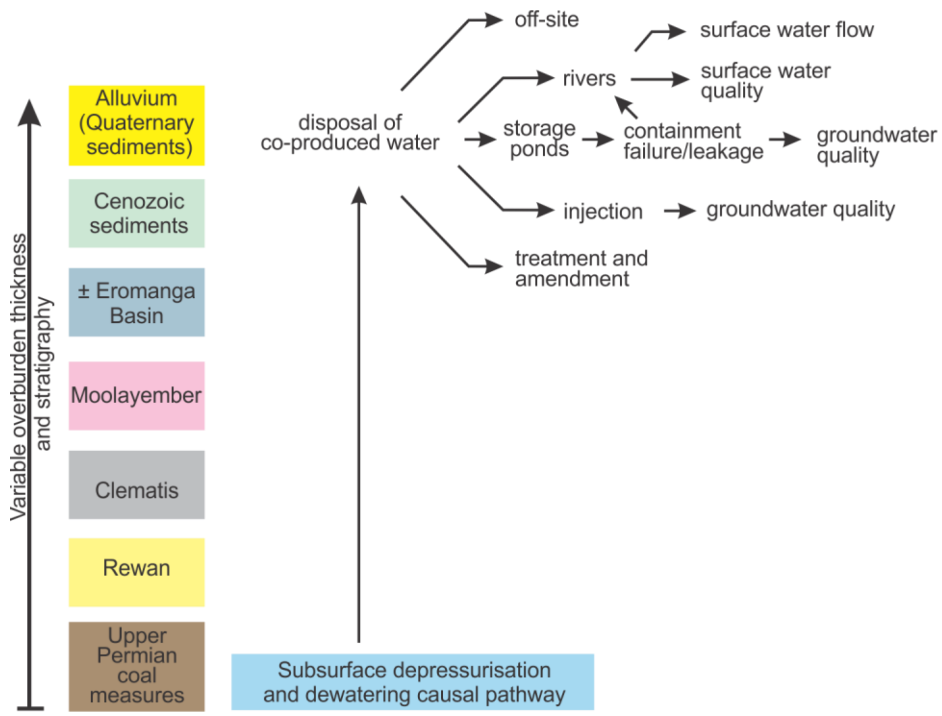

Figure 34 'Operational water management' causal pathway group for coal seam gas operations in the Galilee subregion

Arrows in diagram highlight potential causal pathways.

2.3.5.3.2 Open-cut and underground coal mines

As outlined in Section 2.3.1 and Section 2.3.4, 7 of the 14 coal mine developments in the CRDP have sufficient data and information available for them to be quantitatively assessed through groundwater and surface water modelling. Cumulative hydrological changes resulting from the groundwater and surface water modelling for these seven coal mine developments will be reported in companion product 2.6.1 and (Karim et al., 2018) and companion product 2.6.2 (Peeters et al., 2018) for the Galilee subregion.

In this section, the four causal pathway groups associated with coal mine activities (Table 14) are described to provide subregion-specific context and show how different components of the hydrological system may be affected by coal mine activities. The companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016) provides detail on various causal pathway groups utilised in BAs.

2.3.5.3.2.1 'Subsurface depressurisation and dewatering' causal pathway group

Relevant causal pathways in this group for coal mine developments in the Galilee subregion include 'groundwater pumping enabling open-cut mining' and 'groundwater pumping enabling underground mining'. Dewatering of aquifers is required if mining is to occur below the level of the watertable, as mine working areas have to be relatively dry for safety and operational reasons. This results in development of a drawdown cone (depressurisation) around the mine areas, resulting in localised redirection of groundwater flow towards mine areas.

The method for dewatering may vary with the mining method (e.g. open pit or underground). Open-cut mine areas need to be dewatered down to a depth that is below the floor of the pit and, to a certain extent, away from the pit walls to ensure that groundwater pressures do not cause stability issues for the pit or excessive inflow into the pit. Underground mine areas also need to be dry and dewatered. Groundwater in rock surrounding underground workings can be either completely or partly dewatered. Again this depends on operational requirements and the local hydrogeological regime.

Regardless of the mine type, overall there will be a resultant drop in groundwater levels and pressures around mine areas as all proposed coal mine developments in the Galilee subregion will extend deeper than the watertable. The extent to which drawdown propagates around mine areas can be dependent on:

- local geological architecture and its complexity (e.g. lithological variation, structures)
- configuration of groundwater flow systems (e.g. aquifers, aquitards, flow direction)
- hydraulic properties and connectivity of aquifer systems
- rate and duration of pumping (extent of drawdown is also time dependent)
- mine depth and mining method
- overburden thickness above underground mine workings.

Due to these various complexities, depressurisation at depth in the coal measures does not necessarily equate to the same magnitude of drawdown impact in the watertable aquifer near the surface.

A drawdown cone will develop around each coal mine development as all proposed developments in the CRDP will mine coal to well below the existing watertable level. If the drawdown cones that are generated around each mine by pumping overlap (which is probable given there are mining operations that are adjacent to each other), then the amount of drawdown in the areas of overlap become cumulative in nature. To impact near the surface, drawdown has to propagate through any rocks that overlie the coal seam that is being mined (the overburden). Whether drawdown propagates to the surface through the overburden is dependent on factors listed previously. Across the Galilee subregion, there is considerable variation in thickness of overburden to the top of the upper Permian coal measures varies (Figure 9, Section 2.3.2.2.1.1; Figure 35, Figure 36). Just west of coal mine development areas, overburden thickens considerably to greater than 300 m.

Figure 35 outlines the causal pathway of how dewatering and/or depressurisation may propagate around and away from an open-cut mine area. The far right-hand side of Figure 35 outlines the near mine stratigraphy, which can include upper Permian coal measures, Rewan Group, Clematis Group and Cenozoic sediments. Aquitards in a mine sequence may include clay layers in Cenozoic sediments (not shown in Figure 35), shales in upper Permian coal measures and Rewan Group.

The causal pathway linkage is that pumping around a mine development will draw down groundwater levels/pressures around the mine areas and increase the potential for groundwater to flow towards the mine area. Mine areas become a local groundwater sink due to development of groundwater pressures that are locally lower than what is in the surrounding aquifers.

Depending on the local geological configuration, groundwater flows may be impeded by aquitards in the stratigraphic sequence or enhanced if there are nearby aquifers such as porous sandstones.

Structures such as faults, if present, may either impede flow (a flow barrier, if for instance clay filled) or act as conduit (Bense et al., 2013). As groundwater drawdown propagates towards the surface and laterally, it may encounter other aquifers, (e.g the Clematis Group Aquifer) or if near-the surface groundwater flow systems in unconfined Cenozoic aquifers. The potential impact of groundater drawdown in this instance would be to reduce pressures in the regional confined aquifer, which may affect bore yields or nearby springs, or to lower the watertable in an unconfined aquifer. Lowering the watertable may decrease water availability to groundwater-dependent ecosystems, riparian environments and deep-rooted tree species (e.g. river red gum (*Eucalyptus camaldulensis*)); induce changes to baseflow to river systems; or even change a gaining stream to a losing stream. Changes to baseflow may result in local changes to river flow regime such as decreased river flow and duration of flow during low-flow periods. As outlined in Section 2.3.2.3, most rivers in the Galilee subregion in any given year can have many months of no flow. This may make these river systems more vulnerable if the baseflow component is altered with increases in the durations of low-flow and or zero-flow periods.

Figure 36 outlines the causal pathway for how dewatering and/or depressurisation may propagate around and away from an underground mine. Differences between open-cut and underground dewatering include:

- Groundwater is not necessarily completely dewatered above all underground workings.
- Fracturing above longwall areas may enhance groundwater inflows into mine areas or provide increased connectivity between aquifers or to the surface.

The groundwater systems are not necessarily dewatered above the underground mine workings. However, some degree of depressurisation will occur around the underground mine workings. This depressurisation could be impeded vertically by aquitards in the sequence. Deeper mine workings may also have the potential to increase the lateral extent of the effects of depressurisation and drawdown. Depressurisation associated with underground mine workings would be additive to a drawdown cone associated with dewatering around nearby open pits. As of February 2016, all proposed underground mines in the Galilee subregion are associated either directly or indirectly to open-cut mine operations.

The fractured zones that can form above the goaf of a longwall panel may enhance aquifer connectivity, thereby increasing inflows. Significant fracturing across an aquitard may increase inter-aquifer connectivity or potentially provide a pathway for recharge if fractures reach the surface. Section 2.3.5.3.2.2 provides more detail on causal pathways associated with fracturing and subsidence.

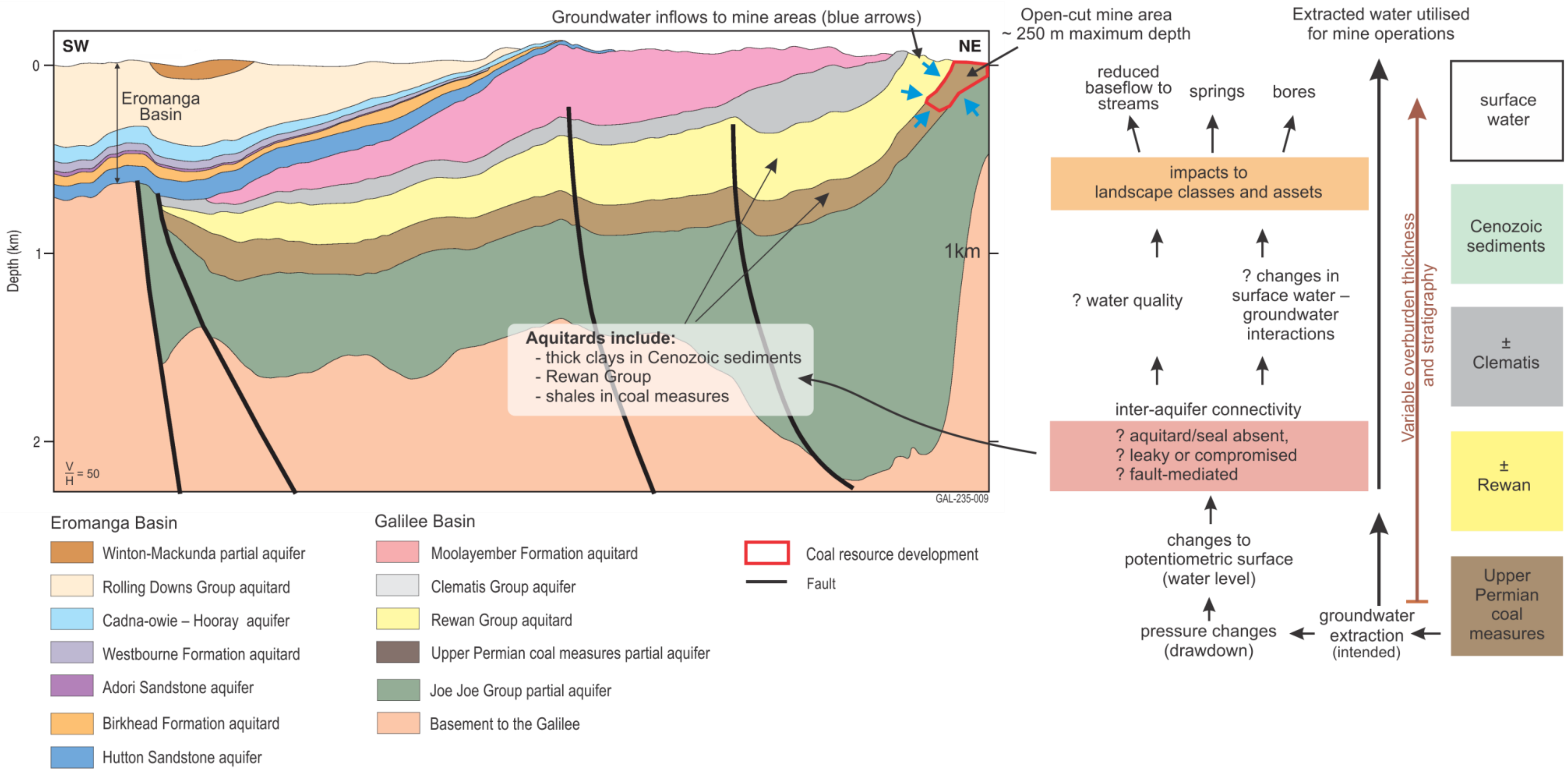

Figure 35 'Subsurface depressurisation and dewatering' causal pathway group for open-cut coal mines in the Galilee subregion

Cross-section is a stylised equivalent of Figure 6 in Section 2.3.2.
Black arrows in diagram highlight potential causal pathways.
Blue arrows in cross-section represent hypothetical groundwater flow induced through depressurisation around coal mine.
Question marks next to text suggest that change may or may not occur. It depends on site-specific circumstances.

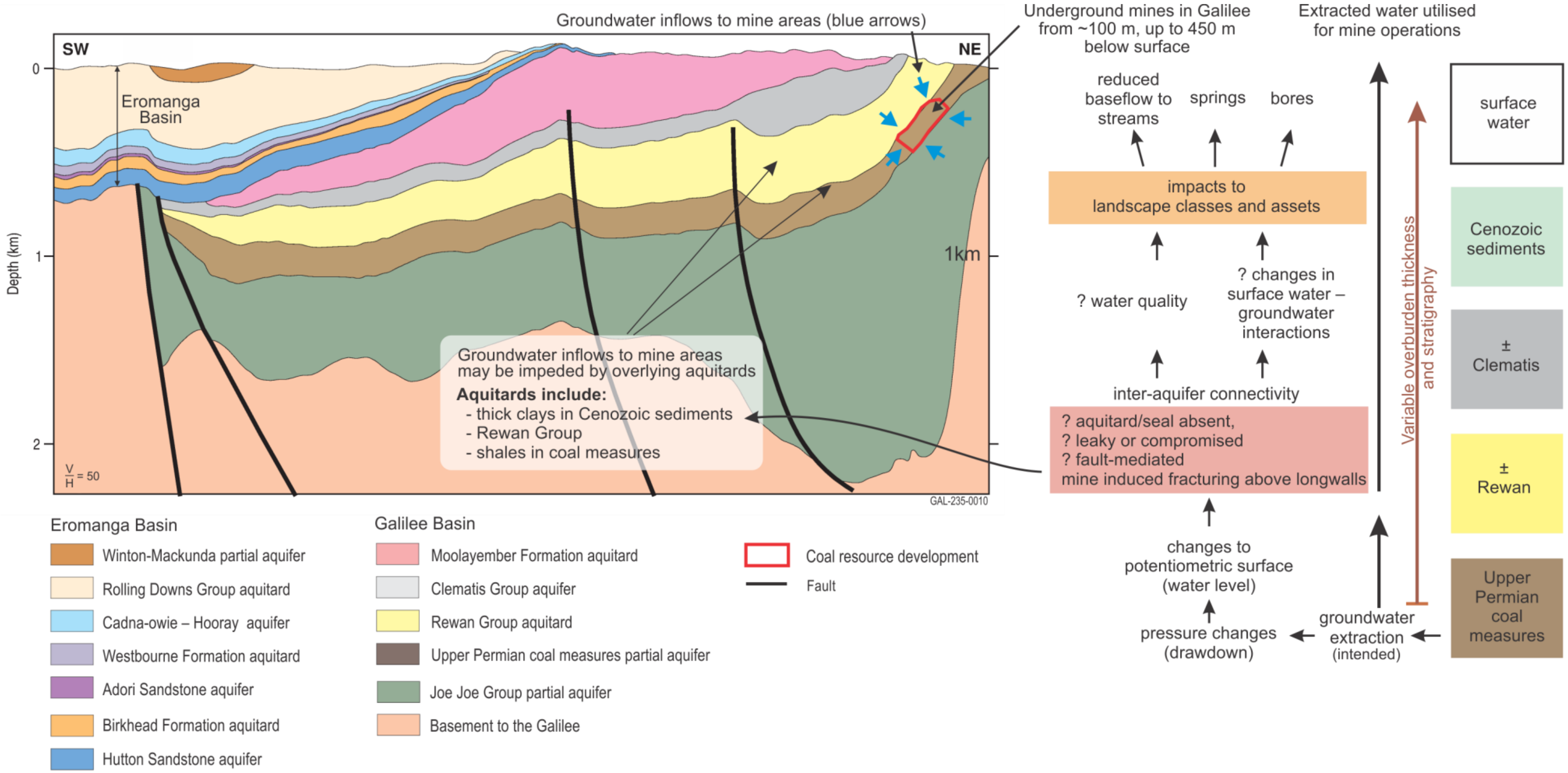

Figure 36 'Subsurface depressurisation and dewatering' causal pathway group for underground coal mines in the Galilee subregion

Cross-section is a stylised equivalent of Figure 6 in Section 2.3.2.
Black arrows in diagram highlight potential causal pathways.
Blue arrows in cross-section represent hypothetical groundwater flow induced through depressurisation around coal mines.
Question marks next to text suggest that change may or may not occur. It depends on site-specific circumstances.

In the Galilee subregion, seven coal mine developments are included in the groundwater and surface water modelling for the CRDP. Groundwater modelling is a component of the BA for the Galilee subregion, the results of which will be reported in companion product 2.6.2 for the Galiliee subregion (Peeters et al., 2018). This modelling will determine if drawdown cones around the proposed coal mine developments will be cumulative and provide an estimate of the extent of hydrological change.

2.3.5.3.2.2 Fracturing and subsidence above underground mine longwall panels

All underground mining is proposed to occur in coal seams in the upper Permian coal measures. Fracturing and subsidence will occur to varying degrees above underground longwall mines once they commence operations in the Galilee subregion. The degree of fracturing and subsidence that occurs is dependent on a number of factors including:

- local geological architecture and complexity (e.g. lithological variation, stratigraphy, structures and other discontinuities such as bedding, bedding thickness)
- geotechnical parameters for coal seams and surrounding rock mass (e.g. rock strength, stiffness)
- overburden thickness, mined coal thickness
- longwall extent and configuration, single- or multi-seam longwall operations
- topography
- angle of draw around longwall areas, which is generally defined as the boundary of an area where subsidence at the surface is greater than 20 mm (Commonwealth of Australia, 2015). The angle of draw can be dependent on the interplay of factors mentioned in previous points.

For BAs, the fracturing component is included under the ‘Subsurface physical flow paths’ causal pathway group as the causal pathway ‘Subsurface fracturing above underground longwall panels’. However, the subsidence component included under the ‘Surface water drainage’ causal pathway group under the causal pathway ‘Subsidence of land surface’ as subsidence is likely to have the most impact on surface features (see companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016)). For the Assessment, fracturing and subsidence related causal pathways will be reported in this section as the two causal pathways (‘Subsurface fracturing above underground longwall panels’ and ‘Subsidence of land surface’) are primarily a result of the one coal mine related activity (underground longwall mining).

Generally, areas affected by subsidence and fracturing are greatest above or immediately adjacent to areas where longwall coal mining has taken place. Horizontal far field effects such as movement on faults or bedding planes can also occur (usually within 500 m of longwall areas; Commonwealth of Australia, 2015). On a more regional scale, the combined cumulative area of the various proposed underground mines may change the surface water regime in the Belyando river basin (Figure 37). The Belyando River is a significant tributary to the Burdekin River. Proposed areas where longwall mining, fracturing and subsidence may occur are shown in Figure 37.

The major changes that can occur below ground level due to 'Subsurface fracturing above underground longwall panels' causal pathway are outlined in Figure 38. Changes may include increased aquifer connectivity due to preferential flow along fractures, or increased flow through an aquitard compromised by fracturing, increased conductivity and lower groundwater levels. Increases in hydraulic conductivity can have implications for dewatering and depressurisation around coal mines as it could result in increases to water production (Section 2.3.5.3.1.1).

Figure 39 shows potential changes relating to 'Subsidence of land surface' causal pathway. Changes may include local changes in topography, ponding of water, increased erosion resulting in sedimentation and nutrient runoff, redirection of surface flows, some changes to surface water regime, and if fracturing reaches the surface there is potential for increased recharge to groundwater. However, the degree of change is strongly dependent on site-specific conditions.

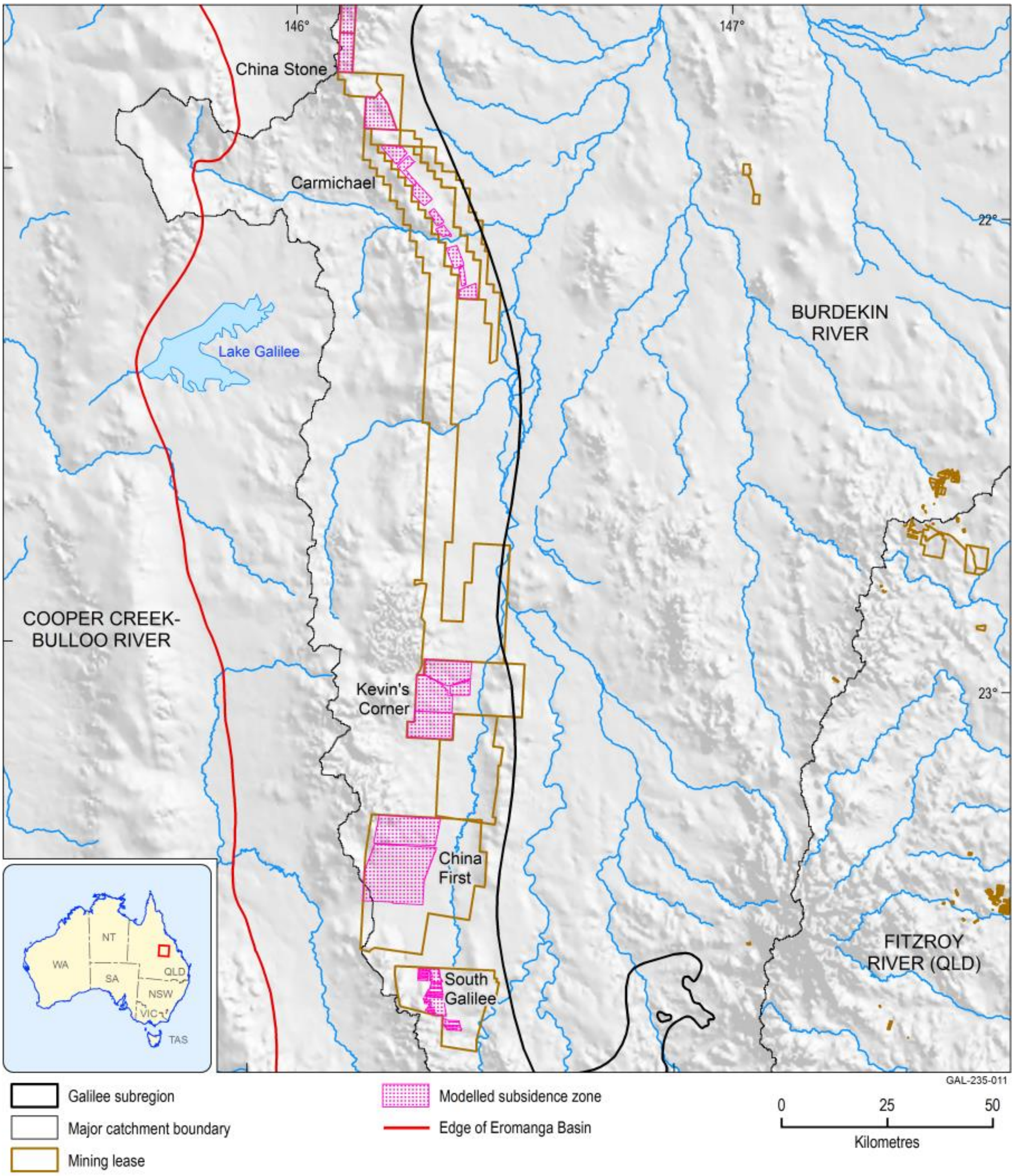

Figure 37 Areas where subsidence may occur above underground mines included in the modelled coal resource development pathway (CRDP) for the Galilee subregion

Subsidence areas derived from relevant mine environmental impact statement.
Data: QDNRM (Dataset 2), Geoscience Australia (Dataset 3)

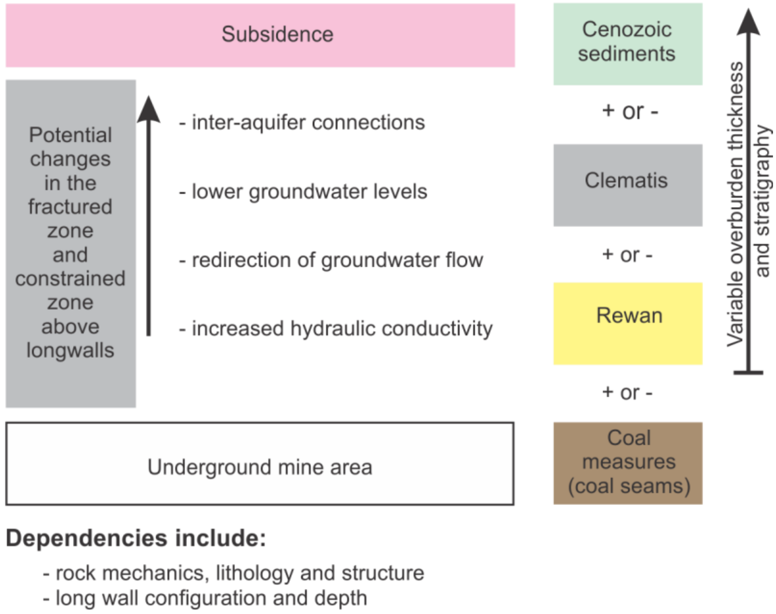

Figure 38 'Subsurface fracturing above underground longwall panels' causal pathway for the Galilee subregion

Arrows in diagram highlight potential causal pathways.

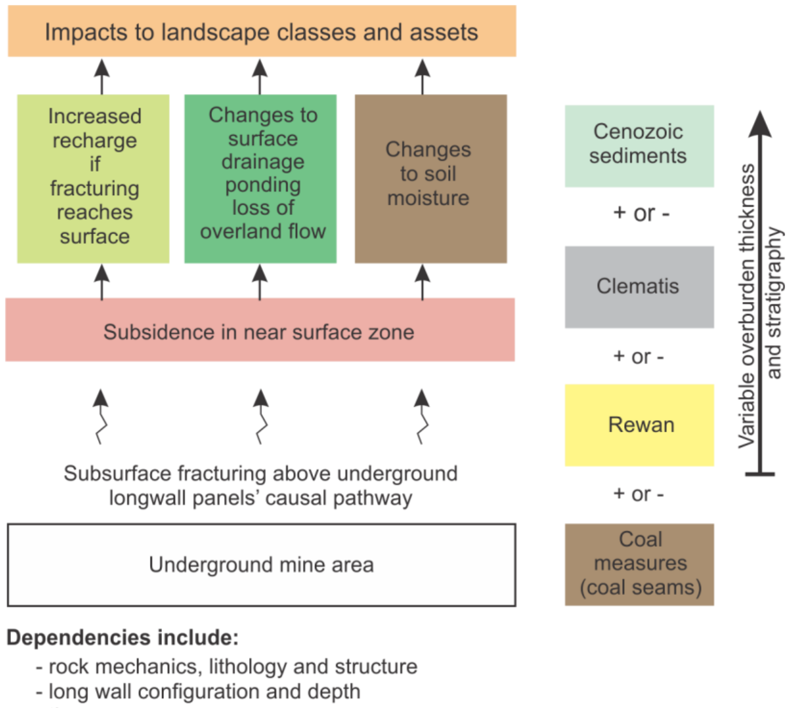

Figure 39 'Subsidence of land surface' causal pathway for the Galilee subregion

Arrows in diagram highlight potential causal pathways.

2.3.5.3.2.3 'Surface water drainage' causal pathway group

'Altering surface water systems' is the causal pathway in this group that is relevant for coal mine developments in the Galilee subregion. For operational reasons surface water drainage needs to be modified in order to control the amount of water at the mine site. It also lessens the potential for inadvertent releases of water from a mine site. Rainfall that falls on site is utilised on site. Some examples of the types of major infrastructure that are part of a typical coal mine site are shown in Figure 40.

Early in the development of a mine site, where the installation of diversion drains is required, bund walls and other measures will divert surface water flows, including overland flow, around the mine site to continue down slope of the mine development. This is done to minimise the amount of water required to be managed on site. This effectively isolates the mine area from the rest of the catchment and reduces the overall catchment area that can contribute to runoff. A reduction in catchment area may reduce surface water flows, which in turn may result in changes to some components of the water balance. Redirection of flow to other parts of the catchment may also increase surface water flows locally in areas where it previously did not occur. Whether these changes are significant or not will vary from site to site.

CRDP coal mines included in the groundwater and surface water modelling for the Galilee subregion (Section 2.3.4) are located in the Belyando river basin, which is part of the larger Burdekin river basin (see also Figure 17 in Section 2.3.2.2). Hence surface water modelling for the Assessment is focused on Burdekin river basin (companion product 2.6.1 for the Galilee subregion (Karim et al., 2018)).

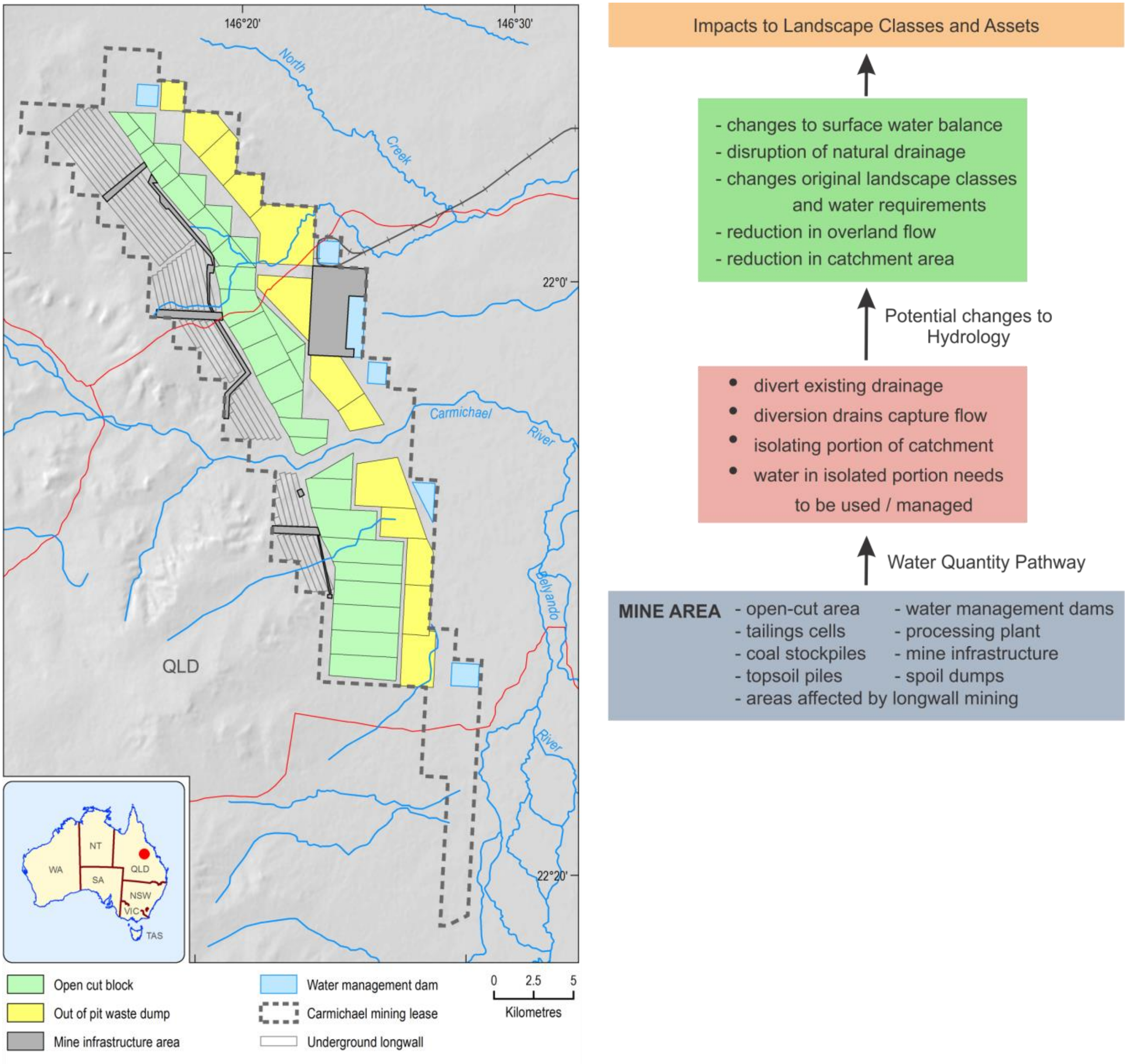

Figure 40 'Altering surface water systems' causal pathway for the Galilee subregion

Data: Queensland Department of State Development, Infrastructure and Planning (Dataset 4)

2.3.5.3.3 Causal pathways for the coal resource development pathway

There were no commercially producing coal mines or CSG fields in the Galilee subregion as of December 2012, which (as outlined in Section 2.3.1.1) is the date used to define the baseline for BAs. This was still the case as of April 2016, as there were no coal mines or CSG fields in construction or producing commercially in the Galilee subregion.

The causal pathways listed in Table 14 and described in Section 2.3.5.3.2 relate only to the coal resource developments in the CRDP that were quantitatively assessed in the groundwater and surface water modelling. Hydrological changes due to any of the causal pathways would contribute to differences that may occur between the CRDP and the baseline (Section 2.3.1.1).

2.3.5.4 Gaps

As of April 2016, there were no operating coal mines or CSG projects in the Galilee subregion. Consequently, developing the conceptual models of causal pathways has been based on available plans and discussions with the various development proponents. Existing projects are at various stages of development and regulatory approval.

Not all coal resource developments in the CRDP are at the same stage in regulatory approvals; therefore, a full suite of information is not always available. Data gaps include:

- area that some of the less advanced coal resource developments may cover and detail on how less advanced projects may develop
- little information on how CSG development will progress. This is mainly due to CSG development in the Galilee subregion being currently (April 2016) at an advanced exploration stage only
- specific information on water management options. Specific conditions on how water can be managed are outlined as part of mine permitting conditions
- greater understanding on distribution and variation of bulk hydraulic properties for Rewan Group and upper Permian coal measures
- estimates on volumes of groundwater that may be produced by developments
- finalisation on exact sources and amounts of external water required for coal mine projects
- calculation of area of draw utilising more local data for fracturing and subsidence associated with longwall coal mines in the Galilee Basin.

Further discussion on gaps and opportunities are also outlined in Section 3.7 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018).

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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

advanced exploration: a stage in the exploration process whereby the particular commodity of interest (such as coal) is known to exist within the exploration tenement, based on analysis of existing data and information, combined with new data obtained from drilling of boreholes, sampling and analyses of rock types, and other relevant geoscientific studies, etc.

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 bores 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

confined aquifer: an aquifer saturated with confining layers of low-permeability rock or sediment both above and below it. It is under pressure so that when the aquifer is penetrated by a bore, the water will rise above the top of the aquifer.

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, in 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).

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

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

diversion: see extraction

drawdown: a lowering of the groundwater level (caused, for example, by pumping). In the bioregional assessment (BA) context this is reported as the difference in groundwater level between two potential futures considered in BAs: baseline coal resource development (baseline) and the coal resource development pathway (CRDP). The difference in drawdown between CRDP and baseline is due to the additional coal resource development (ACRD). Drawdown under the baseline is relative to drawdown with no coal resource development; likewise, drawdown under the CRDP is relative to drawdown with no coal resource development.

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

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

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: a characteristic of the system that, according to the conceptual modelling, potentially changes 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.

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

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) subsidence: localised lowering of the land surface. It occurs when underground voids or cavities collapse, or when soil or geological formations (including coal seams, sandstone and other sedimentary strata) compact due to reduction in moisture content and pressure within the ground.

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.

unconfined aquifer: an aquifer whose upper water surface (watertable) is at atmospheric pressure and does not have a confining layer of low-permeability rock or sediment above it

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

water-dependent asset: an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development

water system: a system that is hydrologically connected and described at the level desired for management purposes (e.g. subcatchment, catchment, basin or drainage division, or groundwater management unit, subaquifer, aquifer, groundwater basin)

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

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

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