Australian Government

BIOREGIONAL ASSESSMENTS

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

# Receptor impact modelling for the Galilee subregion

## Product 2.7 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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Authorship is listed in relative order of contribution.

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### Cover photograph

Artesian Spring Wetland at Doongmabulla Nature Refuge, Queensland, 2013

Credit: Jeremy Drimer, University of Queensland

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# Executive summary

This product details the development of qualitative mathematical models and receptor impact models for the Galilee subregion. Receptor impact models enable the Bioregional Assessment Programme (the Programme) to quantify the potential impacts and risks that coal resource developments pose to water-dependent landscape classes and ecological assets. Applying receptor impact models across landscape classes allows a better understanding of how changes in hydrology may result in ecosystem changes.

A receptor impact model describes the relationship between:

- one or more hydrological response variables, which represent characteristics of the flow regime that potentially change due to coal resource development (for example, drawdown or annual flow volume) and
- a receptor impact variable, which is a characteristic of the system (for example, percent foliage cover) that, according to the conceptual modelling, is potentially sensitive to changes in the hydrological response variables.

The relationship between these variables and subsequent responses will identify where further local-level studies of ecosystems and their response to coal resource development are needed.

***Coal resource developments***

Receptor impact modelling for the Galilee subregion applies the two potential coal resource development futures considered in bioregional assessments (BAs):

- *baseline coal resource development (baseline)*: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as at 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 modelled in the baseline for the purposes of BA
- *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
  - in the Galilee subregion there are 17 proposed new developments, of which 14 are potential new coal mines and 3 are potential new CSG fields. There is enough publicly available information to include seven of these developments in the numerical modelling: open-cut coal mines Alpha and Hyde Park, and combined open-cut and underground coal mines Carmichael, China First, China Stone, Kevin’s Corner and South Galilee.

The difference in results between CRDP and baseline is the change that is primarily reported in a BA. This change is due to additional coal resource development. As there are no coal mines or CSG operations in the Galilee subregion baseline, this effectively means that the CRDP future is simply due to the additional coal resource developments.

### *Methods*

Receptor impact model development is both qualitative and quantitative due to the complexity and uncertainty associated with describing relationships between hydrological change and ecological components of the system. The absence of direct relevant theory and ecological response data of potential impacts due to additional coal resource development that occur in the future requires expert judgement or elicitation to be used in: (i) mapping ecological processes and key components (as signed digraphs); (ii) constructing qualitative models that record – as an increase, decrease or no change – potential landscape class response to sustained hydrological change; and (iii) selecting ecological indicators (receptor impact variables) from the ecological components or processes and the hydrological regimes (hydrological response variables) that support them. The resulting statistical models quantify how changes in hydrological response variables due to coal resource development may potentially impact the receptor impact variables in the short-term (2013 to 2042) and long-term (2073 to 2102) within a landscape class.

### *Ecosystems*

The Galilee subregion occupies diverse environments, from 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. In the conceptual modelling product, the Galilee assessment extent was classified into 11 broad landscape groups which comprise 31 landscape classes. The classification was 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.

Descriptions for the qualitative mathematical models and receptor impact models are provided under landscape group headings. Of the 11 landscape groups in the Galilee subregion, most (73%) of the zone of potential hydrological change supports the 'Dryland' or 'Floodplain, non-wetland' landscape groups and these were not modelled as they rely on incident rainfall and localised runoff. Four of the nine remaining landscape groups cover very small areas within the zone of potential hydrological change and were not further assessed. The remaining five landscape groups represent the ecosystems that were the focus for receptor impact modelling. These potentially impacted landscape groups include 'Springs', 'Floodplain, terrestrial GDE', and 'Non-floodplain, terrestrial GDE'. In addition, the landscape groups 'Streams, GDE' and 'Streams, non-GDE' were combined for the purposes of the receptor impact modelling and are considered further in this product as the 'Streams landscape group'.

### *'Springs' landscape group*

The 'Springs' landscape group contains springs of two types: recharge (also referred to as 'outcrop') springs and discharge springs. There are three clusters of springs that occur within the zone of potential hydrological change of the Galilee subregion. From north to south these are: (i) the Doongmabulla Springs complex, (ii) a series of springs that overlie the Colinlea Sandstone which is of Permian age (hereafter referred to as the 'Permian springs cluster') and (iii) a series of springs associated with Triassic geological units (hereafter referred to as the 'Triassic springs cluster'). Qualitative mathematical models were built for the 'Springs' landscape group that described the general dynamics of the aquatic community associated with springs. A receptor impact model was not developed for 'Springs' because applying a regional-scale groundwater model to the micro scale of 'Springs', was deemed to be inappropriate. Potential hydrological changes at a regional scale cannot be scaled down to apply to 'Springs'. Instead, a qualitative assessment of potential impacts of hydrological change was made using available hydrological and ecological information obtained from the Lake Eyre Basin Springs Assessment Project and other available sources.

Based on the 'Springs' landscape group qualitative mathematical model, experts considered that the critical factor in preserving the aquatic community is the rate of groundwater flow that maintains a damp or submerged state in the spring, such that this surface does not become dry. An increase in water depth above this threshold supports a wetted-area regime around the perimeter and downstream of the spring. Surface water and groundwater modelling predict potential impacts from coal mining on groundwater levels and subsurface water availability. Based on all possible combinations of these potential impacts, three cumulative impact scenarios were developed for qualitative analysis of response predictions.

***Streams landscape groups***

The two streams landscape groups in the Galilee assessment extent contain 10 landscape classes. Four landscape classes are groundwater-dependent ecosystem (GDE) streams (comprising the 'Streams, GDE' landscape group) and six are non-GDE streams (comprising the 'Streams, non- GDE' landscape group). Both GDE streams and non-GDE streams are widespread in the zone of potential hydrological change. Of the 6285 km of streams in the zone of potential hydrological change, 3484 km (55%) are non-GDE streams and are most prominent in the western and southern part of the zone; GDE streams account for 2801 km (45%) of total streams in the zone. Within the zone of potential hydrological change, annual streamflow shows a high degree of interannual variability. Flows in any given year can vary from almost no flow to major floods. Mean monthly flow is also highly variable with minimal to no flow from July to October, while most surface water flows occur between December and April. The streamflow regime within the zone is thus characterised as one of 'dry seasonal flows'. A large portion of the Belyando river basin is within the zone of potential hydrological change, where dry seasonal flows result in a boom–bust ecology that follows an annual hydrological cycle unlike more arid rivers further west in the Galilee subregion.

A combined qualitative mathematical model was developed for the two streams landscape groups. The central feature of the qualitative model was the existence and connectivity of refuge habitats with detritus and algae the principal resources that support populations of aquatic invertebrates and fishes. Surface water also recharges stores of deep groundwater in confined aquifers which can contribute to near-surface groundwater.

Two receptor impact models were developed to examine the potential impact of the additional coal resource development on water-dependent ecosystems within the zone of potential hydrological change. The first receptor impact model focused on the response of woody riparian vegetation to changes in flow regime and groundwater. The second model examined the response of a high-flow macroinvertebrate (mayfly nymphs in the genus *Offadens,* family Baetidae) to changes in flow regime. The density of this species was deemed a suitable indicator of stream health because the species' responds to streamflow and the species density is impacted by water drying up.

Using the woody riparian vegetation receptor impact model, experts were of the opinion that: (i) mean percent foliage cover would decrease as the depth to groundwater increases, (ii) mean percent foliage cover would decrease as the number of low-flow days increased, and (iii) mean percent foliage cover would increase as the number of flood events with peak daily flow exceeding the 1983 to 2012 2-year return period increased.

Results from the high-flow macroinvertebrates receptor impact model indicate that the experts' opinion provides no strong evidence that either the number of low-flow days or the mean maximum spell of low-flow days have a significant effect on mean baetid density. This model also predicts that baetid density under reference conditions does not affect outcomes under different low-flow conditions in future assessment years.

***'Floodplain, terrestrial groundwater-dependent ecosystem' landscape group***

The 'Floodplain, terrestrial GDE' landscape group vegetation depends on the subsurface expression of groundwater on a permanent or intermittent basis to maintain growth or avoid water stress and adverse impacts on condition. The landscape group contains two landscape classes within the Galilee subregion zone of potential hydrological change: 'Terrestrial GDE, remnant vegetation' (about 2358 $km^2$) and 'Terrestrial GDE' (about 75 $km^2$).

The 'Floodplain, terrestrial GDE' landscape group provides potential habitat for a range of nationally listed threatened plant and animal species. Groundwater and surface water are the key hydrological elements that support woodland communities. Four alternative signed digraphs were developed to represent this landscape group because there was uncertainty of the links associated with trees drawing groundwater to the surface, and the potential for groundwater to contribute to soils depleted of oxygen (anoxic). Surface water and groundwater modelling indicate substantial potential impacts of coal mining to groundwater depth and drawdown, and decreased flood events.

The relationships identified in the qualitative mathematical modelling workshop were formalised into a receptor impact model that described the response of annual mean percent foliage cover in a 0.01 $km^2$ plot to changes in groundwater levels and peak daily streamflow.

The experts' elicited responses suggest that percent foliage cover may decrease as groundwater drawdown increases due to additional coal resource development. The mean of the average percent foliage cover will decrease from about 10% without any change in groundwater level, to about 7% if groundwater levels decrease by 6 m relative to the reference level in 2102 (holding all other variables at their median values). However, there is considerable uncertainty within these predictions.

The receptor impact modelling indicates that there is evidence in the experts' responses for overbank flood events (Events R2.0) to have a major quadratic effect on percent foliage cover. The frequency of overbank flood events will generally have a positive effect on average percent foliage cover, unless the frequency of flooding becomes too high. The predicted increase in the average frequency of overbank flood events, from 0.05 in the 30 years preceding the reference year, to an average value of 0.9 over the future period, causes the average percent foliage cover to increase by almost 10%. However, when the frequency of overbank flood events exceeds 1 there is a negative effect on percent foliage cover.

***'Non-floodplain, terrestrial groundwater-dependent ecosystem' landscape group***

The 'Non-floodplain, terrestrial GDE' landscape group contains four landscape classes. Two are distributed within the zone of potential hydrological change: 'Non-floodplain, terrestrial GDE' (about 6 $km^2$) and 'Non-floodplain, terrestrial GDE, remnant vegetation' (1184 $km^2$). The vegetation in this landscape group depends on the subsurface expression of groundwater on a permanent or intermittent basis to maintain growth or avoid water stress and adverse impacts on condition. Much of the vegetation, in particular trees, relies on accessing groundwater from shallow aquifers. Groundwater is needed for trees to persist in areas where evapotranspiration exceeds rainfall.

The geological units of the Rewan Group and Clematis Group are the most likely sources of groundwater for the 'Non-floodplain, terrestrial GDE' landscape group. This landscape group provides potential habitat for a range of nationally listed threatened plant and animal species.

A qualitative model was developed that focused on recruitment dynamics associated with groundwater-dependent native tree species, with tree canopies providing a range of (as yet unspecified) ecosystem roles. A receptor impact model was designed that focused on the response of mean annual percent foliage cover of woody vegetation to changes in groundwater. The quantitative modelling, based on expert elicitation of response values, indicated a site with higher foliage cover at the 2012 reference point is more likely to have higher foliage cover in the future than a site with a lower foliage cover value at this reference point. The model also indicated that percent foliage cover may decrease as groundwater drawdown increases due to the additional coal resource development. The model shows that the mean of the average percent foliage cover will decrease from about 48% without any change in groundwater level, to about 47% if the levels decrease by 10 m relative to the reference level in 2012. However, there is uncertainty in these results.

***Gaps and limitations***

There are a number of gaps and limitations for building qualitative ecosystem models and quantitative receptor impact models. These include:

- the expert elicitation process reflects the subjectivity and bias inherent in the knowledge base of the experts (e.g. in defining the scope of the model; its components and connections; the ecologically important hydrological variables; representative receptor impact variables; and the magnitude and uncertainty of responses to change)
- water quality changes due to a shift in the relative contributions of surface water runoff and groundwater to streamflow, or due to enhanced connectivity between aquifers of differing water quality, are not represented
- there are areas where the hydrological change to the stream network cannot be quantified adjacent to some of the coal mine developments, thus impeding the analysis of potential risks across those parts of the landscape

- limited understanding of the connectivity between groundwater and surface water systems including: the connectivity within landscape classes and groups of classes and between ecosystems; potential surface water – groundwater interaction; the nature of groundwater interactions between riverine and terrestrial ecosystems
- an absence of experts with specific knowledge of the local hydrological and ecological systems within the zone of potential hydrological change of the Galilee subregion.

These gaps and limitations place some constraints on the comprehensiveness of the ecosystem analysis undertaken for this BA, and it is important to flag these so that further investigation can be better targeted.

Results from the application of receptor impact models and the spatial distribution of hydrological results are reported in Section 3.4 of the impact and risk analysis in companion product 3-4 for the Galilee subregion.

# Contents

# Figures

# Tables

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- Independent reviewers: National Centre for Groundwater Research and Training, Andrew Boulton (University of New England)

# 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.

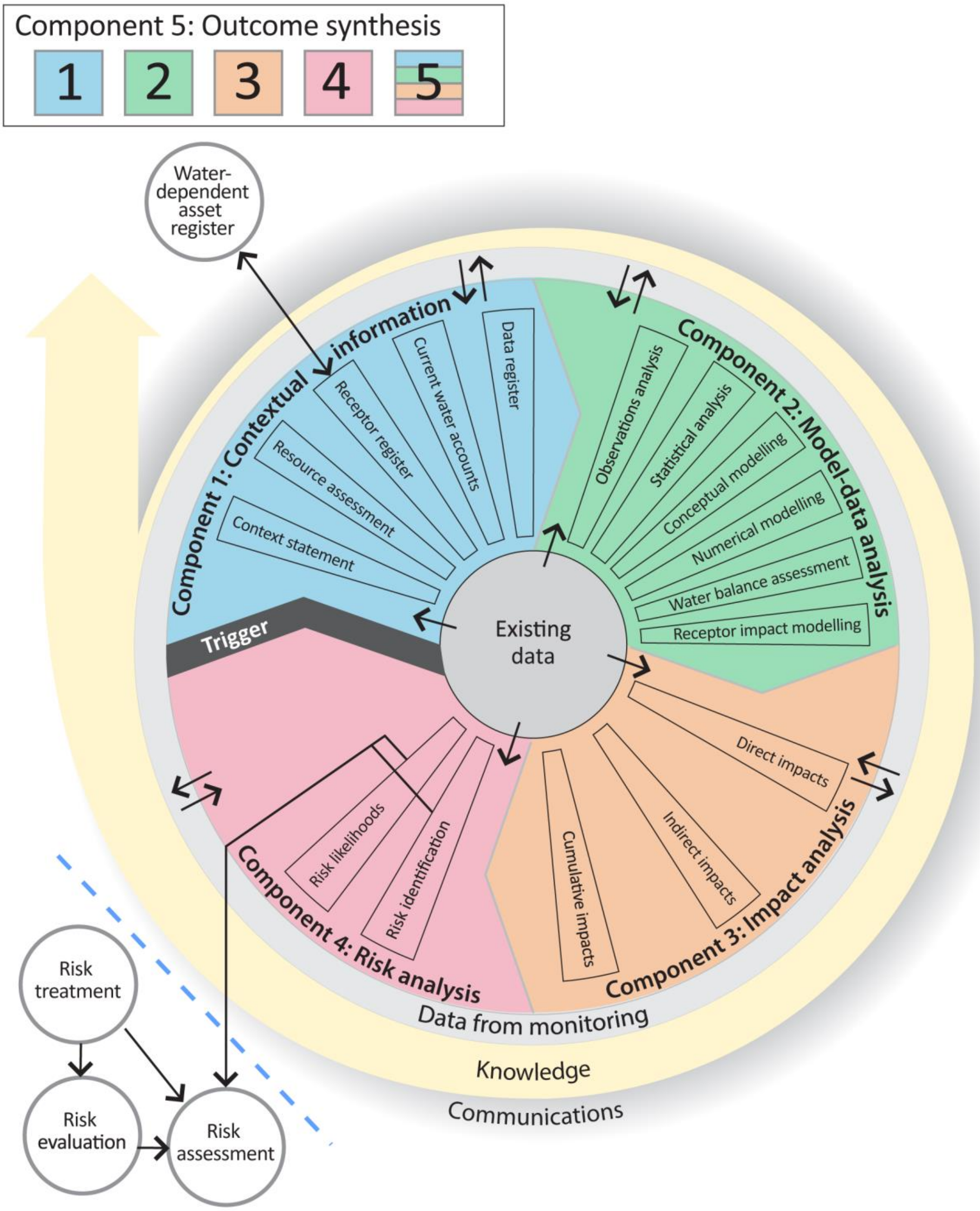


**Figure 1 Schematic diagram of the bioregional assessment methodology**

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.

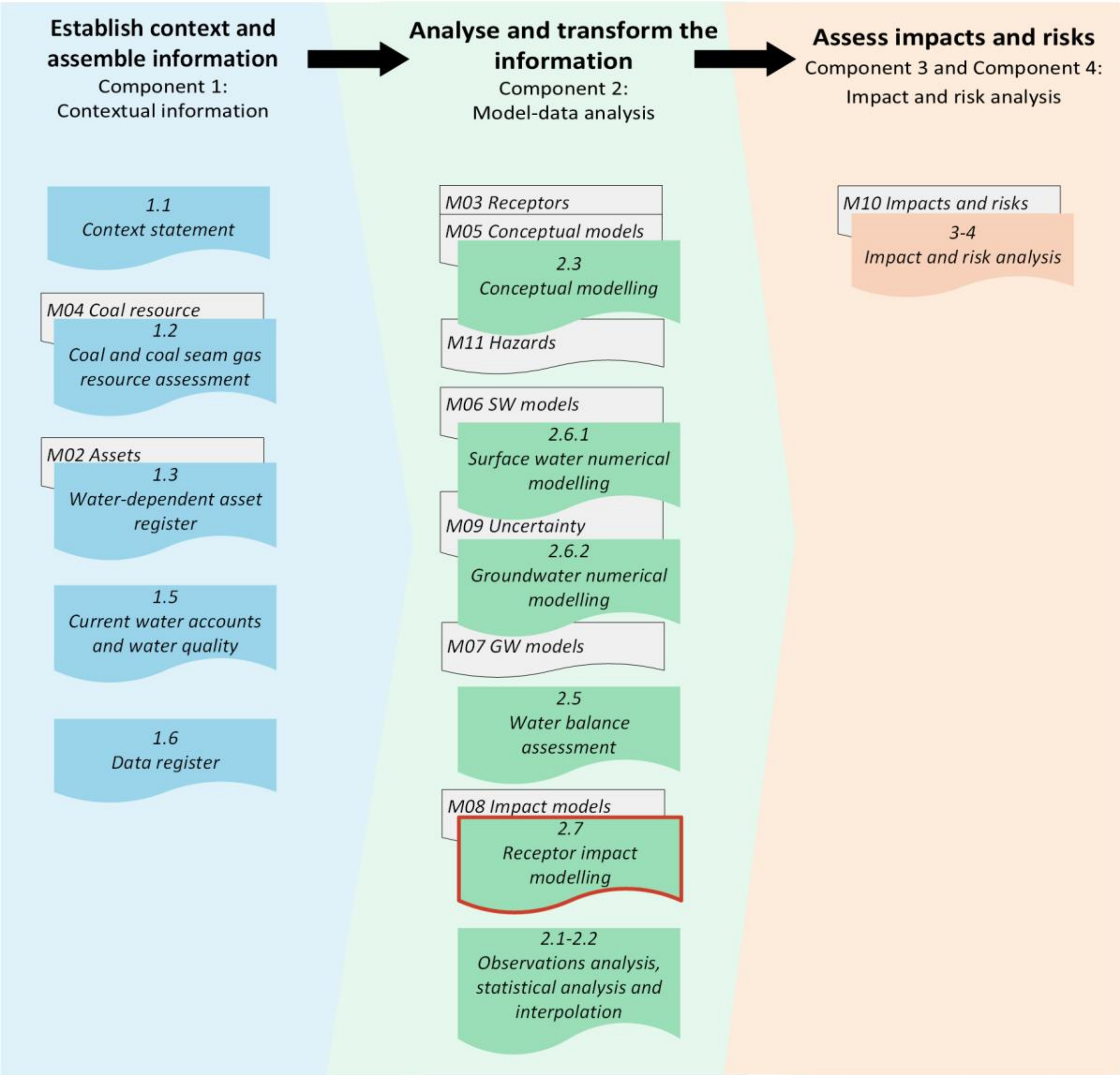


**Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment**

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

### *References*

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 5 June 2018, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 5 June 2018, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

# 2.7 Receptor impact modelling for the Galilee subregion

This product presents receptor impact modelling for the Galilee subregion using results from the model-data analysis (Component 2). Receptor impact models translate predicted changes in hydrology into the distribution of ecological outcomes that may arise from those changes. They perform an essential role in quantifying the potential impact on and risk to water-dependent ecosystems and assets due to coal resource development.

A receptor impact model predicts the relationship between:

- one or more hydrological response variables (hydrological characteristics of the system that potentially change due to coal resource development – for example, maximum groundwater drawdown due to additional coal resource development), and
- a 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, annual mean percent canopy cover of woody riparian vegetation).

Receptor impact models in a bioregion or subregion are developed for a landscape class, which is defined for bioregional assesment (BA purposes as an ecosystem with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. Only those landscape classes that fall within the zone of potential hydrological change are candidates for receptor impact models. Receptor impact variables are chosen as indicators of potential ecosystem change for landscape classes to simplify the analysis for a large number of assets and complexity of ecosystems across the subregion. An assessment of potential impact for a water-dependent asset, which is reported in the impact and risk analysis (product 3-4), considers the intersection of that asset with landscape classes, and the predictions of changes in receptor impact variables for those landscape classes, amongst other lines of evidence.

In receptor impact modelling the critical change is the difference between average groundwater and surface water conditions in the reference period (1983 to 2012), and their predicted average conditions under the baseline future and under the coal resource development pathway (CRDP) future.

BAs also consider impact on, and risk to, economic and sociocultural water-dependent assets; however, receptor impact models are not constructed for these assets. Potential impacts on water-dependent economic assets are assessed through availability of groundwater or surface water and against specific management thresholds, such as cease-to-pump flow rates and drawdown depths at which ‘make good’ provisions might apply. The assessment of potential impacts on sociocultural assets is limited to characterising the hydrological changes that may be experienced by those assets in the risk and impact analysis (product 3-4).

It is important to recognise that receptor impact model interpretation is often presented as statements that are a simple summary of the (often more complicated) relationship between a receptor impact variable and hydrological response variables. They are not impact or risk predictions for the Galilee subregion, which are presented in product 3-4 (impact and risk analysis), and should always be considered alongside other indicators of potential change.

## 2.7.1 Methods


### *Summary*

In bioregional assessments (BAs), receptor impact models are developed to characterise potential ecosystem changes that may result from hydrological changes predicted in response to coal resource development. A receptor impact model is constructed for one or more landscape classes (or landscape groups). A landscape class represents ecosystems with similar water dependencies that are expected to respond similarly to changes in groundwater and/or surface water. Only landscape classes that intersect the zone of potential hydrological change are considered as candidates for receptor impact models. Outside the zone, hydrological changes are considered too small to result in adverse impacts to water-dependent ecosystems.

The potential impacts of coal resource development on ecological assets are initially assessed using qualitative mathematical models. These models are elicited from independent experts and contain key components and processes of the landscape class ecosystems, and the hydrological variables that support them. They are then used to qualitatively predict (reported as increase, decrease or no change) how the landscape class ecosystem will respond to changes in hydrology that may occur as a result of coal resource development.

The receptor impact modelling process continues with the selection of receptor impact variables from the ecological components or processes identified in the qualitative mathematical model, and the hydrological response variables to represent the hydrological regimes that support these components or processes. Thus the landscape classification and qualitative mathematical models provide the framework for elicitations to quantify potential changes in receptor impact variables in response to changes in hydrological response variables for subsequent model predictions.

The elicitation process allows for the construction of a statistical model that predicts how changes in the hydrological response variables due to coal resource development will impact the receptor impact variables. Within a landscape class, this statistical model enables the BA team to quantify the risk to ecological assets from coal resource development using predicted changes in hydrological response variables in a short-term (2013 to 2042) and long-term (2073 to 2102) assessment period.

The receptor impact models predict the distribution function of the receptor impact variables for different futures (baseline and coal resource development pathway) and at specific assessment years (2042 and 2102). The distribution functions are summarised in BAs by a limited series of percentiles (or quantiles), nominally 5% increments between the 5th and 95th percentiles.


### *2.7.1.1 Background and context*

In BAs, receptor impact modelling attempts to capture the direct, indirect and cumulative impacts of coal seam gas (CSG) and coal mining development on the ecosystems that exist within landscape classes or landscape groups. The aim of receptor impact modelling is to convert the potentially abstract information about hydrological changes into quantities (risk assessment endpoints) that stakeholders care about and can more readily understand and interpret. In particular, the model outcomes are anticipated to relate more closely to stakeholder values and beliefs and therefore support community discussion and decision making about acceptable levels of development.

The causal pathways that describe how coal resource development may lead to changes in hydrology are identified in companion product 2.3 for the Galilee subregion (Evans et al., 2018). The receptor impact models generate predictions that represent the subsequent pathways which relate changes in hydrological response variables to potential impacts on water-dependent landscape classes and assets that occur within the zone of potential hydrological change.

To better understand the potential impacts of coal resource development on water resources and water-dependent assets such as wetlands and streams, receptor impact modelling for BAs deals with 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, including expansions of baseline operations, that are expected to begin commercial production after December 2012. In receptor impact modelling, however, the critical change is the difference between average groundwater and surface water conditions in the reference period (1983 to 2012), compared to predicted average conditions under the baseline and the CRDP in the short term (2013 to 2042) and longer term (2073 to 2102). As noted in companion product 2.3 for the Galilee subregion (Evans et al., 2018), the baseline future in the Galilee subregion does not have any coal resource development, as there were no commercially producing coal mines or CSG fields as at December 2012 (the baseline date).

This product presents the receptor impact modelling for the Galilee subregion. The modelling approach is described in detail in the companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018). Section 2.7.1.2 of this document describes how this methodology is applied to the Galilee subregion.

The following terms are used throughout the receptor impact model products to describe the modelling process and its results:

- *hydrological response variable* – a hydrological characteristic of the system (for example, drawdown or the annual flow volume) that potentially changes due to coal resource development (see companion submethodologies M06 (as listed in Table 1) on surface water modelling (Viney, 2016) and M07 on groundwater modelling (Crosbie et al., 2016))

- *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)
- *receptor impact model* – a receptor impact model predicts a relationship between a receptor impact variable (for example annual mean percent foliage cover of woody riparian vegetation), and one or more hydrological response variables (for example, *dmax*, the maximum groundwater drawdown due to additional coal resource development).

### 2.7.1.2 Receptor impact modelling for ecological water-dependent assets

In BA, receptor impact models for ecological water-dependent assets are conditioned upon, and therefore depend on, *landscape classes*. A landscape class is defined as an ecosystem with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. Each bioregion or subregion has multiple landscape classes that are aggregated into landscape groups. In the Galilee subregion, the receptor impact modelling is undertaken for landscape groups, rather than landscape classes, reflecting the advice from the external experts provided at various stages of the modelling process (Figure 3).

The workflow for ecological receptor impact modelling is outlined in Figure 3. Input from independent external ecology experts contributes to the workflow at three separate stages (denoted as stages 2, 3 and 5 in Figure 3), along with output from hydrological modelling (see companion product 2.6.1 (Karim et al., 2018) and companion product 2.6.2 (Peeters et al., 2018) for the Galilee subregion) and the expertise of the hydrology modellers. External experts, hydrologists and risk analysts contribute to the selection of hydrological response variables that are ecologically meaningful and are also able to be generated from the hydrological modelling.

The workflow shown in Figure 3 leads to the construction of a receptor impact model for a particular landscape group that predicts the response of a receptor impact variable to changes in hydrological response variables. The receptor impact models propagate the uncertainty in: (i) the effect of coal resource development on the hydrological response variables under the baseline and CRDP; and, (ii) the uncertainty in the receptor impact variable response to these hydrological changes across a landscape class or group.

#### 2.7.1.2.1 Identification of landscape classes that are potentially impacted

BAs identify landscape classes (or groups) that could potentially be impacted by coal resource development (Stage 1 in Figure 3) as those landscape classes that lie wholly or partially within the zone of potential hydrological change. The zone of potential hydrological change is presented in companion product 3-4 for the Galilee subregion (Lewis et al., 2018) as the union of the groundwater and surface water zones of potential hydrological change. In the Galilee subregion, the groundwater zone of potential hydrological change is defined (using a precautionary approach) as the area where there is a greater than 5% chance of exceeding 0.2 m of drawdown in the near-surface Quaternary alluvium and Cenozoic sediment aquifer (see companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018)). This unconfined aquifer is likely to support most of the groundwater-dependent ecosystems (GDEs) that occur in the zone, with the exception of some discharge springs.


**Figure 3 Outline of the ecological receptor impact workflow identifying (by stage) the contributions of external independent ecology experts, and hydrological modelling for the Galilee subregion**

In this figure the green boxes represent specific stages undertaken by the Assessment team in the overall receptor impact modelling process, the red boxes are the two external workshops and the blue boxes are external expert or modelling inputs. HRV = hydrological response variable, RIM = receptor impact model, RIV = receptor impact variable

The surface water zone of potential hydrological change is defined in a similarly conservative manner. The area contains those river reaches where a change in at least one of eight surface water hydrological response variables exceeds its specified threshold. For the three flux-based hydrological response variables – annual flow (AF), daily streamflow rate at the 99th percentile (P99) and interquartile range (IQR) – the threshold is a 5% chance of a 1% change in the variable. That is, if 5% or more of model runs show a maximum change in results under the CRDP of 1% relative to baseline. For four of the frequency-based hydrological response variables – high-flow days (FD), low-flow days (LFD), length of low-flow spell (LLFS) and zero-flow days (ZFD) – the threshold is a 5% chance of a change of 3 days per year. For the final frequency-based hydrological response variable (low-flow spells, LFS), the threshold is a 5% chance that the maximum difference in the number of low-flow spells between the baseline and CRDP futures is at least two spells per year (companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

Importantly, the zone of potential hydrological change is developed using a precautionary approach to assess those parts of the landscape where there is at least a 5% chance that hydrological changes may exceed specified thresholds for the modelled hydrological response variables (e.g. the relevant groundwater threshold is defined as a 5% chance of 0.2 m drawdown in the upper aquifer). These thresholds were developed using the expert judgement of the Assessment team, and allow for areas outside of the zone to be ruled out from potential impacts. The zone serves to identify those landscape classes (or groups) that should be taken to the next step of the receptor impact modelling methodology from those that should not, on the grounds that the latter are predicted to experience negligible (or insignificant) exposure to hydrological change due to coal resource development.

### 2.7.1.2.2 Qualitative mathematical modelling of landscape classes

BAs use qualitative mathematical models to describe landscape class ecosystems, and to predict (qualitatively) how coal resource development will directly and indirectly affect these ecosystems. Qualitative mathematical models were constructed in dedicated workshops, attended by a variety of experts familiar with these ecosystems and/or the Galilee subregion (Table 3; Stage 2 in Figure 3).

**Table 3 Professional affiliations of the external experts who participated in the Galilee subregion qualitative mathematical modelling (QMM) and receptor impact modelling (RIM) workshops**

| Organisation | Number of attendees at the QMM workshop | Number of attendees at the RIM workshop |
|---|---|---|
| Australian Department of the Environment and Energy | 2 | 2 |
| Bush Heritage | 1 | 0 |
| Canberra University | 1 | 0 |
| Edith Cowan University | 0 | 1 |
| Griffith University | 4 | 5 |
| James Cook University | 0 | 1 |
| Queensland Department of Natural Resources and Mines | 2 | 3 |
| Queensland Herbarium | 0 | 1 |
| University of New England | 1 | 1 |
| University of Technology Sydney | 1 | 1 |

In the workshop, ecological and hydrological experts were asked to describe how the key species and/or functional groups within the landscape group ecosystem interact with each other, and to identify the main physical processes that mediate or otherwise influence these interactions. During this process the experts were also asked to identify how key hydrological processes support the ecological components of the landscape class. The experts' responses were formally translated into qualitative mathematical models which enable the BA team to identify critical relationships and variables that will later become the focus of the quantitative receptor impact models.

Qualitative modelling proceeds from the construction and analysis of sign-directed graphs, or signed digraphs, which are depictions of the variables and interactions of a system. These digraphs are only concerned with the sign (+, –, 0) of the direct effects that link variables. For instance, the signed digraph in Figure 4 depicts a straight-chain system with a basal resource (R), consumer (C) and predator (P). There are two predator-prey relationships, where the predator receives a positive direct effect (i.e. nutrition, shown as a link ending in an arrow (→)), and the prey receives a negative direct effect (i.e. mortality, shown as a link ending in a filled circle (─•)). The signed digraph also depicts self-effects, such as density-dependent growth, as links that start and end in the same variable. In the example in Figure 4 these self-effects are negative.

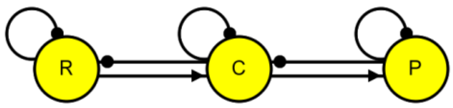


**Figure 4 Signed digraph depicting a straight-chain system with a basal resource (R), consumer (C) and predator (P)**

The structure of a signed digraph provides a basis to predict the stability of the system that it portrays, and also allows the analyst to predict the direction of change of all the model's variables (i.e. increase, decrease, no change) following a sustained change to one (or more) of its variables. The signed digraph in Figure 4, for example, is stable because: (i) it only has negative feedback cycles, (ii) the paths leading from the predators to their prey and back to the predator are negative feedback cycles of length two, and (iii) there are no positive (destabilising) cycles in the system. This model therefore predicts that if this system were to experience a disturbance it would be expected to return relatively quickly to its previous state or equilibrium.

The predicted direction of change of the variables within a signed digraph to a sustained change in one or more of its variables is determined by the balance of positive and negative effects through all paths in the model that are perturbed. Consider, for example, a pressure to the system depicted in Figure 4 that somehow supplements the food available to the predator P causing it to increase its reproductive capacity. The predicted response of C is determined by the sign of the link leading from P to C, which is negative (denoted as P ─• C). The predicted response of R will be positive because there are two negative links in the path from P to R (P ─• C ─• R), and their sign product is positive (i.e. – x – = +).

In the system depicted in Figure 4, the response of the model variables (P, C, and R) to a sustained pressure will always be unambiguous – the predictions are said to be completely sign determined. This occurs in this model because there are no multiple pathways between variables with opposite signs.

By way of contrast, the signed digraph depicted in Figure 5 is more complex because it includes an additional consumer and a predator that feeds on more than one trophic level. This added complexity creates multiple pathways with opposite signs between P and R.

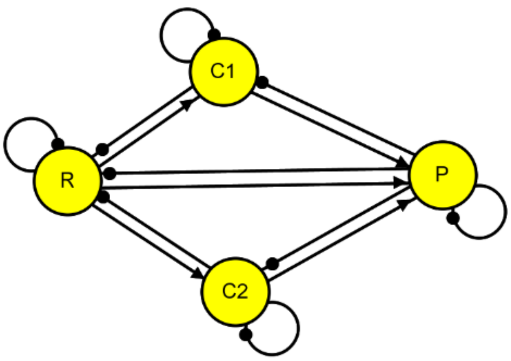


**Figure 5 Signed digraph depicting a more complex system containing an additional consumer and a predator that feeds on more than one tropic level**

Here the predicted response of R due to an input to P will be ambiguous, because there are now three paths leading from P to R, two positive (P —• C1 —• R, P —• C2 —• R) and one negative (P —• R). The abundance of the resource may therefore increase or decrease. This ambiguity can be approached in two ways. One is to apply knowledge of the relative strength of the links connecting P to R. If P was only a minor consumer of R, then R would be predicted to increase. Alternatively, if R was the main prey of P, and C1 and C2 amounted to only a minor portion of its diet, then R would be predicted to decrease in abundance.

In many cases, however, there is insufficient knowledge of the strength of the links involved in a response prediction. In these instances, Dambacher et al. (2003) and Hosack et al. (2008) described a statistical approach that estimates the probability of sign determinacy for each response prediction. In the Figure 5 example, with two positively signed paths and one negatively signed path, there is a net of one positive path (i.e. it is considered that a negatively signed path cancels a positively signed path) out of a total of three paths. According to this approach, in the system depicted in Figure 5, R is predicted to increase 77% of the time because of the ratio of the net to the total number of paths.

The ratio of the net to the total number of paths in a response prediction has been determined to be a robust means of assigning probability of sign determinacy to response predictions. These probabilities of sign determinacy can then be used to assess cumulative impacts that result from a perturbation to the system.

### 2.7.1.2.3 Choice of hydrological response variables and receptor impact variables

In BAs, qualitative mathematical models are used to represent how ecosystems will respond qualitatively (increase, decrease, and no change) to changes in the hydrological variables that support them. The models also provide a basis for identifying receptor impact variables and hydrological response variables that are the subject of the quantitative receptor impact models (Stage 3 in Figure 3).

The qualitative mathematical models identify a suite of ecologically important hydrological requirements (e.g. surface water flow characteristics) that support the landscape class ecosystem. These variables are sometimes expressed as hydrological regimes, for example an overbank flow regime premised on an average recurrence interval of once every three years. The hydrological components in these models are linked to the hazard analysis (companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016)) and provide the mechanism via which the coal resource development can adversely affect groundwater and surface water dependent ecosystems.

Hydrological response variables are derived from the numerical surface water and groundwater model results to represent ecologically important water requirements. The surface water modelling incorporates a mid-range climate projection and potential changes to precipitation. Further details on the climate scenario used are provided in companion product 2.6.1 for the Galilee subregion (Karim et al., 2018). The surface water hydrological response variables in the receptor impact models are defined in terms of mean annual values for two 30-year periods: 2013 to 2042 and 2073 to 2102 (e.g. mean number of low-flow days per year between 2013 and 2042). The hydrological response variables are generalised for the assessment extent and thus serve as indicators of change in ecologically important flows, rather than accurate characterisation of flow regimes at local scales. They differ from the hydrological response variables defined in companion product 2.6.1 for the Galilee subregion (Karim et al., 2018), which represent the maximum difference between the CRDP and baseline over the 90-year simulation period (e.g. the maximum difference in low-flow days per year between 2013 and 2102).

Receptor impact variables are selected according to the following criteria:

- *Is it directly affected by changes in hydrology?* These variables typically have a lower trophic level.
- *Is it representative of the broader landscape class?* Variables (or nodes) within the qualitative model that other components of that ecosystem or landscape class depend on will speak more broadly to potential impacts.
- *Is it something that expertise available can provide opinion on?* There is a need to be pragmatic and make a choice of receptor impact variable that plays to the strengths of the experts available.
- *Is it something that is potentially measurable?* This may be important for validation of the impact and risk analysis.
- *Will the choices of receptor impact variable for a landscape class resonate with the community?* This speaks to the communication value of the receptor impact variable.

Receptor impact variables are chosen as indicators of the response for a particular landscape class or group. Changes in the receptor impact variables (e.g. foliage cover) imply changes to the ecology of the landscape class or group. For example, a decrease in the projected foliage cover of a terrestrial GDE implies a reduction in the abundance and/or health of the trees that comprise that ecosystem. A receptor impact variable does not necessarily have to coincide with an ecological asset, as it may still represent a useful indicator of the overall response of a given asset or landscape class.

The goal of the receptor impact modelling workshop (Stage 5 in Figure 3) is to predict how a given receptor impact variable will respond at future time points to changes in the values of hydrological response variables, whilst acknowledging that this response may be influenced by the status and condition of the receptor impact variable in the reference year (2012). Response variables representing changes in water quality that might be expected to accompany changes in the relative contributions of surface runoff and groundwater inflow to streams are not included in the models or the elicitations. The decision to exclude variables related to water quality reflects the scope of the BAs (as reported in Section 3.1.2.2 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018)), with water quality considerations limited to salinity. Potential changes to surface water and groundwater salinity due to additional coal resource development are assessed qualitatively in this BA (see Section 3.4 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018)), with no salinity modelling undertaken. Further discussion about some of the implications of not including various water quality parameters in the receptor impact modelling process for this BA is provided in Section 2.7.7.2.

The elicitation generates subjective probability distributions for the expected value of the receptor impact variable under a set of hydrological scenarios that represent possible combinations of changes to hydrological response variables. These scenarios are the elicitation equivalent of a sampling design for an experiment where the aim is to maximise the information gain and minimise the cost. The same design principles therefore apply (Stage 4 in Figure 3).

It is essential to have an efficient design to collect the expert information, given the large number of receptor impact models, landscape classes, and bioregions and subregions to address within the operational constraints of the programme. The design must also respect, as much as possible, the predicted hydrological regimes as summarised by hydrological modelling outputs. Without this information, design points may present hydrological scenarios that are unrealistically beyond bounds suggested by the landscape class definition. Alternatively, insufficiently wide bounds on hydrological regimes lead to an overextrapolation problem when receptor impact model predictions are made conditional on hydrological simulations at the risk-estimation stage (Stage 6 in Figure 3). The design must further respect the feasibility of the design space, which may be constrained by mathematical relationships between related hydrological response variables. The design must accommodate the requirement to predict to past and future assessment years. The design must also allow for the estimation of potentially important interactions and nonlinear impacts of hydrological response variables on the receptor impact variable.

#### 2.7.1.2.4 Construction and estimation of receptor impact models

BAs address the question ‘How might selected receptor impact variables change under various scenarios of change for the hydrological response variables?’ through formal elicitation of expert opinion. This is a difficult question to tackle and presents a challenging elicitation task. BAs implement a number of processes that are designed to help meet this challenge: (i) persons invited to the receptor impact modelling workshops are selected based on the relevance of their domain expertise; (ii) all experts are provided with pre-workshop documents that outline the approach, the expectations on the participants, the characteristics of the landscape groups and subsequently the finalised qualitative models; and (iii) experts are given training on subjective probability, common heuristics and biases, together with a practice elicitation.

The elicitation proper follows a five-step procedure (described in detail in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)) that initially elicits fractiles, fits and plots a probability density function to these fractiles, and then checks with the experts if fractiles predicted by the fitted density are sufficiently close to their elicited values. This process is re-iterated until the experts confirm that the elicited and fitted fractiles, and the fitted lower (10th) and upper (90th) fractiles, provide an adequate summary of their opinions for the elicitation scenario concerned.

The experts' responses to the elicitations are treated as data inputs into a Bayesian generalised linear model (Stage 6 in Figure 3; see companion submethodology M08 (as listed in Table 1) (Hosack et al., 2018)). The model estimation procedure allows for a wide variety of possible model structures that can accommodate quadratic responses of receptor impact variables to changes in hydrological response variables, and interactive (synergistic or antagonist) effects between hydrological response variables. The procedure uses a common model selection criterion (the Bayesian Information Criterion) to select the model that most parsimoniously fits the experts' response to the elicitation scenarios.

### 2.7.1.2.5 Receptor impact model prediction

This stage (Stage 7 in Figure 3) applies the receptor impact model methodology to predict the response of the receptor impact variables. The general framework allows for the receptor impact model to be applied either at single or multiple receptor locations. The receptor impact model can therefore be applied at multiple receptor locations that are representative of a landscape class within a bioregion or subregion. The primary endpoint considered, however, is predicting receptor impact variable response to the BA future across an entire landscape class, which is accomplished by including all receptors that represent the hydrological characteristics of the landscape class. The uncertainty from the hydrology modelling is propagated through the receptor impact model at each receptor location to provide the predicted distribution of the receptor impact variable at different time points for the two futures considered by BA (baseline and CRDP). The uncertainties are then aggregated to give the response across the entire landscape group. Companion submethodology M09 (Peeters et al., 2016; as listed in Table 1) provides further details on how uncertainty is propagated through the models.

Integrating across the receptors produces the overall predicted response of the receptor impact variable for the landscape class given the choice of the BA future. These landscape class results are summarised in companion product 3-4 for the Galilee subregion (Lewis et al., 2018). Importantly though, the results do not replace the need for detailed site- or project-specific studies, nor should they be used to pre-empt the results of detailed studies that may be required under state and/or Commonwealth legislation. Detailed site studies may give differing results due to variations and approaches in the scale and type of modelling used.

### 2.7.1.2.6 Receptor impact modelling assumptions and implications

The receptor impact modelling methodology (companion submethodology M08 (as listed in Table 1) (Hosack et al., 2018)) and its implementation was affected by design choices that have been made within BA. Some of these broader choices are described in companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018).

Table 4 summarises some of the assumptions made for the receptor impact modelling, the implications of those assumptions for the results, and how those implications are acknowledged through the BA products.

**Table 4 Summary of the receptor impact modelling assumptions, their implications, and their acknowledgement in the bioregional assessment of the Galilee subregion**

| Assumption of receptor impact modelling | Implications | Acknowledgement |
|---|---|---|
| Segregation of continuous landscape surface | • Provided a defined spatial scope for experts to focus upon<br>• Connections between landscape classes may be broken (i.e. connectivity is ignored)<br>• Changes in one landscape class may have implications for adjacent landscape classes. | • Identified potential connections between landscape classes where possible in the impact and risk product. Some qualitative mathematical models do include links to nearby landscape classes. |
| Data underpinning landscape classes (omissions / incorrect attribution) | • Landscape class definition required data input from pre-existing data sources<br>• Prioritisation for qualitative mathematical models and receptor impact models may be affected<br>• Minimal effect on model development expected for receptor impact models. | • Acknowledged issues with data in companion product 3-4 for the Galilee subregion (Lewis et al., 2018), and also in companion product 2.3 for the Galilee subregion (Evans et al., 2018). While there are always likely to be some limitations for any dataset applied in BAs, the data used to develop the Galilee landscape classification were assessed as being the most appropriate data for this purpose (further information about these datasets is in Section 2.3.3 of product 2.3 for the Galilee subregion (Evans et al., 2018)<br>• In companion product 3-4 for the Galilee subregion (Lewis et al., 2018) acknowledged that mapped results reflect the mapped inputs. |
| Areas of landscape classes are constant over modelling period | • Provided a defined spatial scope for experts to address<br>• BA is about identifying existing areas that are at risk from coal resource development as opposed to predicting the changes in areal extent or transition to different landscape classes. Some potential for changes in the area of the landscape class to affect its sensitivity to hydrological change but would need to be assessed on an asset by asset basis. | • Acknowledged in Methods section of this product |

| Assumption of receptor impact modelling | Implications | Acknowledgement |
|---|---|---|
| Other developments and users of water (e.g. agriculture) are held constant over the time of the simulation period | • Provided a defined context for experts to consider<br>• BA is focused on identifying existing areas that are at risk from coal resource development, as opposed to predicting the changes due to other developments or the relative attribution. | • Acknowledged in Methods section of this product |
| Landscape characteristics other than hydrological variables are not represented in quantitative receptor impact models | • Refined scope for experts to consider how receptor impact models were associated with hydrological variables that could be provided by hydrological models developed by BA. The absence of water quality variables is a noted limitation<br>• Loss of within-landscape class predictive performance from the receptor impact models. | • Identified as knowledge gaps when the hydrological response variables used in the model represent a subset of the key dependencies.<br>• Acknowledged importance of local (vs regional) scale of analyses where the main concern is for particular parts of a landscape class. |
| Selection of experts, limited expert availability, and impact on represented domain knowledge and expertise | • Experts provided domain expertise and experience that informed both model structure and provided quantifiable predictions of the response of receptor impact variables to novel hydrological scenarios<br>• Expert availability affected the quality/utility of the qualitative mathematical model<br>• Identification of receptor impact variables that reflect expertise of those at each receptor impact modelling workshop. | • Acknowledged that the receptor impact variable is an 'indicator' of the potential ecosystem response<br>• Identified as a knowledge gap where part of the landscape class is not represented. |
| Simplification of complex systems | • Provided formal approach to model identification and selection of candidate receptor impact variables<br>• Not all components and relationships are represented by receptor impact models. | • Acknowledged that one or two receptor impact variables can underestimate complex ecosystem function<br>• Experts specifically consider system heterogeneity within landscape groups during elicitation process<br>• Make assumptions clear<br>• High-level interpretation of results<br>• Emphasise importance of interpreting the hydrological change. |
| The common set of modelled hydrological response variables are used across each landscape class | • Refined scope for experts to how receptor impact models were associated with hydrological variables that could be provided by hydrological models developed by BA<br>• Enables some simplification of complex systems<br>• Loss of local specificity in predictions of receptor impact variables. | • Identified the need for local-scale information (in multiple places) |

| Assumption of receptor impact modelling | Implications | Acknowledgement |
|---|---|---|
| Receptor impact variable selection (assumption that receptor impact variable is good indicator of ecosystem response) | • Qualitative mathematical models informed the selection of receptor impact variables within the additional constraints imposed by expert availability given project timelines<br>• Focus on the quantified relationships within the landscape class. | • Identified the need for local-scale information (in multiple places) |
| Extrapolation of predictions beyond elicitation scenarios | • Ranges of hydrological scenarios to be considered at the expert elicitation sessions were informed by preliminary hydrological modelling output and hydrological expert advice within BA<br>• Final model results sometimes extended beyond this preliminary range due to necessary changes in underlying hydrological modelling assumptions and assimilation of data<br>• Extrapolation beyond the range of hydrological response variables considered by the expert elicitation increases uncertainty in receptor impact variable predictions. | • Identified as a limitation for the appropriate landscape class in companion product 3-4 for the Galilee subregion (Lewis et al., 2018) where this occurs |
| Qualitative mathematical models focus on impacts of long-term sustained hydrological changes (press perturbations) to ecosystems. The quantitative receptor impact models can and do account for pulse perturbations and associated responses, where experts were free to include direct and indirect effects as well as pulse and press perturbations within their assessments. | • Qualitative mathematical models may not accurately represent impacts of shorter-term hydrological changes (pulse perturbations) on ecosystems and landscape classes. | • Described rationale for the focus on press perturbations in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)<br>• Noted that many potential pulse perturbations are caused by accidents and managed by site-based processes<br>• Identified as a limitation or knowledge gap<br>• Noted that quantitative receptor impact models account for pulse perturbations. |

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## 2.7.2 Overview


### *Summary*

Landscape groups that intersect the zone of potential hydrological change for the Galilee subregion could potentially be impacted by changes to groundwater and/or surface water systems due to the additional coal resource development. All 11 of the landscape groups in the Galilee subregion have one or more landscape classes that occur within the zone.

Of the 11 landscape groups in the Galilee subregion, most (73%) of the zone of potential hydrological change supports 'Dryland' (8134 $km^2$) or 'Floodplain, non-wetland' (2098 $km^2$) landscape groups. These landscape groups depend on incident rainfall and localised runoff and as such are not considered to be water dependent for the purposes of the BA. These two landscape groups are considered to be *very unlikely* to be impacted by changes in hydrology due to coal resource development.

Four of the remaining landscape groups cover very small areas within the zone of potential hydrological change and are not further assessed within this product. These landscape groups are 'Floodplain, disconnected wetland' that covers about 19 $km^2$ (0.1% of the zone), 'Floodplain, wetland groundwater-dependent ecosystem (GDE)' that covers about 153 $km^2$ (1% of the zone), 'Non-floodplain, disconnected wetland' that covers about 3.6 $km^2$ (0.02% of the zone) and 'Non-floodplain, wetland GDE' that covers 0.2 $km^2$ (<0.01% of the zone).

The remaining five landscape groups represent the ecosystems that were the focus for the impact and risk assessment of the Galilee subregion. These potentially impacted landscape groups include 'Springs', 'Floodplain, terrestrial GDE', and 'Non-floodplain, terrestrial GDE'. In addition, the landscape groups 'Streams, GDE' and 'Streams, non-GDE' were combined for the purposes of the receptor impact modelling and are considered further in this product as the 'Streams landscape group'.

Qualitative mathematical models and receptor impact models were built for the potentially impacted landscape groups. Four receptor impact models were developed, representing four of the landscape groups. In addition, 12 qualitative mathematical models were developed for the five landscape groups. One landscape group, 'Springs', only had qualitative mathematical models built, as it was not possible to develop a receptor impact model.


### *2.7.2.1 Introduction*

The next four sections in this product (Section 2.7.3 to Section 2.7.6, inclusive) focus on the five landscape groups that are considered during subsequent stages of the bioregional assessment (BA) for the Galilee subregion. The purpose of the current section is to provide the rationale for the choice of landscape groups that have been selected for the impact and risk analysis, and to describe the modelling undertaken for each of these groups.

The landscape classification for the assessment extent of the Galilee subregion identified 31 landscape classes that were aggregated into 11 broad landscape groups (see Section 2.3.3 of companion product 2.3 for the Galilee subregion (Evans et al., 2018)). Once the zone of potential hydrological change was developed for the Galilee subregion (as outlined in companion product 3-4 (Lewis et al., 2018)) it was used to (i) identify ecological landscape classes (and the aggregated landscape group) that intersect it and are potentially impacted by the modelled hydrological changes due to additional coal resource development, and (ii) rule out landscape classes that do not intersect the zone and are therefore considered *very unlikely* (less than 5% chance) to be impacted by changes in hydrology. Qualitative mathematical models and receptor impact models were developed only for those landscape groups that are potentially impacted (i.e. occur within the zone of potential hydrological change).

#### 2.7.2.2 Potentially impacted landscape groups

Of the 11 landscape groups that occur in the Galilee subregion, most (73%) of the zone of potential hydrological change supports 'Dryland' (8134 $km^2$) or 'Floodplain, non-wetland' (2098 $km^2$) landscape groups. These landscape groups depend on incident rainfall and localised runoff and as such are not considered to be water dependent for this assessment. Consequently, these two landscape groups are considered to be *very unlikely* to be impacted by changes in hydrology due to coal resource development.

Each of the nine remaining landscape groups is considered to be water dependent. By area or length, the major water-dependent landscape groups in the zone of potential hydrological change are 'Floodplain, terrestrial GDE' that covers 2433 $km^2$ (17% of the zone) and 'Non-floodplain, terrestrial GDE' that covers 1189 $km^2$ (8% of the zone). Groundwater-dependent streams in the zone are classified as 'Streams, GDE' and cover 2801 km (45% of streams in the zone). In comparison, streams that are not dependent on groundwater – 'Streams, non-GDE' – cover 3484 km (55% of streams in the zone) (Table 5). The 'Streams, GDE' and 'Streams, non-GDE' landscape groups were combined and are considered further here as the 'Streams landscape group'.

Springs and their associated wetlands, although small in area, are considered here to be a major landscape group in the zone of potential hydrological change of the Galilee subregion. There are 200 springs and spring complexes within the zone.

The remaining four water-dependent landscape groups were not prioritised for qualitative mathematical modelling and receptor impact modelling given the logistical constraints of the workshops. These landscape groups are 'Floodplain, disconnected wetland' that covers about 19 $km^2$ (0.1% of the zone), 'Floodplain, wetland GDE' that covers about 153 $km^2$ (1% of the zone), 'Non-floodplain, disconnected wetland' that covers about 3.6 $km^2$ (0.02% of the zone) and 'Non-floodplain, wetland GDE' that covers 0.2 $km^2$ (<0.01% of the zone) (Table 5). These landscape groups cover very small areas within the zone of potential hydrological change, and are expected to respond consistently to the modelled landscape groups, though this obviously would need to be confirmed through more detailed assessment. These landscape groups are not reported separately in this product.

Table 5 lists the landscape groups that occur within the zone of potential hydrological change of the Galilee subregion. It also details whether qualitative mathematical models were built for that landscape group and whether one or more receptor impact models were built.

**Table 5 Summary of landscape groups developed for the bioregional assessment of the Galilee subregion**

| Landscape group | Length, area or number | Extent in assessment extent[a] | Extent in zone of potential hydrological change | Qualitative mathematical model | Receptor impact model |
|---|---|---|---|---|---|
| Dryland | Area ($km^2$) | 419,657 | 8,134 | No | No |
| Floodplain, disconnected wetland | Area ($km^2$) | 6,558 | 19 | No | No |
| Floodplain, non-wetland | Area ($km^2$) | 72,016 | 2,098 | No | No |
| Floodplain, terrestrial GDE | Area ($km^2$) | 79,229 | 2,433 | Yes – 'Floodplain, terrestrial GDE' signed digraph model ×4 | Yes – 'Response of woody vegetation to changes in flow regime and groundwater' |
| Floodplain, wetland GDE | Area ($km^2$) | 4,948 | 153 | No | No |
| Non-floodplain disconnected wetland | Area ($km^2$) | 8,784 | 3.6 | No | No |
| Non-floodplain, terrestrial GDE | Area ($km^2$) | 20,800 | 1,189 | Yes – 'Non-floodplain, terrestrial GDE' signed digraph model ×2 | Yes – 'Response of woody vegetation to changes in groundwater' |
| Non-floodplain, wetland GDE | Area ($km^2$) | 259 | 0.2 | No | No |
| **Total area of landscape groups ($km^2$)** | | **612,251** | **14,030** | | |
| Streams, GDE | Length (km) | 48,538 | 2,801 | Yes – 'Streams' signed digraph model ×2 | Yes – 'Response of woody riparian vegetation to changes in flow regime and groundwater' |
| Streams, non-GDE | Length (km) | 344,916 | 3,484 | Yes – 'Streams' signed digraph model ×2 | Yes – 'Response of aquatic nymphs of *Offadens* sp. (type of mayfly) to changes in flow regime' |
| **Total length of streams (km)** | | **393,454** | **6,285** | | |
| Springs | Number | 1,559 | 200 | Yes – 'Springs' signed digraph model ×2 | No |

[a]Extent of each landscape group is either an area of land ($km^2$), length of stream network (km) or number of springs (number).
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 1)

In total, four receptor impact models were built, representing four landscape groups ('Floodplain, terrestrial GDE', 'Non-floodplain, terrestrial GDE', 'Streams, GDE' and 'Streams, non-GDE'). In addition, 12 qualitative mathematical models were built covering five landscape groups. One landscape group, 'Springs', had qualitative mathematical models built without having a receptor impact model (Table 5). Details of the qualitative mathematical models and receptor impact models are provided for each landscape group separately in Section 2.7.3, Section 2.7.4, Section 2.7.5 and Section 2.7.6, while the results from modelling the effects of coal resource development on landscape groups using these models are presented in Section 3.4 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018).

#### *2.7.2.3 'Springs' landscape group*

Within the zone of potential hydrological change for the Galilee subregion, there are 200 springs or spring complexes (Table 5). These are all placed in a single landscape class within the 'Springs' landscape group. The main clusters of springs/spring complexes are described in Section 2.7.3.

Two qualitative mathematical models were developed that describe the general dynamics of the aquatic communities associated with springs in the 'Springs' landscape group. The two models differ in that one considers that benthic algae respond to an increase in water depth whereas the other model considers that benthic algae do not respond to this variable.

No receptor impact model was developed for the 'Springs' landscape group, as there were insufficient available data to model the response of springs to groundwater drawdown in this part of the Galilee subregion.

#### *2.7.2.4 Streams landscape groups*

The total length of stream landscape classes within the zone of potential hydrological change is 6285 km. Of this length, 45% are 'Streams, GDE', which are considered to be groundwater dependent. All four of the landscape classes within this group occur in the zone. The remaining 55% are 'Steams, non-GDE'. The latter category is considered to be predominantly rainfall dependent. Four of the six landscape classes within this group occur in the zone. The exceptions are the two estuarine stream classes 'Near-permanent, estuarine stream' and 'Temporary, estuarine stream' which only occur outside of the zone of potential hydrological change and thus are *very unlikely* to be impacted by coal resource development.

For the purposes of qualitative and quantitative modelling, these two landscape groups were merged to produce a single composite landscape group category – Streams. Initially, during the qualitative modelling workshop a separate modelling effort was conducted for both temporary and permanent stream systems; however, after completion of a model for temporary streams in a flowing state the various external experts concluded that the essential dynamics of both systems could be adequately addressed by the same model.

Two qualitative mathematical models were developed that describe the general dynamics of the aquatic community associated with the streams landscape groups. The two models differ in the relationship between surface water and near-surface (shallow) groundwater. Specifically, an uncertain link in the modelling process was the degree to which stores of near-surface groundwater could contribute to surface water that enters the stream channel. This uncertainty led to the development of two alternative models, one with and one without a link from near-surface groundwater to surface water.

Two receptor impact models were developed based on expert elicitation during the quantitative modelling workshops. The first model examined the response of woody riparian vegetation to changes in flow regime and groundwater. Therefore, the model is applicable to streams where both surface water and groundwater are key hydrological components. The model is therefore relevant to the 'Streams, GDE' landscape group. This model used annual mean percent foliage cover of the woody riparian vegetation as the receptor impact variable.

The second model examined the response of high-flow macroinvertebrates to changes in flow regime. High-flow macroinvertebrates were represented by a mayfly species in the genus *Offadens*, for which data were available for streams outside the zone of potential hydrological change but within the broader Burdekin river basin. These data informed the expert elicitation process. This model is applicable to streams where surface water is the key hydrological component (i.e. it is relevant to the 'Streams, non-GDE' landscape group). The receptor impact variable was the annual mean density of the mayfly species, three months after the end of the wet season.

### *2.7.2.5 'Floodplain, terrestrial GDE' landscape group*

The 'Floodplain, terrestrial GDE' landscape group consists of two landscape classes. Of these, the zone of potential hydrological change contains 2358 $km^2$ of 'Terrestrial GDE, remnant vegetation' and 75.2 $km^2$ of non-remnant 'Terrestrial GDE'.

Four qualitative mathematical models were developed for the 'Floodplain, terrestrial GDE' landscape group. The models focused on the influence of surface water and groundwater hydrology on trees that support a woodland community, and create local conditions and a microclimate (i.e. shade, leaf litter and soil moisture) that favours mesic vegetation and suppresses xeric vegetation. During the process of developing the models at the qualitative modelling workshop, debate surrounded the role of deep-rooted trees in drawing groundwater to the surface where it can become available for shallow-rooted mesic vegetation. The strength or existence of this effect was deemed to be uncertain. Seasonal floods are generally shown to suppress xeric vegetation in the floodplain and to favour trees and other mesic species. Seasonal floods are important contributors to groundwater recharge, but excessive groundwater recharge could potentially contribute to saturated soil conditions where an anoxic root zone suppresses deep-rooted vegetation (i.e. trees connected to groundwater and mesic non-tree deep rooted vegetation). However, it is uncertain whether these floodplains could develop anoxic soil conditions, and thus the existence of this link was also uncertain. Four alternative models were developed to address the uncertainty for the links associated with trees drawing groundwater to the surface and the potential for groundwater to contribute to anoxic soils.

A single receptor impact model was developed based on expert elicitation during the quantitative modelling workshops. The model examined the response of woody vegetation to changes in flow regime and groundwater, thus indicating the dual influences of surface water and groundwater on this landscape group. The model used the annual mean percent foliage cover of woody vegetation as the receptor impact variable.

### *2.7.2.6 'Non-floodplain, terrestrial GDE' landscape group*

The 'Non-floodplain, terrestrial GDE' landscape group consists of two landscape classes. Of these two classes, most of the landscape group within the zone of potential hydrological change is classed as remnant vegetation. Specifically, 'Non-floodplain, terrestrial GDE, remnant vegetation' occupies an area of about 1184 $km^2$ within the zone, whereas 'Non-floodplain, terrestrial GDE' occupies about 5.5 $km^2$.

Two relatively simple signed digraph models were developed during the qualitative modelling workshop for the vegetative community associated with the 'Non-floodplain, terrestrial GDE' landscape group. The models focused on recruitment dynamics associated with groundwater-dependent native tree species. The primary production from trees provides a range of ecosystem services such as food and shelter for fauna. There was uncertainty in the extent to which native trees benefited native non-groundwater-dependent vegetation (i.e. canopy microclimate) or suppressed invasive non-groundwater-dependent vegetation. This uncertainty led to the development of two alternative signed digraph models. The models differed in that one featured connectivity between recruitment and invasive non-groundwater vegetation and between full canopy and both invasive non-groundwater vegetation and native non-groundwater vegetation. The other model did not have these links.

A single receptor impact model was developed based on expert elicitation during the quantitative modelling workshop. The model recognised groundwater as the key hydrological component for the 'Non-floodplain, terrestrial GDE' landscape group. The receptor impact model examined the response of woody vegetation to changes in groundwater. The model used the annual mean percent foliage cover of the woody vegetation as the receptor impact variable.

### *2.7.2.7 Outline of content in the following landscape group sections*

Section 2.7.3 to Section 2.7.6 of this product focus, respectively, on each of the four main landscape groups potentially impacted by coal resource development in the Galilee subregion. After the summary of baseline information, each section details the qualitative mathematical modelling that was undertaken. The qualitative modelling component includes the development of signed digraph models of key ecosystem components, a summary of cumulative impact scenarios and calculation of predicted responses of the signed digraph variables in each of the models to changes in hydrological response variables. Each section then describes the receptor impact modelling, if undertaken, detailing the elicitation scenarios that were presented to the experts at the workshops and the receptor impact models developed.

The details provided in this product on the ecology of the landscape groups together with results of qualitative mathematical modelling and receptor impact modelling are in effect an appendix of information that is used in the impact and risk analysis of the BA for the Galilee subregion (companion product 3-4 (Lewis et al., 2018)).

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## *Datasets*

Dataset 1 Bioregional Assessment Programme (2017) GAL Impact and Risk Analysis Database 20170630 v01. Bioregional Assessment Derived Dataset. Viewed 17 July 2017, http://data.bioregionalassessments.gov.au/dataset/3dbb5380-2956-4f40-a535-cbdcda129045.

## 2.7.3 ‘Springs’ landscape group


***Summary***

The ‘Springs’ landscape group contains springs of two types: recharge (also referred to as ‘outcrop’) springs and discharge springs. Recharge springs typically occur in topographically elevated areas. The source aquifers are unconfined, with groundwater draining under gravity or where the saturated aquifer intersects the ground surface. In contrast, discharge springs originate from aquifers under confined pressure, or form where the confining bed (aquitard) is weakened or thin, or where the aquifer is disrupted by faults, folds or basement rocks. Water is brought to the surface under artesian pressure. At the surface, the discharge spring is commonly mounded and there is moisture accumulation around the vent. Discharge springs are located remote from their recharge zones.

The Lake Eyre Basin Springs Assessment Project recognised three geographical clusters of springs that occur within the zone of potential hydrological change of the Galilee subregion, and these may potentially be impacted by the additional coal resource development. From north to south these are: (i) the Doongmabulla Springs complex, (ii) a series of springs that overlie the Colinlea Sandstone or Joe Joe Group, which are geological units of Permian age (hereafter referred to as the ‘Permian springs cluster’), and (iii) a series of springs associated with Triassic geological units (hereafter referred to as the ‘Triassic springs cluster’). The physical environment of these three spring clusters is described in this section, focusing on the geographic location of springs/spring clusters, vegetation assemblages, flora and fauna at the species level (with a focus on endemicity and threatened species), and hydrological regimes and connectivity.

A qualitative mathematical model is presented for the ‘Springs’ landscape group. This includes two signed digraphs showing key components of the spring ecosystems. In these models, experts considered that the critical factor in preserving the aquatic communities associated with springs is the rate of groundwater flow that maintains a damp or submerged state in the spring. An increase in water depth above this threshold supports a wetted-area regime around the perimeter and downstream of the spring that is beneficial to emergent vegetation, the building of peat mounds, tail vegetation (i.e. vegetation at the outfall or tail end of a spring) and groundwater-dependent vegetation. Within the free-water area of a spring, an increase in surface water depth supports an increase in primary production (i.e. phytoplankton, macrophytes and benthic algae), and increases habitat for aquatic grazers.


### *2.7.3.1 Description*

#### 2.7.3.1.1 Overview

The ‘Springs’ landscape group contains a single landscape class (‘Springs’; see Section 2.3.3 in companion product 2.3 for the Galilee subregion (Evans et al., 2018b)). Within the zone of potential hydrological change, the springs that comprise this landscape group occur mainly in the central and western parts of the zone (Figure 6). There are two main types of springs defined within this landscape group: recharge (also referred to as ‘outcrop’) springs and discharge springs

(Figure 7). Section 2.3.2.2.2.3 in companion product 2.3 for the Galilee subregion (Evans et al., 2018b) provides a detailed conceptualisation of the groundwater flow systems that contribute to both spring types.

In the Galilee subregion, recharge springs are typically associated with topographically elevated areas, such as along the eastern margin of the Eromanga Basin where major aquifers of the Great Artesian Basin (GAB) outcrop. For this spring type, the aquifer is largely unconfined, and groundwater flow occurs away from topographically high areas, discharging near to where the ground surface intersects with a saturated aquifer. As a consequence, recharge springs may be strongly influenced by rainfall events and can exhibit dynamism in flow in response to recent rainfall (Fensham et al., 2016). Groundwater flow paths for recharge springs are thought to be relatively short and associated with shallow, local-scale groundwater systems (Figure 7).

In contrast to recharge springs, the source aquifers for discharge springs tend to be regional-scale confined aquifer systems with longer groundwater flow paths (Figure 7). Discharge springs originate from aquifers that are largely confined and under pressure, and form in areas where the confining bed or aquitard is weakened or thin, or where groundwater flow is disrupted by faults, folds or some other flow barrier such as a change in rock type (e.g. associated with geological basement rocks). In these aquifers groundwater typically has a longer residence time compared to groundwater that occurs in source aquifers for recharge springs. Unlike recharge springs, discharge springs are generally located remote from their recharge zones.

At the surface, discharge springs are commonly mounded with moisture accumulation around the vent. In contrast to recharge springs, the water flow of discharge springs is disconnected from the local rainfall regime. However, the size of the wetland area surrounding a spring is influenced by seasonal conditions and may fluctuate, for example, between the dry and wet seasons. Another feature of some discharge springs is the presence of salt scalds (Fensham et al., 2016). These form in areas surrounding spring wetlands due to the precipitation of salts (including carbonates) when the discharged groundwater evaporates. In arid regions, salt scalds are accentuated because of the absence of flushing by overland flow.

The three geographic clusters of springs that occur within the zone of potential hydrological change of the Galilee subregion were all previously recognised and described as part of the work presented in the Lake Eyre Basin Springs Assessment (Fensham et al., 2016). This is one of a series of research projects funded by the Department of the Environment and Energy as part of the broader Bioregional Assessment Programme. From north to south these spring clusters are: (i) the Doongmabulla Springs complex, (ii) a series of springs that overlie either the Colinlea Sandstone or the Joe Joe Group, which are geological units of Permian age (hereafter referred to as the 'Permian springs cluster'), and (iii) a series of springs associated with Triassic geological units (hereafter referred to as the 'Triassic springs cluster'). The assessment that follows in this section covers each of the three geographic clusters separately as there are important differences between them. The Barcaldine Springs supergroup in the Lake Eyre Basin Springs Assessment Project (Fensham et al., 2016) includes springs associated with GAB recharge beds around the margin of the Eromanga Basin and the Doongmabulla Springs complex. The Permian and Triassic springs clusters are separate entities and are not recognised as part of the Barcaldine Springs supergroup (Figure 8).

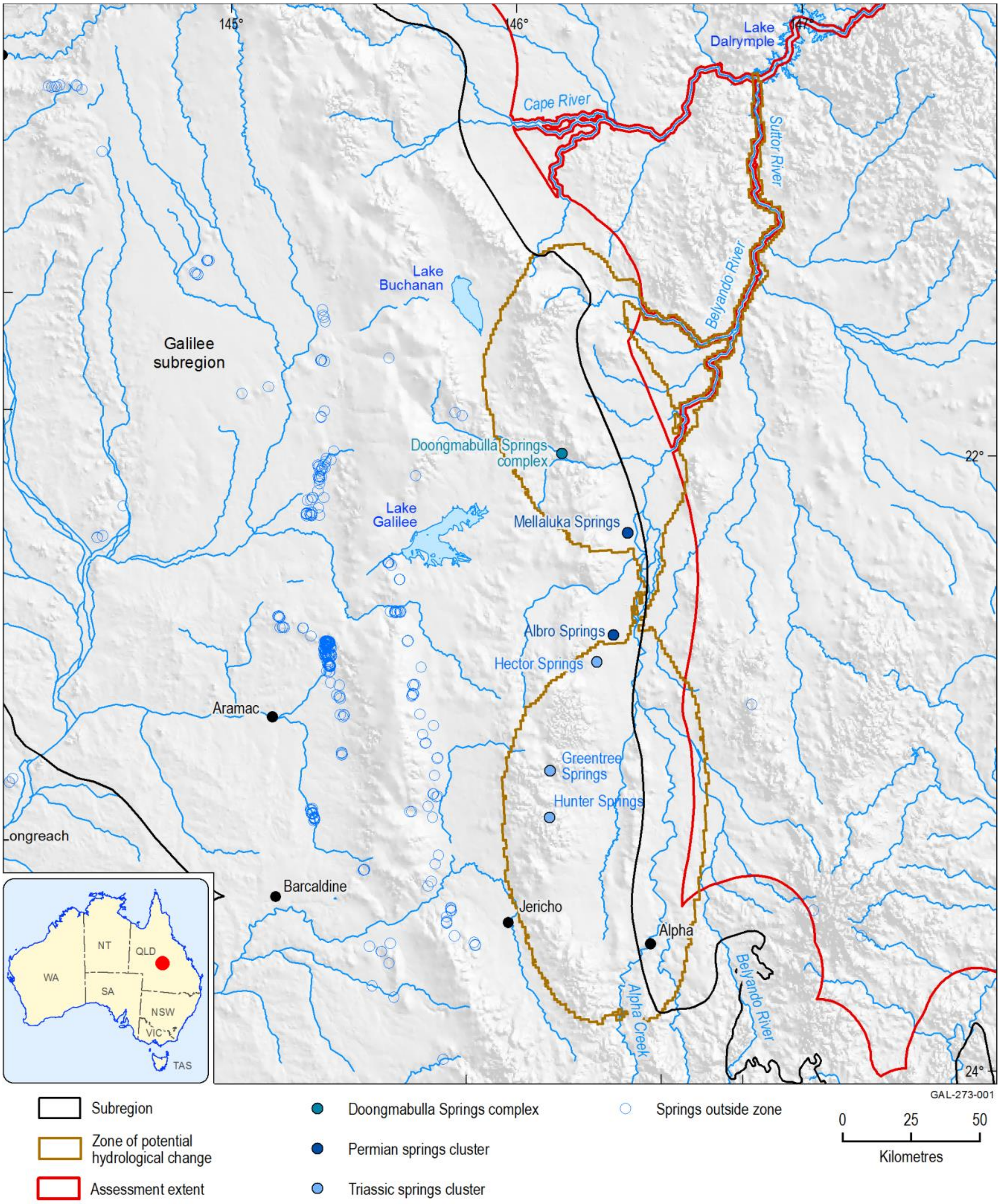


**Figure 6 Location of individual springs and spring complexes in the 'Springs' landscape group within the zone of potential hydrological change of the Galilee subregion**

Data: Bioregional Assessment Programme (Dataset 1); Queensland Herbarium, Department of Science, Information Technology, Innovation and the Arts (Dataset 2)

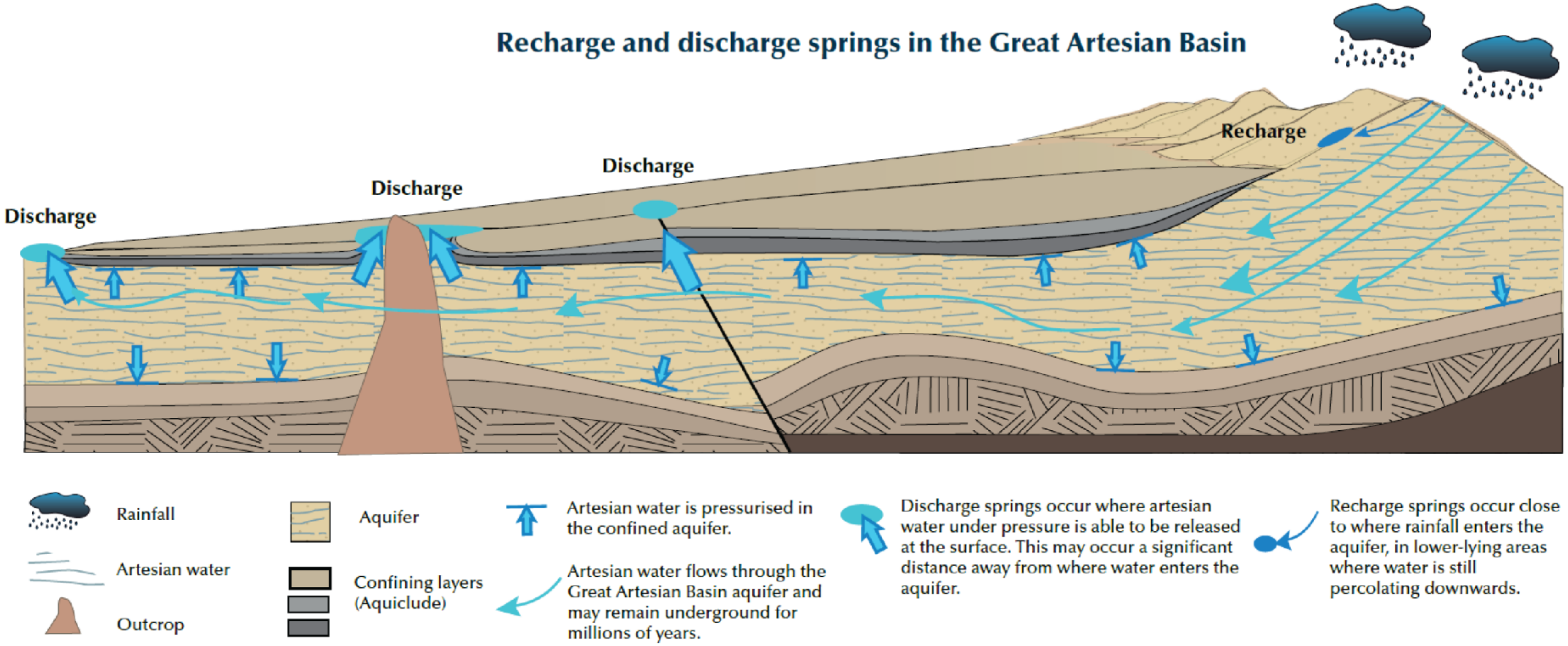


**Figure 7 Conceptualisation of the main hydrogeological characteristics of recharge (outcrop) and discharge springs**

Discharge springs occur in areas where the hydrostatic pressure in a confined aquifer is artesian, and where the overlying aquitard is compromised, for example, by thinning of the aquitard or due to the influence of geological structures, or the presence of a barrier that disrupts regional groundwater flow. Discharge springs are typically remote from the recharge areas for their source aquifers. Recharge (or outcrop) springs, are associated with unconfined aquifers that occur either at or near to aquifer outcrop areas. In contrast to discharge springs, groundwater flow systems tend to be more localised, with recharge springs commonly occurring around outcrop margins or near the break of a valley slope.
Source: DEHP (2013)

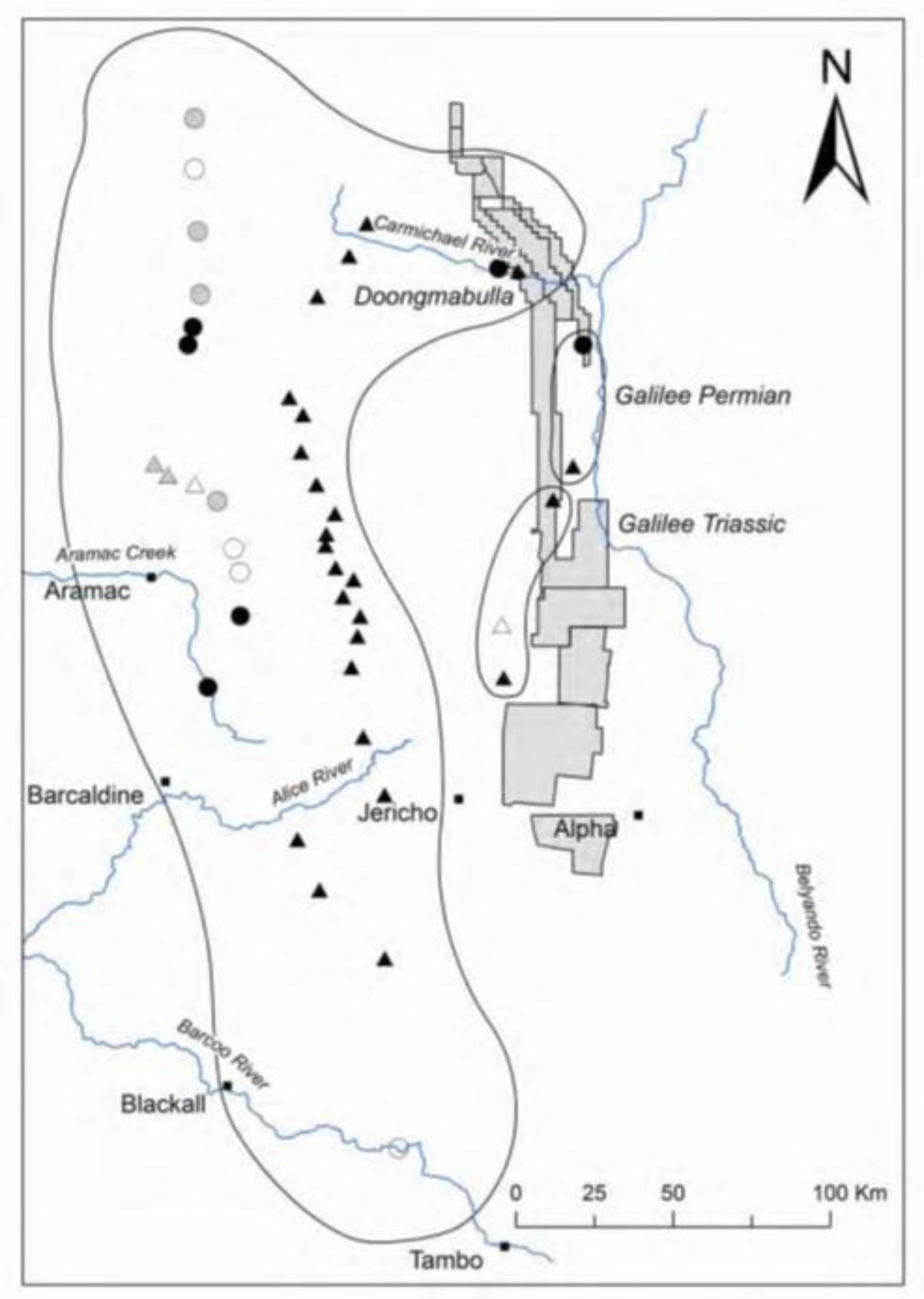


**Figure 8 Distribution of the three spring groups (Doongmabulla Springs complex, Permian springs cluster and Triassic springs cluster) in relation to the Barcaldine Springs supergroup and the proposed coal resource developments for the Galilee Basin**

Spring complexes showing 100% active springs (solid), partially (1% to 99%) active (grey) and 100% inactive (open symbols).
Recharge springs (triangles) are distinguished from discharge springs (circles).
Fensham et al. (2016) included the Doongmabulla Springs complex as part of the Barcaldine Springs supergroup.
The Barcaldine Springs supergroup (springs enclosed by black line) includes two north-trending lines of springs to the north of Blackall, as well as the Doongmabulla Springs complex.
Source: Fensham et al. (2016)

### *Doongmabulla Springs complex*

The Doongmabulla Springs complex is located on Doongmabulla and Labona pastoral stations near the confluence of Dyllingo Creek and Cattle Creek. The springs form an isolated cluster of wetlands associated with the Carmichael River and its tributaries (Figure 9). The springs complex consists of 187 individual spring vents forming 160 separate wetlands (Fensham et al., 2016).

Springs situated in areas underlain by Triassic rocks of the Moolayember Formation are classed as discharge springs (Figure 9). This categorisation is based on the relatively flat topography, mounded vents and the absence of source aquifer outcrop (Fensham et al., 2016). Discharge springs in the Doongmabulla Springs complex include: the House Springs, Joshua Spring, the Mouldy Crumpet Springs, the Stepping Stone Springs, the Moses Springs (comprising 65 separate vents), the Keelback Springs, Geschlichen Spring, Camp Springs (Figure 10), Bush Pig Trap Springs, Camaldulensis Spring, the Wobbly Springs and the Bonanza Springs. One of the largest of these individual spring groups, the Moses Springs, includes spring-fed wetlands with a combined area of approximately 3.25 ha (about 0.03 $km^2$) (GHD, 2012a, 2013a).

The more easterly springs in the Doongmabulla Springs complex are interpreted (based on morphology) as being recharge springs as they occur in areas where either the Clematis Group aquifer or the Dunda beds aquifer (the upper part of the generally low permeability Rewan Group) subcrops beneath the Carmichael River. These springs have vents on the edge of wetlands at the base of gentle slopes which suggests lateral discharge (Fensham et al., 2016) and include Little Moses Springs and Yukunna Kumoo Springs (Figure 9). Little Moses Springs (Figure 11) supports a wetland of 200 m by 50 m (GHD, 2013a).

Dusk Springs and Surprise Spring are the most easterly springs in the Doongmabulla Springs complex. The source aquifer for these recharge springs is likely to be the Dunda beds aquifer, as they are both situated in areas dominated by Dunda beds outcrop. For most hydrogeological interpretation purposes of the bioregional assessment (BA) for the Galilee subregion, the Dunda beds were grouped with the thicker and more extensive (underlying) Rewan Group aquitard. This is due to a lack of data specifically defining the lateral and vertical extents of the Dunda beds at an appropriate regional scale (companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)).

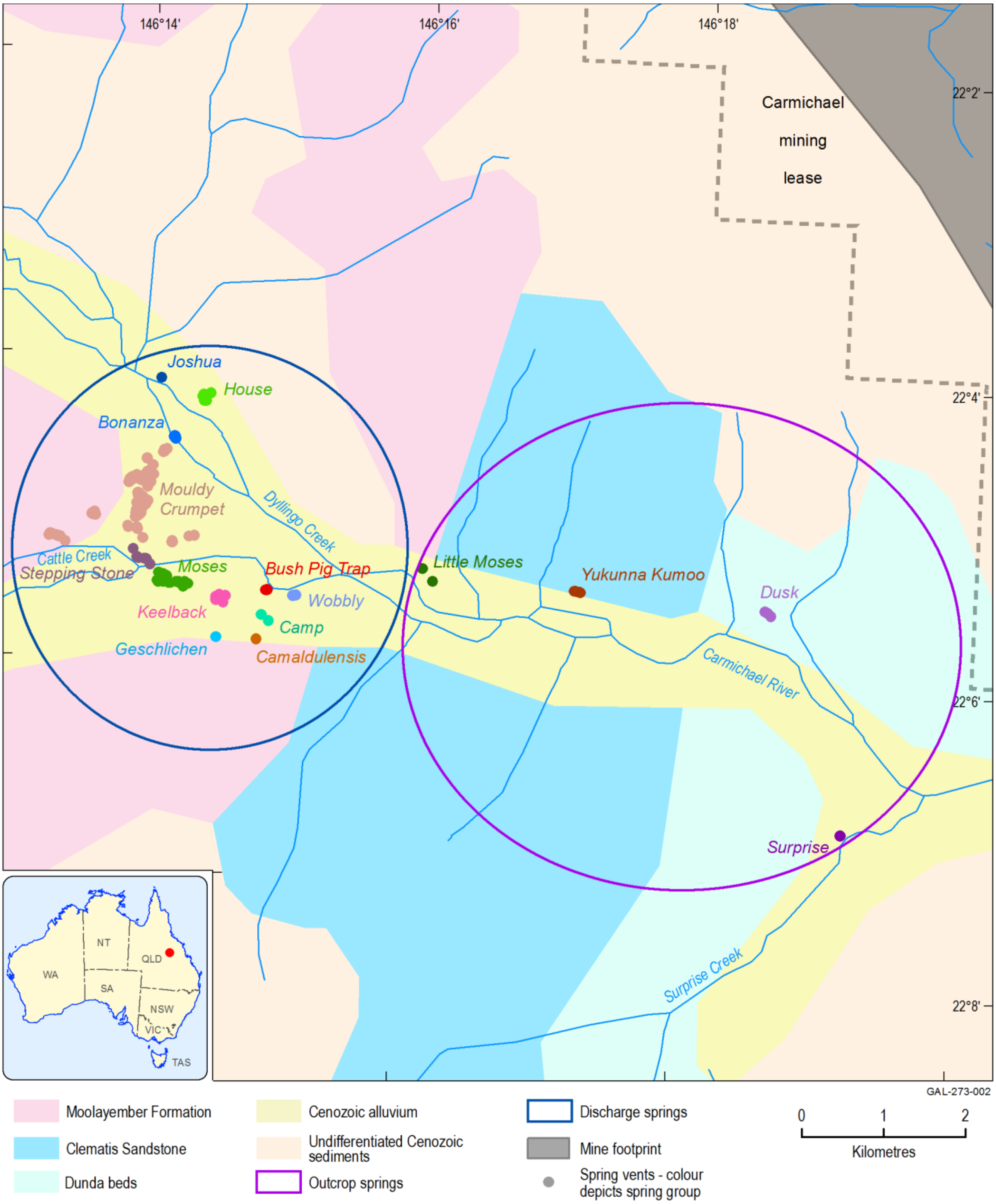


**Figure 9 Distribution of springs and spring groups that comprise the Doongmabulla Springs complex, relative to underlying geological units**

Data: Queensland Herbarium, Department of Science, Information Technology, Innovation and the Arts (Dataset 2); Bioregional Assessment Programme (Dataset 3, Dataset 4, Dataset 5); Queensland Department of State Development, Infrastructure and Planning (Dataset 6)

**Figure 10 Main discharge vent at Camp Spring in the Doongmabulla Springs complex**

Source: Fensham et al. (2016)

**Figure 11 Aerial view of the Little Moses Spring at the Doongmabulla Springs complex**

Source: Fensham et al. (2016)

***Permian springs cluster***

The Permian springs cluster consists of springs that are interpreted as being sourced from aquifers of Permian age within the Galilee Basin, particularly the Colinlea Sandstone or Joe Joe Group (Land Court of Queensland, 2015a). The Permian springs cluster includes: Lignum Spring, the Mellaluka Springs complex and the Albro Springs. The Mellaluka Springs complex consists of three vents and the Albro Springs group has two vents (Fensham et al., 2016). Of these three spring groups, the Albro Springs group are considered to be recharge springs and Lignum and Mellaluka springs are considered to be discharge springs by Fensham et al. (2016). In contrast to Fensham et al. (2016), work undertaken to support the environmental impact statement for the proposed Carmichael Coal Mine defined the Mellaluka Springs complex to include the Mellaluka Springs, Stories Spring and Lignum Spring (GHD, 2013a).

***Triassic springs cluster***

Relatively little information is known about the Triassic springs cluster, which encompasses the southernmost springs within the zone of potential hydrological change. Fensham et al. (2016) included three groups in the Triassic springs cluster: Hunter, Greentree and Hector. Hunter Springs consists of two vents, whereas Hector Springs has three main vents and several smaller ones (Fensham et al., 2016). Greentree Springs is inactive, and has not flown since the 19th century (Fensham et al., 2016). All springs in the Triassic springs cluster are interpreted as being recharge springs by Fensham et al. (2016). As Hunter and Greentree springs are situated on Dunda beds outcrop (i.e. the upper and more permeable part of the Rewan Group), the Dunda beds is considered the likely source aquifer. However, outcrop at Hector Springs is obscured by an extensive cover of Cenozoic sediments. It is possible though that the primary groundwater source is the Dunda beds, as the Hector Springs group is located several kilometres east of Dunda beds outcrop (Fensham et al., 2016), but west of known occurrences of sedimentary rocks that comprise the upper Permian coal measures.

## 2.7.3.1.2 Hydrological regimes and connectivity

***Doongmabulla Springs complex***

Both recharge and discharge springs occur within the Doongmabulla Springs complex (refer to Section 2.7.3.1.1 and companion product 3-4 (Lewis et al., 2018) for the Galilee subregion). Fensham (as cited in GHD, 2012a) estimated the daily flow rate of all the springs in this complex (combined) to be about 1.35 ML/day , which equates to some 493 ML/year (companion product 2.5 for the Galilee subregion (Karim et al., 2018a)). The daily flow rate of Joshua Spring is estimated to be 432 to 864 KL/day (GHD, 2013b). There was no information provided in either GHD (2012a) or GHD (2013b) to indicate how these various spring flow rate estimates were derived.

Discharge from some springs of the Doongmabulla Springs complex contributes flow to tributaries of the Carmichael River (Figure 9). The outflow from Joshua Spring and the House Springs group converge to provide the main discharge feeding the Carmichael River for a distance of up to 20 km downstream (Fensham et al., 2016). These springs also provide surface water to adjacent wetlands. As noted previously, the Doongmabulla Springs complex has 187 vents that feed 160 separate wetlands, of which 149 wetlands are fed by discharge springs (Fensham et al., 2016). The largest spring wetland in the complex is about 8.7 hectares (Fensham et al., 2016, p. 189). The surface water in the springs is perennial. The larger wetlands, such as those fed by Moses Springs and Keelback Springs, flow into permanent open pools and channels in the bed of Cattle Creek. In turn, these flow into the Carmichael River. However, during periods of low flow due to lower rainfall or drought conditions, the channels do not discharge into the Carmichael River (Fensham et al., 2016). Further information and analysis of hydrological dynamics and temporal variability of the different spring vents that comprise the Doongmabulla Springs complex is in companion product 3-4 for the Galilee subregion (Lewis et al., 2018). This includes preliminary analysis of remotely sensed data sourced from the available 30-year Landsat archive provided by Digital Earth Australia (see Section 3.2 in companion product 3-4 for the Galilee subregion (Lewis et al., 2018) for further details).

The source of groundwater that supplies the Doongmabulla Springs complex has been a contentious issue, and the cause of considerable debate. Further detail on the available evidence and the various interpretations that have been made about the spring's source aquifer is in Section 3.4.3.1.1 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018). In the context of the BA for the Galilee subregion, the primary source aquifer of the Doongmabulla Springs complex is considered to be the Clematis Group aquifer. The multiple lines of evidence and reasoning supporting this interpretation is outlined in Section 3.4.3.1.1 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018), as well as Section 2.3.2 of companion product 2.3 for the Galilee subregion (Evans et al., 2018b).

For the purposes of the BA of the Galilee subregion, the main features of the hydrogeological conceptualisation of the Doongmabulla Springs complex includes:

1. The discharge springs (mound springs) in the western part of the Doongmabulla Springs complex (Figure 9) are most likely fed by groundwater leakage from the confined Clematis Group aquifer through the Moolayember Formation aquitard. This occurs in areas where the integrity of the aquitard is compromised, which may be due thinning or weathering of the aquitard near its contact with the Clematis Group aquifer, or the influence of geological structures (or possibly a combination of these factors). At the surface, the discharge springs are formed on alluvium that overlies the Moolayember Formation aquitard. The discharge springs source water from regional-scale groundwater flow that occurs in confined parts of the Clematis Group aquifer. Groundwater flow within this aquifer occurs from the west and south, and focuses towards the discharge springs.
2. The recharge (outcrop) springs immediately east of the discharge springs are sourced from the unconfined parts of the Clematis Group aquifer. These include the Little Moses (Figure 11) and Yukunna Kumoo springs (Figure 9), which are located on or near outcrop of the Clematis Group. These springs are fed by more local-scale groundwater systems with recharge to the aquifer occurring in nearby hills to the east and north of the springs.
3. The source for the easternmost recharge springs in the Doongmabulla springs complex (Figure 9, Surprise and Dusk) is likely to be the Dunda beds aquifer. This aquifer outcrops in nearby hills, as well as underlying the alluvium where these springs occur in the valley of the Carmichael River.

4. Groundwater discharge at the surface across the Doongmabulla Springs complex contributes directly to baseflow in the Carmichael River and helps to maintain permanent pools in nearby drainage channels (discussed in Section 3.5 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018)). There is also potential for groundwater from the Clematis Group and Dunda beds aquifers to discharge directly into the alluvium, where these units subcrop beneath alluvium (Figure 9).

***Permian springs cluster***

The Permian springs cluster occurs to the west of the Belyando River. The likely groundwater sources for these springs are either the Colinlea Sandstone (part of the upper Permian coal measures) or the stratigraphically lower Joe Joe Group (the basal sequence of the Galilee Basin's Carboniferous to Permian stratigraphy).

The Permian springs cluster has four wetlands fed by the springs. The flow is predominantly south to north in this region. Albro Springs has moderate flows (combined flow of the two vents is about 40 L/min) and Lignum Spring has low flows (about 0.5 L/min). The highest flows are in the three vents of the Mellaluka Springs complex (~1200 L/min, combined).

***Triassic springs cluster***

The springs in the Triassic springs cluster are all recharge springs. All three of these springs groups are likely to source groundwater from the Dunda beds aquifer. The Greentree and Hunter springs are surrounded by outcrop of the Dunda beds. Hector Springs are about 2 km east of the currently mapped extent of the Dunda beds but also appear to have a gravity-fed source.

### 2.7.3.1.3 Vegetation

The three geographic clusters of springs vary in vegetation composition. There is also considerable variation within the clusters.

***Doongmabulla Springs complex***

Within the Doongmabulla Springs complex some springs and spring groups are substantially disturbed, either by human activity or by the actions of livestock. An example of this is Joshua Spring (Figure 12), which has been heavily modified to provide drinking water for the Doongmabulla Station homestead and for livestock water supplies. It is now enclosed by a turkey's nest dam (GHD, 2012a).

Other springs and spring groups are relatively intact. Dominant vegetation surrounding the various springs includes: (i) bare, scalded plains supporting very sparse grass and herb cover; (ii) grassland generally dominated by *Sporobolus pamelae*; (iii) mixed sedgeland dominated by sedges in the genus *Cyperus*; (iv) coolibah (*Eucalyptus coolabah*) or river red gum (*E. camaldulensis* var. *obtusa*) woodland and open woodland; (v) weeping paperbark (*Melaleuca leucadendra*) forest; (vi) peppermint box (*E. persistens*) low open woodland with a grassy ground layer dominated by spinifex (*Triodia*); and (vii) Reid River box (*E. brownii*) woodland.

The first three vegetation assemblages and the weeping paperbark forest are contained within regional ecosystem (RE) 10.3.31 under the Queensland Government's remnant vegetation mapping (GHD, 2013a). This RE is described as 'Artesian springs emerging on alluvial plains'. It has the conservation status 'Of concern'. Three of the four vegetation assemblages within RE 10.3.31 (the exception is bare, scalded plains) are considered to be obligate groundwater-dependent systems.

The vegetation assemblage containing coolibah and/or river red gum woodland is contained within RE 10.3.14 'Eucalyptus camaldulensis and/or E. coolabah woodland to open woodland along channels and on floodplains'. It is considered to be a facultative groundwater-dependent ecosystem although in some areas around the springs access to groundwater will be permanent. This RE is listed as 'Least concern'. The Reid River box woodland occurs within RE 10.3.6, whereas the peppermint box low open woodland is within RE 10.7.2 (GHD, 2013a). These vegetation assemblages are not considered to be groundwater-dependent and both are listed as 'Least concern'.

**Figure 12 (left) aerial view of Joshua Spring highlighting the rectangular 'turkey's nest' dam (foreground) that now encloses the spring; (right) outflow pipe for Joshua Spring constructed through the right-hand dam wall**

Source: Fensham et al. (2016)

### *Permian springs cluster*

The wetland vegetation in the Mellaluka Springs group is mostly a tall sedgeland dominated by the sedge *Baumea rubiginosa*, the fern *Cyclosorus interruptus* and the grass *Phragmites australis*. Drier areas adjacent to the springs support grassland of *Sporobolus mitchellii* with a variety of chenopod shrubs and sub-shrubs. The vegetation in the vicinity of the springs group is mostly 'non-remnant'; however, the springs supports up to 0.04 $km^2$ of RE 11.3.22 that is classified as 'Of concern'. RE 11.3.22 is described as 'Springs associated with recent alluvia, but also including those on fine-grained sedimentary rocks, basalt, ancient alluvia and metamorphic rocks'.

The wetlands at Lignum Spring and Stories Spring almost exclusively contain cumbungi (*Typha domingensis*) (GHD, 2013a). The springs are surrounded by grassy woodland that is either silver-leaved ironbark (*E. melanophloia*) woodland (RE 10.3.28) or Reid River box woodland (RE 10.3.6). Both REs are classified as 'Least concern'.

***Triassic springs cluster***

The springs in the Triassic springs cluster have all been heavily modified (Fensham et al., 2016). Specifically, two of the three Hector Springs have been excavated to provide access for cattle.

### 2.7.3.1.4 Flora and fauna

Springs in the GAB are known to be sites of high endemicity. Within the 'Springs' landscape group of the zone of potential hydrological change, the spring wetlands support endemic plants as do the salt scalds surrounding discharge springs.

***Doongmabulla Springs complex***

The discharge springs in the Doongmabulla Springs complex are part of a nationally threatened ecological community listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act), 'The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin' (Fensham et al., 2010). The community occurs in parts of NSW, within the Galilee assessment extent (and elsewhere in Queensland), and also in parts of SA (Fensham et al., 2010). The Doongmabulla Springs complex differs from other GAB spring complexes in being adjacent to an easterly flowing, outward-draining river system. Specifically, it occurs in the vicinity of the Carmichael River which flows into the Burdekin River and then to the sea along the east coast of Queensland between Ayr and Home Hill. By comparison, the other major GAB spring complexes are in the internally draining Lake Eyre Basin, and occur in more arid environments.

The wetlands associated with discharge springs in the Doongmabulla Springs complex support a number of spring-endemic plants. These include two nationally threatened herbs, salt pipewort (*Eriocaulon carsonii)* and blue devil (*Eryngium fontanum)* (Fensham et al., 2010). Other spring-endemic plants include *Hydrocotyle dipleura*, *Myriophyllum artesium*, *Sporobolus pamelae* and *Utricularia fenshamii*.

Salt pipewort is a small aquatic herb that grows in shallow water (including water depths as shallow as 10 cm) where it forms dense floating mats. It is listed as 'Endangered' nationally under the EPBC Act and as 'Endangered' under Queensland's *Nature Conservation Act 1992* (Nature Conservation Act). The species occurs in 20 spring complexes within the GAB in Queensland, NSW and SA. It also occurs at two non-GAB springs in Queensland (Fensham et al., 2010).

Blue devil is an erect perennial herb that can reach a height of up to 80 cm. The entire distribution of this species occurs in only two spring complexes, one of which is the Moses Springs group in the Doongmabulla Springs complex, within the zone of potential hydrological change (Fensham et al., 2010). It is listed as 'Endangered' both nationally (EPBC Act) and in Queensland (Nature Conservation Act). The species occupies two spring wetlands at Moses Springs. One wetland has an area of 2.4 ha, and the other, 0.02 ha. The approximate population size of the species at Moses Springs is estimated at 10,000 plants (Fensham et al., 2010).

*Hydrocotyle dipleura*, *Myriophyllum artesium* and *Sporobolus pamelae* are listed as threatened in Queensland under the Nature Conservation Act, but not nationally. *Hydrocotyle dipleura* is a perennial prostrate herb that occurs in saline sands and clay soils beyond the saturated zone of discharge spring wetlands. It has been recorded in low woodland of *Melaleuca bracteata.* The distribution of this species is confined to seven springs complexes in the GAB of Queensland including the Moses Springs group at the Doongmabulla Springs complex (Fensham et al., 2010). It is listed as ‘Vulnerable’ in Queensland (Nature Conservation Act).

*Myriophyllum artesium* is an aquatic, mat-forming herb that grows to 15 cm. It has a distribution that is confined to wetland habitat in arid Queensland and is listed as ‘Endangered’ in Queensland (Nature Conservation Act). This species generally grows in shallow pools of spring wetlands and is also found in bore drains (Fensham et al., 2010).

*Sporobolus pamelae* is a tussock grass that grows to a height of 80 to 120 cm along the margins of springs and spring wetlands. It has a geographic range that is confined to six spring complexes in the GAB of Queensland (Fensham et al., 2010). It is listed as ‘Endangered’ in Queensland (Nature Conservation Act). The species is found at 15 spring wetlands within the Doongmabulla Springs complex (Fensham et al., 2016).

The salt scalds around spring wetlands at Moses and Mouldy Crumpet springs support endemic plants – so called ‘scald endemics’ (Fensham et al., 2016). These species include *Sporobolus partimpatens*, *Sclerolaena “dioceia”* and *Trianthema* sp. (Coorabulka RW Purdie 1404). None of these scald endemics is currently listed as threatened.

In addition to spring wetland and scald endemics, another threatened plant occurs at Doongmabulla Springs complex. Waxy cabbage palm (*Livistona lanuginosa)*, a species that occurs mainly in the ‘Streams’ landscape group, has been recorded at Moses Springs (GHD, 2013c). It is endemic to the Burdekin river basin and is listed as ‘Vulnerable’ both nationally (EPBC Act) and in Queensland (Nature Conservation Act) (Department of the Environment, 2015). The population at Moses Springs is the only one known to occur at a GAB spring and is estimated to be about 20 individuals (GHD, 2013c).

The Doongmabulla Springs complex supports a diversity of fish species though, based on current knowledge, none are known to be endemic. Up to 18 fish species are expected to occur in the area (GHD, 2012b). Eleven fish species were recorded during recent surveys in the vicinity of the Doongmabulla Springs complex (GHD, 2012b): Agassiz's glassfish (*Ambassis agassizii*), Midgley's carp gudgeon (*Hypseleotris* species 1), purple-spotted gudgeon (*Mogurnda adspersa*), sleepy cod (*Oxyeleotris lineolata*), eastern rainbowfish (*Melanotaenia splendida splendida*), Hyrtl's tandan (*Neosilurus hyrtlii*), spangled perch (*Leiopotherapon unicolor*), barred grunter (*Amniataba percoides*), flyspecked hardyhead (*Craterocephalus stercusmuscarum*), western carp gudgeon (*Hypseleotris klunzingeri*) and bony bream (*Nematalosa erebi*). Most of these species are likely to periodically occupy the spring wetlands.

The aquatic invertebrates of the Doongmabulla Springs complex are poorly known. Two spring-endemic invertebrate species have been recorded from the area. These are the mollusc *Gabbia* *rotunda*, which is endemic to the Doongmabulla Springs complex, and the water mite *Mammersela* sp. AMS KS85341, which is endemic to GAB spring wetlands (GHD, 2012b). It is highly likely that further sampling will detect new (previously unknown) species of molluscs and other aquatic invertebrates.

***Permian springs cluster***

The Permian springs cluster does not support any spring endemics (Fensham et al., 2016). The plants present are common and widespread species of no conservation significance. The fish fauna is limited, with only the spangled perch and eastern rainbowfish positively identified (GHD, 2013a).

***Triassic springs cluster***

The plants and invertebrates identified from the springs of the Triassic springs cluster are all common and widespread wetland species (Fensham et al., 2016). None are of specific conservation significance.

### *2.7.3.2 Qualitative mathematical model*

For the purposes of this BA, a qualitative mathematical model was developed that described the general dynamics of the aquatic community associated with springs in the zone of potential hydrological change (Figure 13). A critical factor in preserving the aquatic community is the rate of groundwater flow that maintains a damp or submerged state in the spring, such that its surface does not become dry. An increase in water depth above this rate of flow (which is specified as the depth of water in the spring greater than maintaining a damp state (or 'D>Dam') in the two signed digraphs for the 'Springs' landscape group shown in Figure 13 and Figure 14) supports a wetted-area regime around the perimeter and downstream of the spring that is beneficial to emergent vegetation, the building of peat mounds, tail vegetation (i.e. vegetation at the outfall or tail end of a spring) and groundwater-dependent vegetation. Within the free-water area downstream of a spring, an increase in surface water depth supports an increase in primary production (i.e. phytoplankton, macrophytes and benthic algae), and habitat for aquatic grazers. The growth of macrophytes and benthic algae is mediated by competition for space and light, while emergent vegetation provides a substrate for the growth of benthic algae. Algae (phytoplankton and benthic) are the basal resources for grazers, filter feeders and omnivorous invertebrate predators. Top (vertebrate) predators that rely on these aquatic food resources are also maintained by habitat provided by adjacent groundwater-dependent vegetation. There was uncertainty in the model structure arising from the extent to which benthic algae could (or could not) respond to an increase in surface water depth. This led to two alternative qualitative models, one with (Figure 13) and one without (Figure 14) a positive link from depth of water to benthic algae.

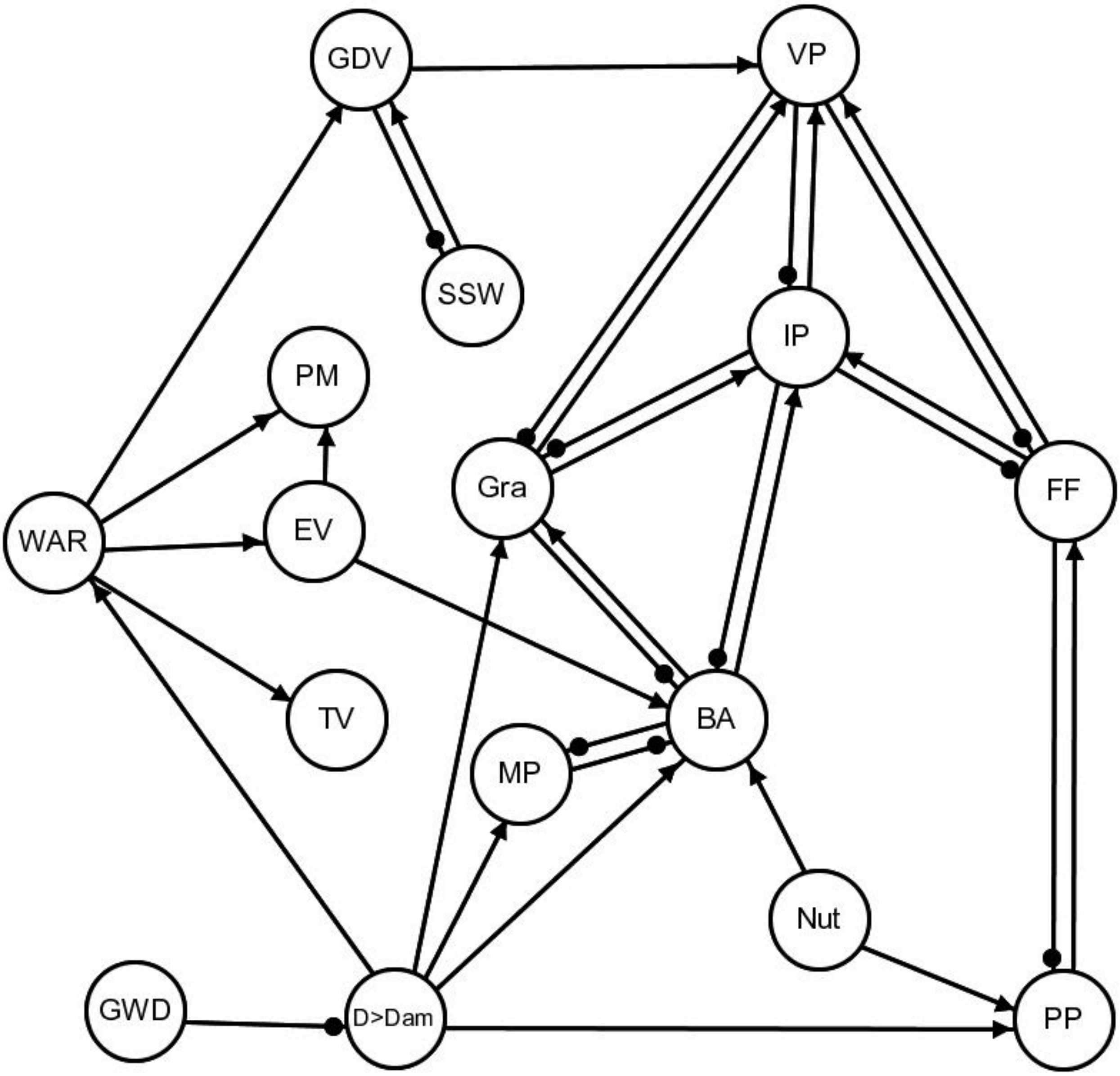


**Figure 13 Signed digraph model (Model 1) of the 'Springs' landscape group in the zone of potential hydrological change of the Galilee subregion, which has a positive link between depth of water in a spring (D>Dam) and benthic algae (BA)**

Model variables are: benthic algae (BA), depth of spring greater than damp (D>Dam), emergent vegetation (EV), filter feeders (FF), groundwater-dependent vegetation (GDV), grazers (Gra), groundwater depletion (GWD), invertebrate predators (IP), macrophytes (submerged and floating) (MP), nutrients (Nut), peat mound (PM), phytoplankton (PP), subsurface water (SSW), tail vegetation (TV), vertebrate predators (VP), wetted-area regime (WAR).
Data: Bioregional Assessment Programme (Dataset 7)

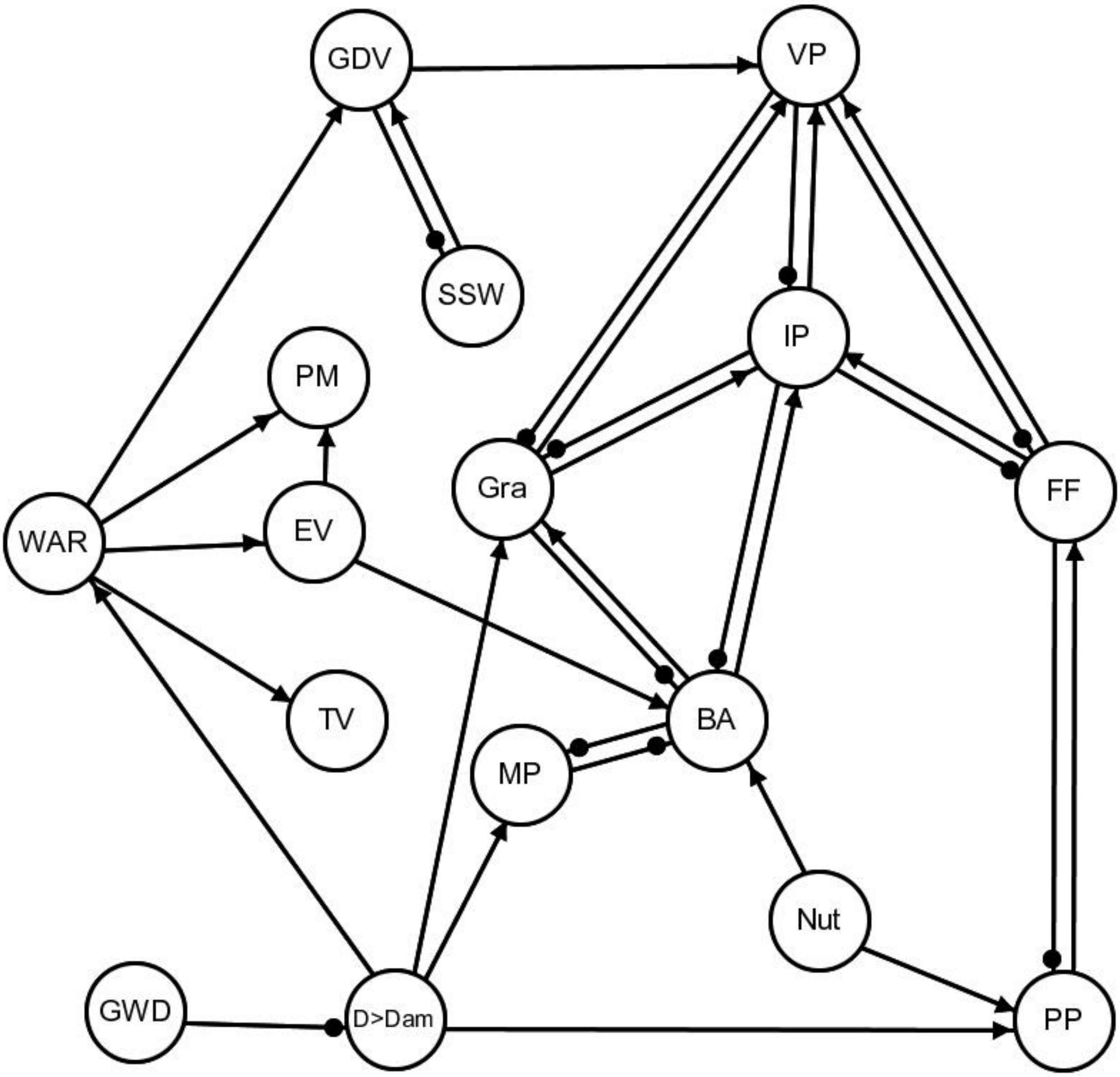


**Figure 14 Signed digraph model (Model 2) of the 'Springs' landscape group in the zone of potential hydrological change of the Galilee subregion, which lacks a positive link between depth of water in a spring (D>Dam) and benthic algae (BA)**

Model variables are: benthic algae (BA), depth of spring greater than damp (D>Dam), emergent vegetation (EV), filter feeders (FF), groundwater-dependent vegetation (GDV), grazers (Gra), groundwater depletion (GWD), invertebrate predators (IP), macrophytes (submerged and floating) (MP), nutrients (Nut), peat mound (PM), phytoplankton (PP), subsurface water (SSW), tail vegetation (TV), vertebrate predators (VP), wetted-area regime (WAR).
Data: Bioregional Assessment Programme (Dataset 7)

Surface water and groundwater modelling indicate potential impacts of coal mining to groundwater depletion and subsurface water availability in some parts of the zone of potential hydrological change (see companion product 2.6.1 (Karim et al., 2018b) and companion product 2.6.2 (Peeters et al., 2018) for further details of the surface water and groundwater modelling undertaken, respectively, for the BA of the Galilee subregion). Based on all possible combinations of these potential impacts, three cumulative impact scenarios were developed for qualitative analysis of response predictions (Table 6).

**Table 6 Summary of the cumulative impact scenarios (CISs) for the 'Springs' landscape group in the Galilee subregion**

| CIS | GWD | SSW |
|---|---|---|
| C1 | + | 0 |
| C2 | 0 | – |
| C3 | + | – |

Pressure scenarios are determined by combinations of no-change (0), increase (+) or decrease (–) in the following signed digraph variables: groundwater depletion (GWD) and subsurface water (SSW).
Data: Bioregional Assessment Programme (Dataset 7)

Qualitative analysis of the two signed digraph models in Figure 13 and Figure 14 indicated a zero or ambiguous response prediction (Table 7 and Table 8, respectively) for the majority of biological variables within the ecosystems associated with the 'Springs' landscape group as a result of depletion of groundwater and subsurface water. The high level of ambiguity in the response predictions results from the influence of positive feedback in the macrophytes–benthic algae subsystem and the influence of multiple pathways of interaction that have both positive and negative effects on predicted response variables. These ambiguous predictions could be either positive or negative depending on the strength of interactions attributed to the model's links. The only variable that had a positive response prediction was macrophytes (submerged and floating) which had a positive response in both models to C2 (a decrease in subsurface water). The only variable that had a negative response prediction was benthic algae which had a negative response in both models to C2 (a decrease in subsurface water). Note that the predictions for depletion of groundwater in the cumulative impact scenarios are within the context of still keeping the spring in damp conditions such that the model variables can still persist. With severe depletion and drying of springs, many of the model variables would disappear and the system, as modelled, would no longer exist.

As noted in Section 2.7.2.3 there were no receptor impact models developed for the 'Springs' landscape group in the Galilee subregion, despite preliminary efforts by the external experts at the receptor impact modelling workshop. The main reason for not being able to develop receptor impact models for the 'Springs' landscape group was the lack of data and knowledge about critical hydrogeological parameters for the various springs (and spring complexes) within the zone of potential hydrological change. In particular, there was insufficient information available about the magnitude of hydraulic pressure (head) from the source aquifers that drives spring flow in the zone, as well as lack of data about the relationship between hydraulic head and various spring discharge characteristics (e.g. volume, timing, variability etc.). As noted during discussions at the receptor impact modelling workshop, these parameters are likely to be unique to each spring complex in the zone (and may even be unique to individual springs within a complex). This means that spring flow data that may be known for other springs in the GAB (e.g. springs near Lake Blanche in South Australia; Keppel et al., 2016) could not be reliably substituted (i.e. for receptor impact modelling purposes) for the springs in the Galilee subregion's zone of potential hydrological change. Consequently, without specific estimates of these important hydrogeological parameters for the springs in the zone, the critical relationship that the external experts had identified for developing a springs receptor impact model (i.e. the proportion of pressure head decline that would substantially alter the magnitude of spring flow and effectively represent an ecological 'tipping point' in the long-term health and condition of the spring) could not be reliably established for any of the springs or spring complexes within the zone.

Although it was not possible to develop a receptor impact model for the 'Springs' landscape group in this BA, some preliminary analysis of remotely sensed data relevant to better understanding near-surface hydrological variability for different springs is presented in companion product 3-4 for the Galilee subregion (Lewis et al., 2018). This work, which has leveraged the available Landsat archive provided by Digital Earth Australia, examines temporal variations in various spring parameters (such as wetness and greenness) within the zone of potential hydrological change. The potential for further research opportunities to build upon this preliminary analysis is also discussed in Lewis et al. (2018).

**Table 7 Predicted response of the signed digraph variables (Model 1) in the 'Springs' landscape group to (cumulative) changes in hydrological response variables in the zone of potential hydrological change of the Galilee subregion**

| Signed digraph variable (name) | Signed digraph name (shortened form) | C1 | C2 | C3 |
|---|---|---|---|---|
| Tail vegetation | TV | ? | 0 | ? |
| Emergent vegetation | EV | ? | 0 | ? |
| Peat mound | PM | ? | 0 | ? |
| Groundwater-dependent vegetation | GDV | ? | ? | ? |
| Wetted area regime | WAR | ? | 0 | ? |
| Macrophytes (submerged and floating) | MP | ? | (+) | ? |
| Subsurface water | SSW | ? | ? | ? |
| Grazers | Gra | ? | ? | ? |
| Vertebrate predators | VP | ? | ? | ? |
| Invertebrate predators | IP | ? | ? | ? |
| Filter feeders | FF | ? | ? | ? |
| Phytoplankton | PP | ? | ? | ? |
| Nutrients | Nut | 0 | 0 | 0 |
| Benthic algae | BA | ? | (–) | ? |
| Depth of spring greater than damp | D>Dam | ? | 0 | ? |
| Groundwater depletion | GWD | ? | 0 | ? |

Qualitative model predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
Data: Bioregional Assessment Programme (Dataset 7)

**Table 8 Predicted response of the signed digraph variables (Model 2) in the 'Springs' landscape group to (cumulative) changes in hydrological responses variables in the in the zone of potential hydrological change of the Galilee subregion**

| Signed digraph variable (name) | Signed digraph name (shortened form) | C1 | C2 | C3 |
|---|---|---|---|---|
| Tail vegetation | TV | ? | 0 | ? |
| Emergent vegetation | EV | ? | 0 | ? |
| Peat mound | PM | ? | 0 | ? |
| Groundwater-dependent vegetation | GDV | ? | ? | ? |
| Wetted area regime | WAR | ? | 0 | ? |
| Macrophytes (submerged and floating) | MP | ? | (+) | ? |
| Subsurface water | SSW | ? | ? | ? |
| Grazers | Gra | ? | ? | ? |
| Vertebrate predators | VP | ? | ? | ? |
| Invertebrate predators | IP | ? | ? | ? |
| Filter feeders | FF | ? | ? | ? |
| Phytoplankton | PP | ? | ? | ? |
| Nutrients | Nut | 0 | 0 | 0 |
| Benthic algae | BA | ? | (–) | ? |
| Depth of spring greater than damp | D>Dam | ? | 0 | ? |
| Groundwater depletion | GWD | ? | 0 | ? |

Qualitative model predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
Data: Bioregional Assessment Programme (Dataset 7)

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## 2.7.4 Streams landscape groups


### *Summary*

The streams landscape groups in the Galilee assessment extent contain 10 landscape classes. Four landscape classes are groundwater-dependent ecosystem (GDE) streams (comprising the 'Streams, GDE' landscape group) and six are non-GDE streams (comprising the 'Streams, non-GDE' landscape group). Both GDE and non-GDE streams are widespread in the zone of potential hydrological change in the central-eastern part of the Galilee subregion, and mainly occur in the Belyando river basin (a headwater catchment of the larger Burdekin river basin). Of the 6285 km of streams in the zone, GDE streams account for 2801 km (45%) of all streams, and non-GDE streams total 3484 km. Non-GDE streams are most common in the western and southern parts of the zone.

Within the zone of potential hydrological change, annual streamflow shows a high degree of interannual variability. Flows in any given year can vary from almost no flow to major floods. Mean monthly flow is also highly variable. Flows vary between months with minimal to no flow from July to October, while most surface water flows occur between December and April. The streamflow regime within the zone is characterised as one of dry seasonal flows.

The dry seasonal flows of the streams within the Belyando river basin result in the ecosystems of the streams landscape groups being characterised by 'boom–bust' cycles. Specifically, diversity in the system is maintained by natural cycles of river flow and drying, driven by surface water inputs. Although more arid rivers further west in the Galilee subregion are driven by highly unpredictable rainfall, the 'boom–bust' cycle in the Belyando river basin is more predictable. Ecological processes within the zone of potential hydrological change operate in an environmental context where there is seasonally predictable summer rainfall, which produces in-channel flows (flow pulses), followed by a predictable period of drying. The drying phase is a relatively constant process in an average year uninterrupted by rainfall outside the summer period. During summers with very high rainfall, the in-channel flow is replaced by flooding. Overbank flows connect the riverine and floodplain environments during these 'boom' periods and primary productivity is greatly enhanced.

A combined qualitative mathematical model was developed for the two streams landscape groups. The central feature of the qualitative model was the existence and connectivity of refuge habitats. Surface water serves a key role in providing both lateral and downstream transport of detritus in the stream channel and floodplain. It also determines, through wetted area of the channel, the amount of primary production generated by algae. Detritus and algae are the principal resources that support populations of aquatic invertebrates and fishes. Surface water also plays a key role in recharging stores of deep groundwater in confined aquifers, and in turn, stores of deep groundwater can contribute to maintaining groundwater levels in near-surface (unconfined) aquifers.

Two receptor impact models were developed to examine the potential impact of the additional coal resource development on water-dependent ecosystems within the zone of potential hydrological change. The first receptor impact model focused on the response of

woody riparian vegetation to changes in flow regime and groundwater. The second model examined the response of a high-flow macroinvertebrate (mayfly nymphs in the genus *Offadens,* family Baetidae) to changes in flow regime.

With regard to the first receptor impact model, the independent experts who contributed to the elicitation process were of the opinion that: (i) mean percent foliage cover would decrease as depth to groundwater increased, (ii) mean percent foliage cover would decrease as the number of low-flow days increased, and (iii) mean percent foliage cover would increase as the number of flood events with peak daily flow exceeding the 1983 to 2012 2-year return period increased.

Results from the second receptor impact model indicate that the experts' opinion provides no strong evidence that either the number of low-flow days or the mean maximum spell of low-flow days have a significant effect on mean baetid density. This model also predicts that baetid density under reference conditions does not affect outcomes under different low-flow conditions in future assessment years.

### *2.7.4.1 Description*

#### 2.7.4.1.1 Overview

The classification of the stream network in Section 2.3.3 of companion product 2.3 for the Galilee subregion (Evans et al., 2018) was based on catchment position, water regime, and water source. This classification produced 10 landscape classes. Of these, four classes are GDE streams (comprising the 'Streams, GDE' landscape group) and six are non-GDE streams (comprising the 'Streams, non-GDE' landscape group) (Table 9 in companion product 2.3 (Evans et al., 2018)). The streams landscape groups occur widely within the zone of potential hydrological change of the Galilee subregion (Figure 15). Of the 6285 km of streams in the zone, 2801 km (45%) are in the 'Streams, GDE' landscape group, whereas the majority (55% or 3484 km) is in the 'Streams, non-GDE' landscape group. Non-GDE streams are most prominent in the western and southern area of the zone (Figure 15).

The Galilee subregion straddles the Great Dividing Range and includes the headwaters of six major river basins. Much of the Galilee subregion lies in the Cooper Creek – Bulloo and Diamantina river basins (see companion product 1.1 for the Galilee subregion (Evans et al., 2014)). There are proposed coal seam gas projects in the Cooper Creek – Bulloo river basin, however, these projects are at a less advanced stage than coal mine developments and were unable to be quantitatively evaluated for this bioregional assessment (BA) (Section 2.3.4 of companion product 2.3 for the Galilee subregion (Evans et al., 2018)). Most of the proposed coal mine developments in the Galilee subregion are located in the Burdekin river basin, with the most advanced coal mine developments situated on the western side of the Belyando river basin. As a consequence, the zone of potential hydrological change of the Galilee subregion is focused on the Belyando river basin (Figure 16) and includes the Carmichael River, Belyando River Floodplain, Fox Creek, Sandy Creek and Native Companion Creek subcatchments (Dight, 2009).

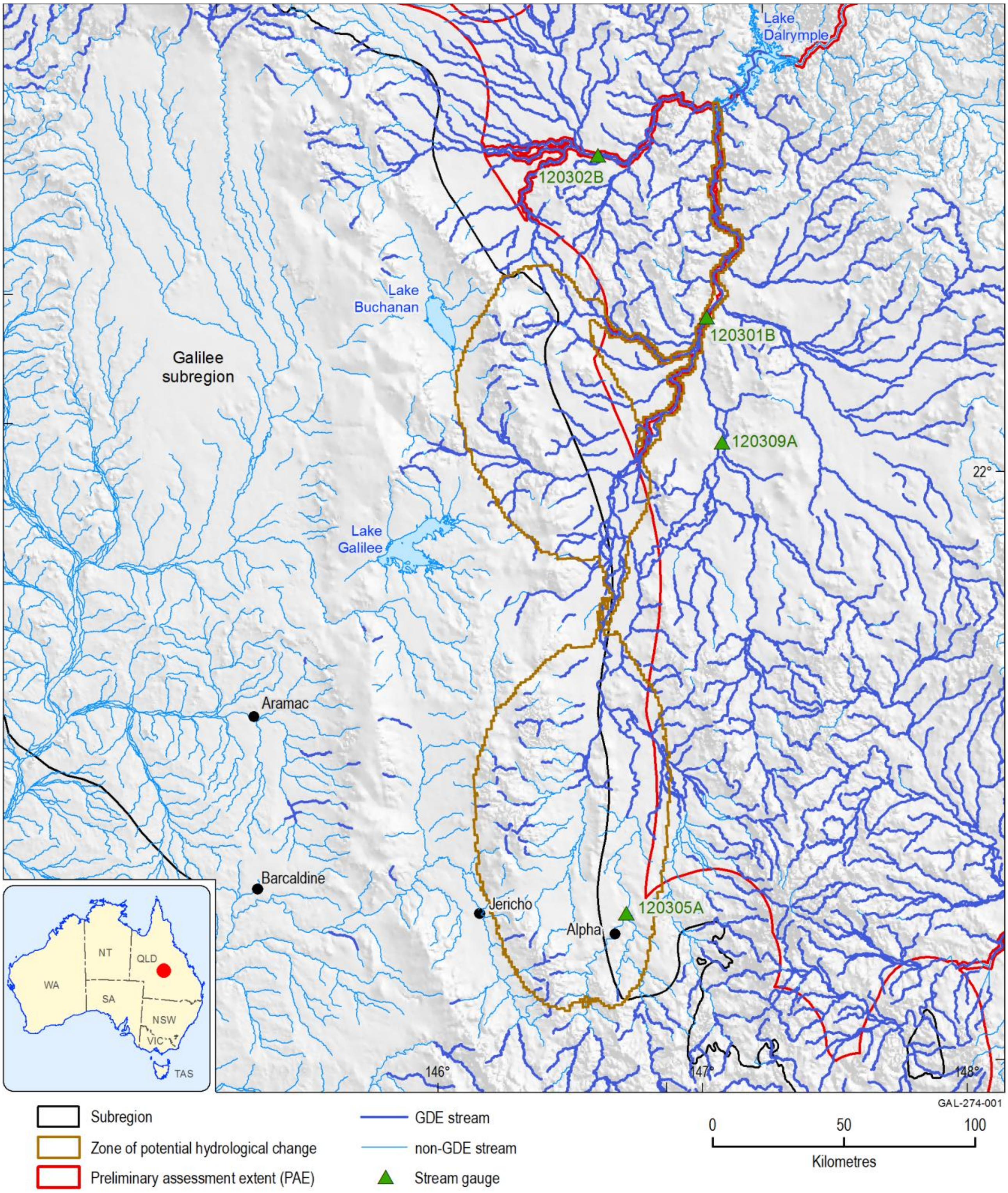


**Figure 15 Distribution of the streams landscape groups within the zone of potential hydrological change of the Galilee subregion, with location of selected stream gauges**

River cross-sections and flow duration curves for the four stream gauges shown on this map are shown in Figure 17.
GDE = groundwater-dependent ecosystem
Data: Queensland Herbarium, Department of Science, Information Technology, Innovation and the Arts (Dataset 1); Geoscience Australia (Dataset 2)

**Figure 16 Belyando River at Belyando Crossing in the Galilee assessment extent**

Credit: Bioregional Assessment Programme, Chris Pavey (CSIRO), September 2017

### 2.7.4.1.2 Hydrological regimes and connectivity

Within the zone of potential hydrological change, mean annual potential evaporation far exceeds rainfall, particularly in the summer months (companion product 1.1 for the Galilee subregion (Evans et al., 2014)). Furthermore, rainfall is highly variable. These major components of the water balance assert a substantial control on the availability of surface water in the streams landscape groups of the zone. Limited available streamflow data suggest that surface water flows are variable in river systems within the zone (Figure 17).

Within the zone of potential hydrological change, annual streamflow shows a high degree of interannual variability (companion product 1.1 for the Galilee subregion (Evans et al., 2014)). Flows in a given year can vary from almost no flow to major floods, although there is at least some flow each year in the main river channels (Figure 47a of companion product 1.1 (Evans et al., 2014)).

Mean monthly flow is also highly variable. Most streams within the zone of potential hydrological change have prolonged no-flow periods each year (Dight, 2009). Flows vary greatly between months with minimal to no flow from July to October, while most flows occur between December and April (Figure 47b of companion product 1.1 (Evans et al., 2014)). The streamflow within the zone is thus characterised as one of dry seasonal flows (Figure 17).

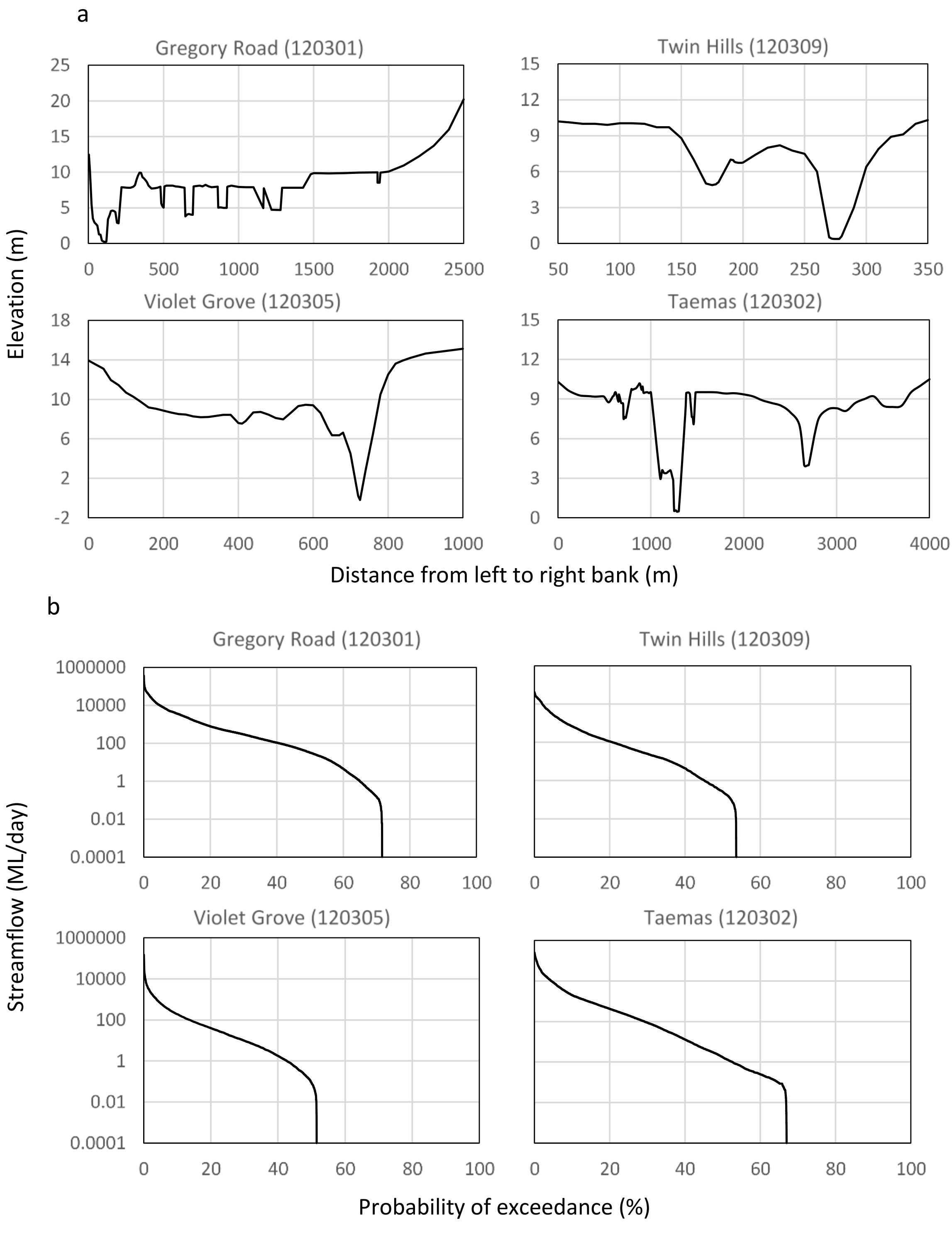


**Figure 17 River cross-sections (a) and flow duration curves (b) at stream gauges 120301 (Belyando River at Gregory Development Road), 120309 (Mistake Creek at Twin Hills), 120305 (Native Companion Creek at Violet Grove) and 120302 (Cape River at Taemas)**

Stream gauge locations are shown in Figure 15.
Source: https://water-monitoring.information.qld.gov.au/ Accessed 1 February 2017

Surface water – groundwater connectivity in the Belyando river basin is thought to occur in a number of different ways. First, there is discharge from shallow groundwater systems to rivers. Another form of interaction is discharge from springs creating outflow pools in rivers. An example of this situation is where the outflow from Joshua Spring and the House Springs group (part of the Doongmabulla Springs complex) converge to provide the main discharge feeding the Carmichael

River for a distance of up to 20 km (Fensham et al., 2016; see Section 2.7.3.1.1). There is also some discharge from groundwater systems to lakes (e.g. Lake Galilee and Lake Buchanan).

Groundwater may also be important in providing moisture for vegetation within the streams landscape groups. As an example, shallow groundwater (i.e. <20 m depth from surface to watertable) may be transpired by deep-rooted riparian trees such as river red gums and other GDEs (Section 2.3.2 of companion product 2.3 for the Galilee subregion (Evans et al., 2018)).

### 2.7.4.1.3 Ecological processes

The hydrological regimes and surface water – groundwater connectivity within the zone of potential hydrological change of the Galilee subregion result in surface water within the streams landscape groups being available for limited periods in any given year (Figure 17). A conceptual model for a riverine landscape with dry seasonal flows and groundwater – surface water connectivity, such as within the zone, is provided in Figure 18.

The dry seasonal flows of the streams within the Belyando river basin result in the ecosystems of the streams landscape groups being characterised by 'boom–bust' cycles. Specifically, diversity in the system is maintained by natural cycles of river flow and drying, driven by surface water inputs (Sternberg et al., 2015). Although more arid rivers further west in the Galilee assessment extent are driven by highly unpredictable rainfall, the 'boom–bust' cycle in the Belyando river basin is predictable and follows an annual hydrological cycle (Blanchette and Pearson, 2012, 2013). Ecological processes within this system operate in an environmental context where there is seasonally predictable summer rainfall which produces a resource pulse that is followed by a predictable period of drying. The drying phase is a relatively constant process in an average year uninterrupted by rainfall outside the summer period (Blanchette and Pearson, 2013).

During the months of high rainfall (generally between December and April), the dry rivers begin to flow and seasonally isolated water-dependent habitats (e.g. waterholes) are connected. This annual period of in-channel flow, or flow pulses, may be associated with large flood events producing overbank flow (see below) or it may occur independently in response to localised rainfall (Sheldon et al., 2010). Periods of very high rainfall, which occur infrequently, are responsible for large flood events. During these high rainfall periods, there is overbank flow and the environment becomes a large network of interconnected river channel and floodplain habitat (Figure 19). These overbank flooding events are used to identify the onset of the 'boom' phase in Australia's dryland rivers (e.g. Sheldon et al., 2010).

During the 'boom' phase, aquatic and terrestrial productivity is high. Dispersal of freshwater fauna occurs during this phase and important life-history stages are completed. A large component of the aquatic fauna in this system and elsewhere in the Galilee assessment extent is capable of long-distance dispersal, with animals recolonising areas from distant waterholes once movement pathways are opened by flooding. Fish are a prime example of such a group (e.g. Kerezsy et al., 2013). At the end of the wet phase, all of the waterholes are likely to be replenished and exist at their most productive levels (Figure 19).

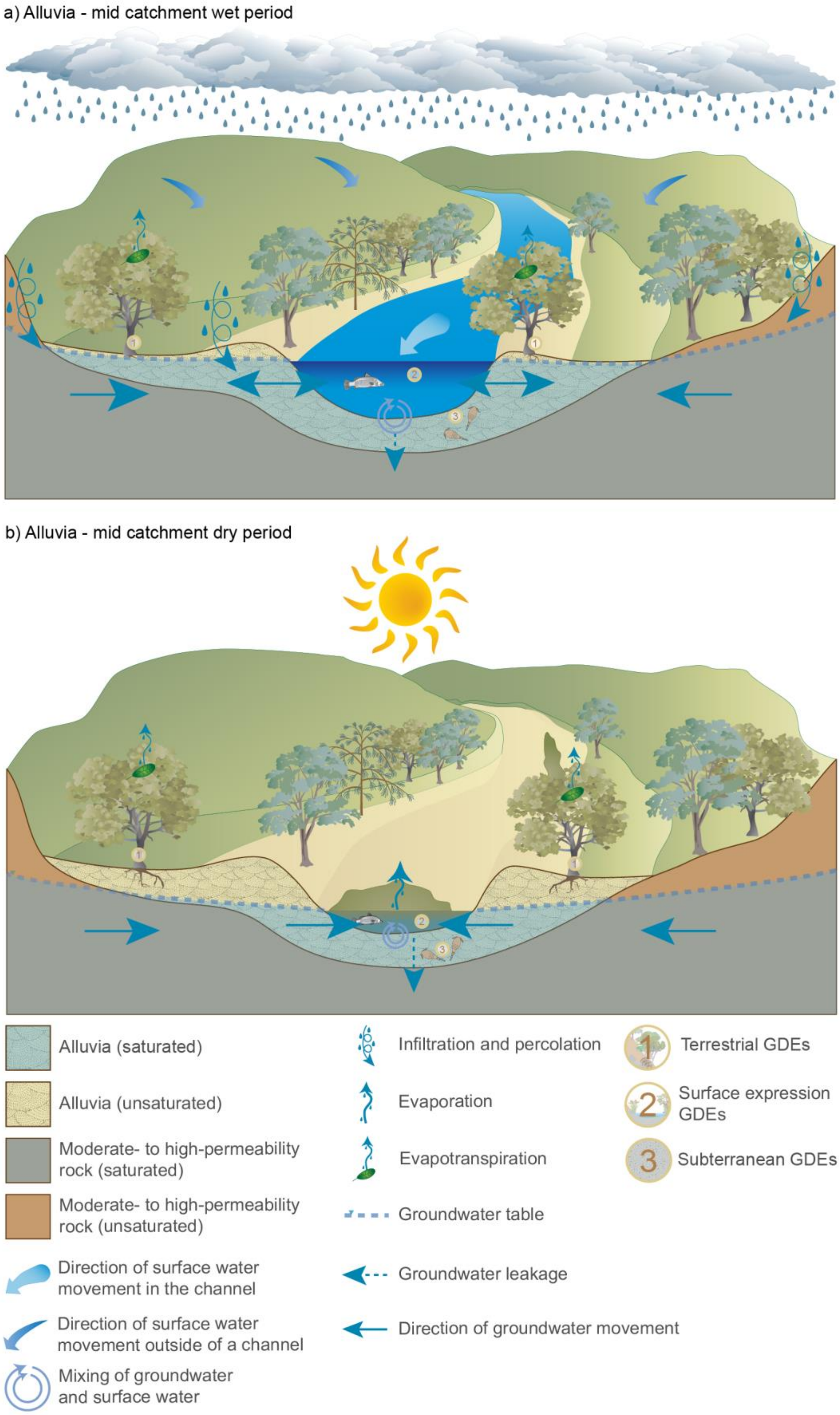


**Figure 18 Conceptual model of a riverine landscape in the zone of potential hydrological change of the Galilee subregion, showing seasonal variation in streamflow**

GDE = groundwater-dependent ecosystem

Source: adapted from Queensland Department of Science, Information Technology and Innovation (Dataset 3), © The State of Queensland (Department of Science, Information Technology and Innovation) 2015

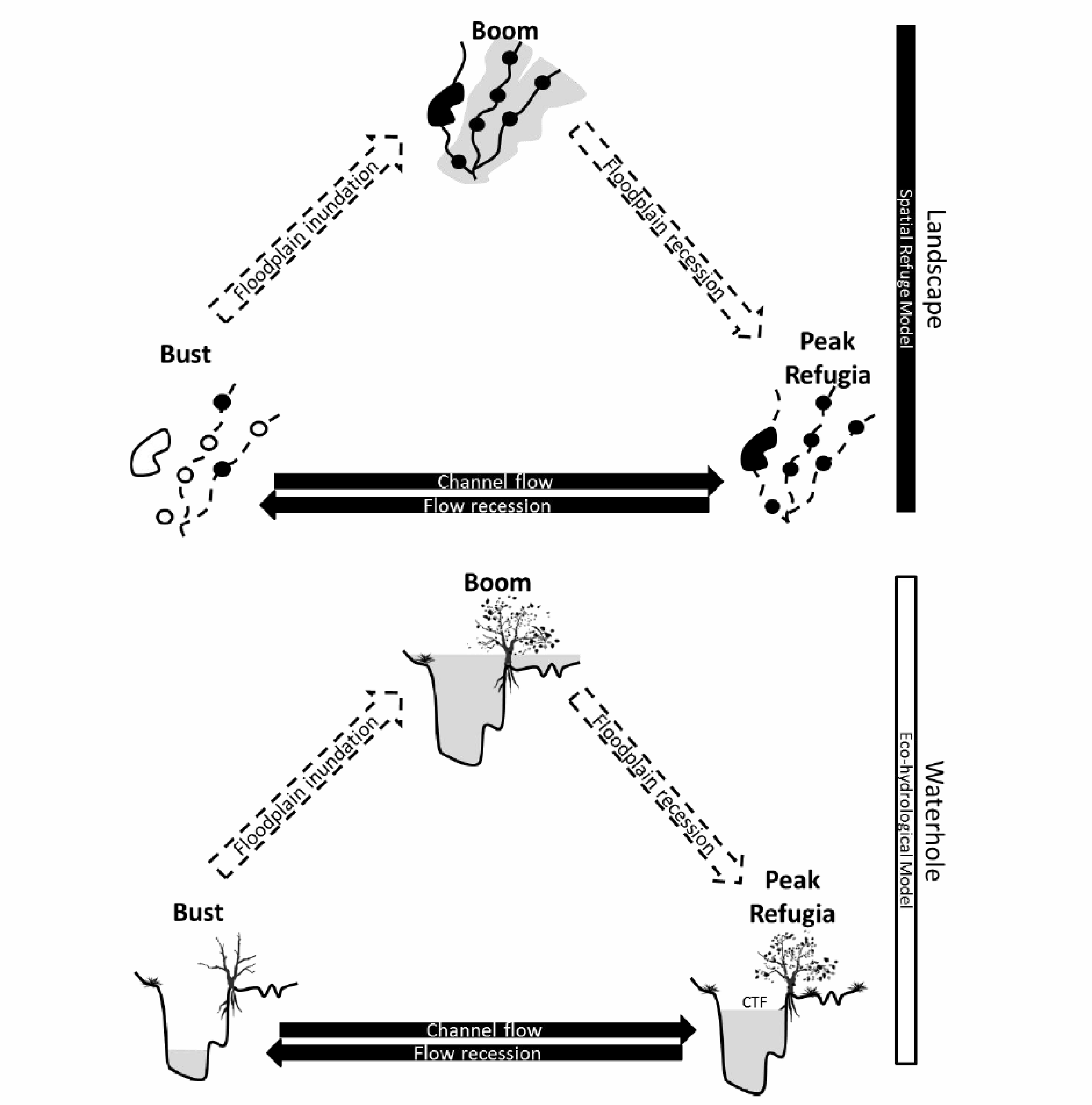


**Figure 19 Model of the 'boom–bust' dynamics of the streams landscape groups within the Galilee subregion zone of potential hydrological change, showing hydro-ecological associations over a range of flow conditions at the scale of the landscape (top) and an individual waterhole (bottom)**

CTF = cease to flow
Source: Sternberg et al. (2015), Figure 1

Thus, the streams landscape groups of the Galilee subregion's zone of potential hydrological change experience annual in-channel flows each summer and flood events at irregular intervals. The in-channel flows are important for maintaining connectivity and dispersal of aquatic organisms; however, they do not feature the high primary productivity of the flood events (Sheldon et al., 2010).

During the months of low or no rainfall (generally May to November), drying of the drainage system produces a series of waterholes and running reaches that have variable connectivity

(Pusey and Arthington, 1996). Where the drying results in cease-to-flow events, shallow waterbodies dry out and chains of pools, isolated pools or completely dry riverbeds result, depending on riverbed morphology (Figure 19). As conditions continue to dry, evaporation will reduce the depth of each waterhole. Over time, productivity will change and the physico-chemical conditions decline. Changes occur in dissolved oxygen, conductivity, and pH (Blanchette and Pearson, 2013). Within the 'Streams, GDE' landscape group, groundwater inputs may be important to maintain waterholes during this 'bust' phase.

Waterholes during low-flow or no-flow periods tend to be characterised by high turbidity and limited light penetration. The aquatic food webs of these waterholes are typically driven by energy inputs from filamentous algae that form as a highly productive band in the shallow littoral margins. Phytoplankton blooms and zooplankton may also be important parts of the aquatic food web during the 'bust' phase. The algae, phytoplankton and zooplankton support large populations of snails, crustaceans and fish (Bunn et al., 2003).

### 2.7.4.1.4 Vegetation

Dominant canopy species in the riparian vegetation of the streams landscape groups include various eucalypts (*Eucalyptus camaldulensis*, *E. coolabah* and others), red bauhinia (*Lysiphyllum carronii*), whitewood (*Atalaya hemiglauca*), *Melaleuca leucadendra* and *M. fluviatilis* and several bloodwood (*Corymbia*) species including *C. plena*, *C. dallachiana*, *C. erythrophloia* and *C. leichhardtii*. The riparian regional ecosystems (REs) that occur within the zone of potential hydrological change include:

- RE 10.3.12 'Corymbia dallachiana and C. plena or C. terminalis woodland to open woodland on sandy alluvial terraces (eastern)'. Within the zone, this RE usually has *Aristida* spp. as the dominant component of the ground layer. An example of this RE is found fringing Sandy Creek on the proposed site of the Kevin's Corner Coal Mine.
- RE 10.3.13 'Melaleuca fluviatilis and/or Eucalyptus camaldulensis woodland along watercourses'. This RE is found along larger watercourses as narrow bands along channels and levees with sandy to clayey soils. As an example, it occurs along the Carmichael River on the lease area for the proposed Carmichael Coal Mine. RE 10.3.13 is considered to be of high biological value both in terms of the habitat it provides and also in functioning as a corridor for movement of animals. Seasonal nectar availability is high. It provides habitat for a threatened plant, the waxy cabbage palm (*Livistona lanuginosa*).
- RE 10.3.14 'Eucalyptus camaldulensis and/or E. coolabah woodland to open woodland along channels and on floodplains'. This RE is considered to be a facultative GDE. It has high biological value both in terms of the habitat it provides and also in functioning as a corridor for movement of animals. When water is present the RE provides habitat for waterbirds. It occurs along the larger creeks and rivers such as the Carmichael River.
- RE 11.3.2 'Eucalyptus populnea woodland on alluvial plains'
- RE 11.3.25 'Eucalyptus tereticornis or E. camaldulensis woodland fringing drainage lines'. This RE occurs on fringing levees and banks of major rivers and drainage lines where the soils are very deep, alluvial, cracking clays. It comprises the major vegetation fringing the Carmichael River within the zone and is considered a GDE.

- RE 11.3.27 'Freshwater wetlands'. The vegetation of this RE is variable and it includes fringing sedgelands and eucalypt woodlands around lakes, billabongs and depressions on floodplains. It is present as a fringing open forest/woodland along Cabbage Tree Creek just to the south of the Carmichael River.
- RE 11.5.3 'Eucalyptus populnea +/- E. melanophloia +/- Corymbia clarksoniana woodland on Cainozoic sand plains and/or remnant surfaces'.

Overall, riparian vegetation within the Belyando river basin is considered to be in very poor condition and to have experienced a major decline over the last 30 years. This decline is mostly the consequence of floodplain clearing (Dight, 2009).

'Brigalow (Acacia harpophylla dominant and co-dominant)' which is listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) as an 'Endangered' ecological community, occurs within the streams landscape groups. This ecological community occurs patchily in the eastern half of the Galilee subregion's zone of potential hydrological change (see companion product 3-4 for the Galilee subregion (Lewis et al., 2018)). The vegetation types that make up the Brigalow ecological community mostly occur on acidic and salty clay soils. Within the zone of potential hydrological change these are mostly on deep cracking clay soils. A small proportion of the Brigalow ecological community is associated with river and creek flats (Department of the Environment and Energy, 2017a).

## 2.7.4.1.5 Flora and fauna

Macrophytes are rare and macrophyte assemblages are poorly developed in the drainages along the zone of potential hydrological change of the Galilee subregion. As an example, sampling at three locations close to the zone during the assessment and benchmarking of key sentinel wetlands in the Burdekin river basin, Loong et al. (2005) failed to locate any macrophytes (Table 9). However, sampling as part of the proposed Carmichael Coal Mine environmental impact statement, GHD (2012a) located macrophytes in low diversity and abundance. Macrophytes were detected at one of five sampling sites along the Carmichael River, at one of three sites along Cabbage Tree Creek, at a gilgai site and at multiple dam sites (GHD, 2012a). Abundance was higher in Cabbage Tree Creek than in the Carmichael River. The macrophyte species present were *Persicaria attenuata*, *Ottelia ovalifolia* (swamp lily), *Cyperus difformis* (dirty dora), *Cyperus* sp., *Monochoria cyanea*, *Myriophyllum* sp. and *Potamogeton* sp. These species are typical of shallow or still water conditions in these parts of central Queensland.

**Table 9 Presence of macrophytes in the Belyando river basin**

| Site | Waterway | River basin | Macrophytes |
|---|---|---|---|
| N009 | Suttor River | Belyando/Suttor | Non-recorded |
| N011 | Mistake Creek | Belyando/Suttor | Non-recorded |
| N014 | Suttor River | Belyando/Suttor | Non-recorded |

Source: Loong et al. (2005)

Different dispersal strategies are used by animal species that have evolved to live in environments with 'boom–bust' dynamics such as the streams landscape groups of the Galilee assessment extent (Sheldon et al., 2010). Some species are mobile and move readily between suitable habitats irrespective of flow conditions. Examples of this strategy include Coleoptera (beetles) and Hemiptera (bugs). Another group, that includes crustaceans and some types of fish, disperses between waterholes during periods of streamflow. A third group, that includes snails, mussels and some fishes, exhibits little dispersal even when flow conditions are favourable (Sheldon et al., 2010). Streams within the zone of potential hydrological change support a wide range of fish and invertebrates such that each of these dispersal strategies is likely to be present.

Eleven species of fish have been recorded from the streams landscape groups within the zone of potential hydrological change. A further six species are predicted to occur within the zone (Table 10). None of the species are restricted to the Belyando river basin and each species has a large geographic range.

A diverse range of aquatic invertebrates occurs in the streams landscape groups within the zone of potential hydrological change. In general, available information on the taxa present is limited, thus further sampling is likely to identify the presence of additional taxa. Ten orders of invertebrates were recorded during sampling undertaken for environmental impact statements for many of the proposed coal mines within the Galilee subregion. Within the 10 orders, 48 families of aquatic invertebrates were identified. These included three families of decapod crustacean, eight families of beetle, three families of fly, three families of mayfly, ten families of bug, five families of dragonfly and damselfly, five families of caddisfly, two families of bivalve mollusc and four families of gastropod mollusc.

The streams landscape groups are important habitat for a range of threatened plants and vertebrate animals. The threatened species known or predicted to occur within the Galilee subregion zone of potential hydrological change are detailed below.

In parts of the zone the waxy cabbage palm is present in the riparian zone. It occurs in the lower Suttor and Belyando river basins (Pettit and Dowe, 2004; GHD, 2013a, 2013b). Within the zone, it has been recorded on the proposed Carmichael Coal Mine tenement along a 17.5 km stretch of the Carmichael River and associated tributaries (GHD, 2013b). Within the Carmichael River, waxy cabbage palms occur within the channel bed and on channel bars (GHD, 2013a). The species is listed as 'Vulnerable' nationally under the EPBC Act and under Queensland's *Nature Conservation Act 1992* (Nature Conservation Act).

The koala (*Phascolarctos cinereus*) occurs within the streams landscape groups in the Galilee subregion zone of potential hydrological change. Koalas in Queensland are listed as 'Vulnerable' nationally (EPBC Act) and under Queensland legislation (Nature Conservation Act). Koalas in semi-arid environments, including the zone, inhabit forest and woodland dominated by *Eucalyptus* species with important food and habitat trees including *Eucalyptus camaldulensis*, *E. populnea*, *E. crebra*, *E. tereticornis*, *E. melanophloia*, *E. tessellaris* and *Melaleuca bracteata* (Gordon et al., 1988; Ellis et al., 2002). *Eucalyptus camaldulensis* is the dominant tree in several of the regional ecosystems within the streams landscape groups (see Section 2.7.4.1.4). Koalas occur in riparian *E. camaldulensis* woodland along Tallarenha Creek on the South Galilee Coal Mine development (MET Serve, 2012a, 2012b). In semi-arid Queensland, riparian vegetation along drainage lines is considered to be an important refuge area for koalas during droughts (Sullivan et al., 2002 cited in Department of the Environment and Energy, 2017b).

**Table 10 Summary of fish species recorded during surveys for environmental impact statements at five proposed coal mine developments in the Galilee subregion zone of potential hydrological change**

| Species | Proposed coal mining project | | | | |
|---|---|---|---|---|---|
| | Alpha | Carmichael | China Stone | Kevin’s Corner | South Galilee |
| Bony bream *Nematalosa erebi* | ✓ | ✓ | x | ✓ | ✓ |
| Hyrtl's tandan *Neosilurus hyrtlii* | ✓ | ✓ | x | ✓ | ✓ |
| Black catfish *Neosilurus ater* | x | * | x | x | x |
| Rendahl's catfish *Porochilus rendahli* | x | * | x | x | x |
| Soft-spined catfish *Neosilurus mollespiculum* | x | * | x | x | x |
| Flyspecked hardyhead *Craterocephalus stercusmuscarum* | x | ✓ | x | x | x |
| Desert rainbowfish *Melanotaenia splendida splendida* | ✓ | ✓ | ✓ | ✓ | ✓ |
| Agassiz's glassfish *Ambassis agassizii* | ✓ | ✓ | ✓ | ✓ | ✓ |
| Spangled perch *Leiopotherapon unicolor* | ✓ | ✓ | ✓ | ✓ | ✓ |
| Banded/barred grunter *Amniataba percoides* | ✓ | ✓ | x | x | x |
| Small-headed grunter *Scortum parviceps* | x | * | x | x | x |
| Carp gudgeon sp. *Hypseleotris sp.* | ✓ | x | x | ✓ | x |
| Midgley's carp gudgeon *Hypseleotris species 1* | x | ✓ | x | x | ✓ |
| Western carp gudgeon *Hypseleotris klunzingeri* | x | ✓ | x | x | ✓ |
| Flathead gudgeon *Philypnodon grandiceps* | x | * | x | x | x |
| Purple-spotted gudgeon *Mogurnda adspersa* | ✓ | ✓ | x | ✓ | ✓ |
| Sleepy cod *Oxyeleotris lineolata* | x | ✓ | x | x | x |
| Seven-spot archerfish *Toxotes chatareus* | x | * | x | x | x |

✓ indicates the species was recorded at the location, * indicates the species is predicted to occur at the location, x indicates the species was not recorded at the location. Scientific names for each species are shown in italics below each common species name.
Source: Environmental impact statements for Alpha (Hancock Prospecting Pty Ltd, 2010), Carmichael (GHD, 2012a), China Stone (Cumberland Ecology, 2015), Kevin’s Corner (Hancock Galilee Pty Ltd, 2011) and South Galilee (ALS Water Resources Group, 2011)

The ornamental snake (*Denisonia maculata*) occurs within the zone of potential hydrological change. The species is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017c). Within the zone, it will potentially occupy all four of the broad landscape groups but is most likely to occur in the streams landscape groups and 'Floodplain, terrestrial GDE' landscape group. The ornamental snake is considered to be water-dependent as it feeds almost exclusively on frogs. It occurs in riparian vegetation along watercourses, on the margins of wetlands including lakes and swamps and in terrestrial vegetation that is likely to be groundwater-dependent. The latter category includes woodland and open woodland of coolibah (*Eucalyptus coolabah*), poplar box (*E. populnea*), brigalow (*Acacia harpophylla*), gidgee (*A. cambagei*) and blackwood (*A. argyrodendron*) (Department of the Environment and Energy, 2017c). The REs in which it has been found all have clay soils. These REs include 11.4.3, 11.4.6, 11.4.8 and 11.4.9 (Department of the Environment and Energy, 2017c).

The yakka skink (*Egernia rugosa*) is a threatened lizard that occurs within the Galilee subregion zone of potential hydrological change. It is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017d). The species occurs in woodland and open forest dominated by a range of trees including species of *Acacia*, *Eucalyptus*, *Casuarina* and *Callitris* spp. Yakka skinks are burrowing animals that occur in colonies or small groups (Chapple, 2003). Within the zone the yakka skink is likely to occupy sand plains, clay and clay loam plains, sandstone rises and minor pediments and vegetation fringing watercourses and stream channels and on alluvial plains. Therefore, it is expected to occupy the streams landscape groups. Potential habitat includes riparian vegetation along the Carmichael River and Cabbage Tree Creek on the Carmichael Mine site (GHD, 2012b). The water-dependency of the species is poorly understood.

The southern subspecies of the squatter pigeon (*Geophaps scripta scripta*) is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017e). It is a granivorous bird that occurs through much of the Galilee subregion zone of potential hydrological change. It was recorded during surveys as part of the environmental impact statements for five of the major coal mine developments in the zone. From north to south these are China Stone, Carmichael, Kevin's Corner, Alpha and China First. The squatter pigeon (southern) forages and breeds in a range of open-forest, woodland and open-woodland vegetation types that have a grassy understory. It depends on surface water as it needs to drink on a daily basis and, as a consequence, foraging and nesting sites are located within 3 km of a water source. Water sources used by the species include rivers, lakes and artificial sources such as farm dams (Department of the Environment and Energy, 2017e). Therefore, the squatter pigeon uses water sources within the streams landscape groups.

The red goshawk (*Erythrotriorchis radiatus*) is listed as 'Vulnerable' nationally (EPBC Act) and 'Endangered' in Queensland (Nature Conservation Act). The range of this species includes small areas of the zone of potential hydrological change within the Galilee subregion. The species can be considered to be water-dependent because of the nest sites it uses. Nests are constructed in tall trees (mean height of 31 m) that are located within 1 km of, and commonly beside, permanent water. Water sources include rivers, swamps and pools (DERM, 2012). Given this nesting preference, the red goshawk is likely to occur within the streams landscape groups.

The eastern/southern subspecies of the star finch (*Neochmia ruficauda ruficauda*) is classified as 'Endangered' nationally (EPBC Act) and in Queensland (Nature Conservation Act). However, an assessment of the conservation status of all Australian bird taxa in 2010 concluded that its status should be critically endangered (possibly extinct) (Garnett et al., 2011). The star finch (eastern) may previously have occurred in the Galilee subregion zone of potential hydrological change; however, there are no confirmed records (Department of the Environment and Energy, 2017f). The star finch needs surface water from which it drinks daily. It occupies grassland and grassy woodland close to freshwater, in particular in riverine habitats (Garnett et al., 2011). Within the zone it is most likely to occur in the streams landscape groups.

### *2.7.4.2 Qualitative mathematical model*

At the qualitative modelling workshop, separate modelling efforts were initially conducted for both temporary and permanent stream systems, but after completion of a model for temporary streams in a flowing state it was concluded that the essential dynamics of both systems could be addressed by the same model. Therefore, the 'Streams, GDE' and 'Streams, non-GDE' landscape groups were combined within a single qualitative mathematical model.

An ecologically important feature of temporary streams is the existence and connectivity of refuge habitats (e.g. Sheldon et al., 2010; Robson et al., 2011). In seasons or years where stream reaches are dry, isolated pools and springs within the floodplain may persist depending on factors that control their depth and persistence. Populations of aquatic primary producers, invertebrates and vertebrates within these refuge habitats serve as a critical source of propagules that, following high rainfall events that reconnect the stream channel with flowing surface water, can fuel a 'mini-boom' state for the stream ecosystem (Arthington et al., 2010; Arthington and Balcombe, 2011; Kerezsy et al., 2011). Once isolated pools and springs (non-flowing temporary stream) have been transformed into a flowing stream with a fully functioning stream ecosystem, it was considered that its basic ecological features are functionally the same as those for permanent stream systems.

In the model for temporary streams (in a flowing state) and permanent streams, surface water serves a key role in providing both lateral and downstream transport of detritus in the stream channel and floodplain. It also determines, through wetted area of the channel, the amount of primary production generated by algae. Detritus and algae function as the principal resources that support populations of aquatic invertebrates and fishes (Blanchette, 2012; Guo et al., 2016). Surface water also plays a key role in recharging stores of deep groundwater in confined aquifers, and in turn, stores of deep groundwater can contribute to shallow groundwater. Potential impacts from mining operations include direct interception of precipitation, draining or capture of surface water through subsidence and fracturing of the surface, and dewatering of shallow and deep aquifers. An uncertain link in the model was the degree to which stores of near-surface or shallow groundwater could contribute to surface water that enters the stream channel. This led to the development of two alternative models, one with (Figure 20) and one without (Figure 21) a link from shallow groundwater to surface water.

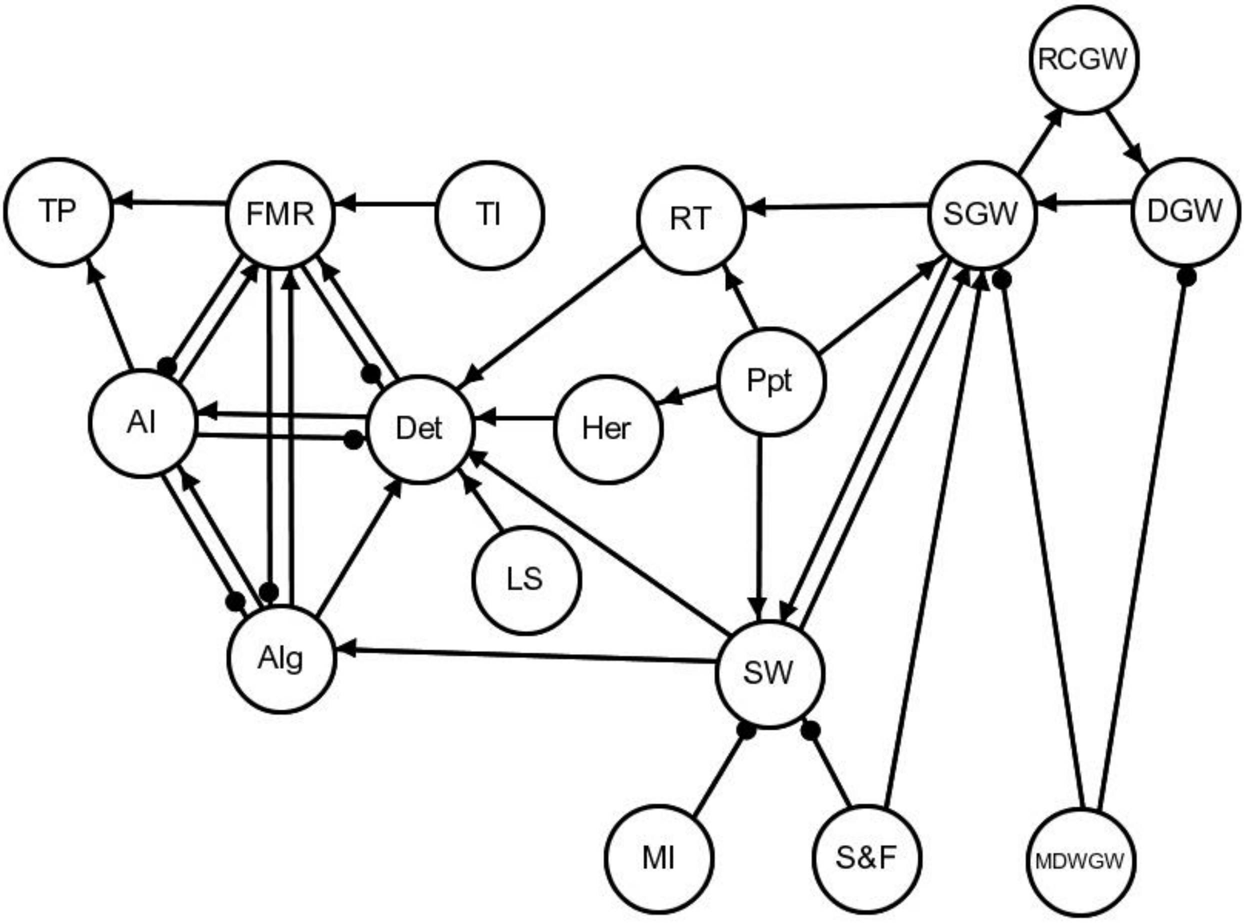


**Figure 20 Signed digraph model (Model 1) of the streams landscape groups in the Galilee subregion zone of potential hydrological change, with a direct link between shallow groundwater (SGW) and surface water (SW)**

Model variables are: aquatic invertebrates (AI), algae (Alg), detritus within stream channel (Det), deep groundwater (confined aquifers) (DGW), fishes (migrant and refugial populations) (FMR), herbs (Her), lateral stores of detritus (LS), mine dewatering of ground water (MDWGW), mine interception (MI), precipitation (Ppt), recharge of confined groundwater (RCGW), riparian trees (RT), subsidence and fracturing from mining (S & F), shallow groundwater (SGW), surface water (SW), terrestrial invertebrates (TI), terrestrial predators (TP).

Data: Bioregional Assessment Programme (Dataset 4)

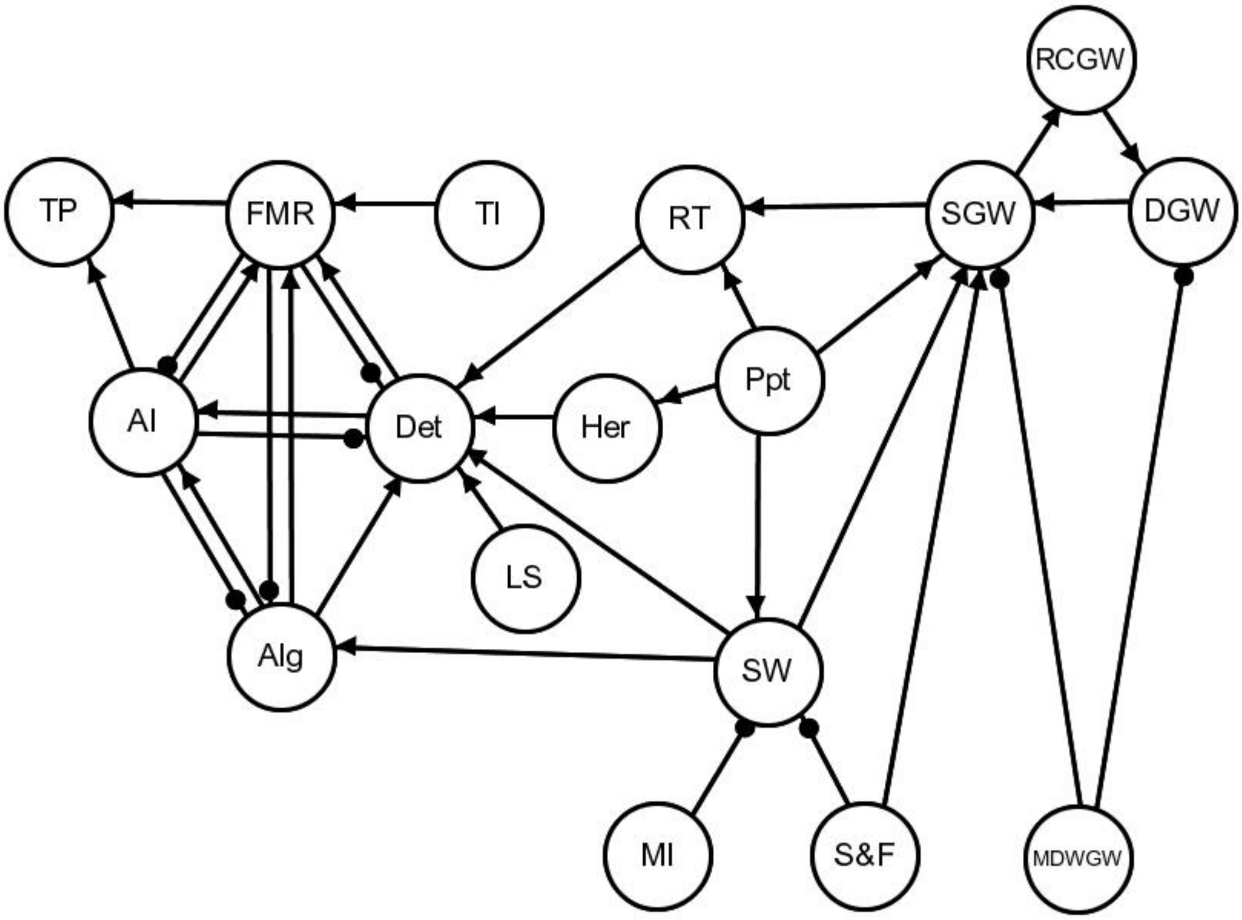


**Figure 21 Signed digraph model (Model 2) of the streams landscape groups in the Galilee subregion zone of potential hydrological change, which has no direct link between shallow groundwater (SGW) and surface water (SW)**

Model variables are: aquatic invertebrates (AI), algae (Alg), detritus within stream channel (Det), deep groundwater (confined aquifers) (DGW), fishes (migrant and refugial populations) (FMR), herbs (Her), lateral stores of detritus (LS), mine dewatering of ground water (MDWGW), mine interception (MI), precipitation (Ppt), recharge of confined groundwater (RCGW), riparian trees (RT), subsidence and fracturing from mining (S&F), shallow groundwater (SGW), surface water (SW), terrestrial invertebrates (TI), terrestrial predators (TP).
Data: Bioregional Assessment Programme (Dataset 4)

At the qualitative modelling workshop there was discussion about the importance of pool refugia and connectedness among pools by floods/pulses, and how this relates to higher trophic level organisms such as fish. At the same time, it was recognised that pool refugia would be a difficult receptor impact variable target for ecologists as it requires knowledge of depth of channel and related factors. It is arguably closer to a hydrology question than an ecology question, as pointed out by some of the expert commentary. For that reason, discussion at the workshop led to the development of a Galilee subregion streams qualitative model that identifies algae as a basal resource variable. This is in turn linked to the surface water regime as mediated through wetted area, not only of pools but also reaches and other stream components. For example, wetted area and hence algae may have a predictable relationship with no-flow days in the streams landscape groups.

Conceptual, surface water and groundwater modelling for the Galilee subregion indicated that potential impacts may occur from mine interception of rainfall, subsidence and fracturing from mining and aquifer dewatering adjacent to mines. Based on all possible combinations of these potential impacts, a total of seven cumulative impact scenarios were developed for qualitative analyses of response predictions (Table 11).

**Table 11 Summary of the cumulative impact scenarios (CISs) for the streams landscape groups in the Galilee subregion zone of potential hydrological change**

| CIS | MI | S&F | MDWGW |
|---|---|---|---|
| C1 | + | 0 | 0 |
| C2 | 0 | + | 0 |
| C3 | 0 | 0 | + |
| C4 | + | + | 0 |
| C5 | + | 0 | + |
| C6 | 0 | + | + |
| C7 | + | + | + |

Pressure scenarios are determined by combinations of no-change (0) or an increase (+) in the following signed digraph variables: mine interception (MI), subsidence and fracturing from mining (S&F), and mine dewatering of groundwater (MDWGW).
Data: Bioregional Assessment Programme (Dataset 4)

Qualitative analysis of the signed digraph models in Figure 20 and Figure 21 generally indicates a zero, ambiguous or negative response prediction for all biological variables within the ecosystem associated with the streams landscape groups as a result of mine interception (e.g. of rainfall or overland flow), subsidence and fracturing, and mine dewatering (Table 12 and Table 13, respectively). The only variable that had a positive response prediction was algae for Model 1 as a result of impacts from mine dewatering of groundwater under cumulative impact scenario 3 (increased mine dewatering of groundwater (MDWGW), no changes related to other variables). For Model 2, which omitted the link of replenishment of surface water from shallow groundwater, there was less ambiguity for the response of fish, with negative response predictions across all scenarios except for a stand-alone impact from subsidence and fracturing (cumulative impact scenario C2, Table 13) for fish.

**Table 12 Predicted response of the signed digraph stream and riparian variables (Model 1) in the streams landscape groups to (cumulative) changes in hydrological response variables**

| Signed digraph variable (name) | Signed digraph name (shortened form) | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
|---|---|---|---|---|---|---|---|---|
| Surface water | SW | (–) | ? | 0 | ? | (–) | ? | ? |
| Lateral stores of detritus | LS | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Aquatic invertebrates | AI | ? | ? | ? | ? | ? | ? | ? |
| Algae | Alg | ? | ? | (+) | ? | ? | ? | ? |
| Detritus within stream channel | Det | (–) | ? | (–) | ? | (–) | ? | ? |
| Herbs | Her | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Precipitation | Ppt | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fishes (migrant and refugial populations) | FMR | (–) | ? | (–) | ? | (–) | ? | ? |
| Terrestrial invertebrates | TI | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Shallow groundwater | SGW | (–) | ? | (–) | ? | (–) | ? | ? |
| Deep groundwater (confined aquifers) | DGW | (–) | ? | (–) | ? | (–) | ? | ? |
| Riparian trees | RT | (–) | ? | (–) | ? | (–) | ? | ? |
| Recharge of confined groundwater | RCGW | (–) | ? | (–) | ? | (–) | ? | ? |
| Terrestrial predators | TP | ? | ? | ? | ? | ? | ? | ? |

Qualitative model predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
Data: Bioregional Assessment Programme (Dataset 4)

**Table 13 Predicted response of the signed digraph variables (Model 2) of the stream and riparian variables in the streams landscape groups to (cumulative) changes in hydrological response variables**

| Signed digraph variable (name) | Signed digraph name (shortened form) | C1 | C2 | C3 | C4 | C5 | C6 | C7 |
|---|---|---|---|---|---|---|---|---|
| Surface water | SW | (–) | (–) | 0 | (–) | (–) | (–) | (–) |
| Lateral stores of detritus | LS | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Aquatic invertebrates | AI | ? | ? | ? | ? | ? | ? | ? |
| Algae | Alg | ? | ? | (+) | ? | ? | ? | ? |
| Detritus within stream channel | Det | (–) | ? | (–) | ? | (–) | ? | (–) |
| Herbs | Her | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Precipitation | Ppt | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Fishes (migrant and refugial populations) | FMR | (–) | ? | (–) | (–) | (–) | (–) | (–) |
| Terrestrial invertebrates | TI | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Shallow groundwater | SGW | (–) | ? | (–) | ? | (–) | ? | ? |
| Deep groundwater (confined aquifers) | DGW | (–) | ? | (–) | ? | (–) | ? | (–) |
| Riparian trees | RT | (–) | ? | (–) | ? | (–) | ? | ? |
| Recharge of confined groundwater | RCGW | (–) | ? | (–) | ? | (–) | ? | ? |
| Terrestrial predators | TP | ? | ? | ? | ? | ? | ? | ? |

Qualitative model predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
Data: Bioregional Assessment Programme (Dataset 4)

### *2.7.4.3 Temporal scope, hydrological response variables and receptor impact variables*

In BAs, the potential ecological impacts of coal resource development are assessed in two future time periods – 2013 to 2042 and 2073 to 2102. These are labelled as the short- and long-assessment periods, respectively. Potential ecological changes are quantified in BAs by predicting the state of a select number of receptor impact variables in the short- and long-assessment years. These predictions are made conditional on the values of certain groundwater and surface water statistics that summarise the outputs of numerical model predictions in an interval of time that precedes the assessment year. In all cases these predictions also allow for the possibility that changes in the future may depend on the state of the receptor impact variable in the reference year 2012, and consequently this is also quantified by conditioning on the predicted hydrological conditions in a reference interval that precedes 2012 (see companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)).

For surface water and groundwater variables predicted from the numerical modelling in the Galilee subregion, the reference assessment interval is defined as the 30 years preceding 2012 (i.e. 1983 to 2012). For surface water variables in the Galilee subregion, the short-assessment interval is defined as the 30 years preceding the short-assessment year (i.e. 2013 to 2042), and similarly the long-assessment interval is defined as the 30 years that precede the long-assessment year (i.e. 2073 to 2102). Maximum groundwater drawdown (metres) is considered across the full 90-year simulation period (2013 to 2102). However, for the uppermost groundwater model layer (Layer 1 – Quaternary alluvium and Cenozoic sediments), the conceptualisation of the boundary conditions means that maximum drawdown does not occur before 2102 (this is explained further in Section 2.6.2.8.1 of companion product 2.6.2 for the Galilee subregion (Peeters et al., 2018)). Thus, for the purposes of the receptor impact modelling workshop, the time to maximum drawdown was effectively considered fixed at 2102.

In BAs, choices about receptor impact variables must balance the project's operational constraints with the objectives of the assessment and the expectations of the community (companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018)). This choice is guided by selection criteria that acknowledge the potential for complex direct and indirect effects within perturbed ecosystems, and the need to keep the expert elicitation of receptor impact models tractable and achievable (companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et. al., 2018)).

For the streams landscape groups, the qualitative modelling workshop identified mine dewatering of shallow and deep groundwater, mine interception of surface water through subsidence and fracturing, and mine interception of precipitation and its effect on the recharge of confined groundwater and surface water flows as the hydrological factors that were thought to: (i) be instrumental in maintaining and shaping the ecosystem's components and processes, and the ecological values provided by the ecosystem and, (ii) have the potential to change due to coal resource development (Figure 20). All of the ecological components and processes represented in the qualitative model are potential receptor impact variables and most of these are predicted to vary as the hydrological factors vary either individually or in combination (Table 12 and Table 13). Further information about the surface water and groundwater modelling approaches used to simulate the hydrological effects of the main mining processes identified above is discussed in companion product 2.6.1 (Karim et al., 2018) and companion product 2.6.2 (Peeters et al., 2018) for the Galilee subregion. For example, the surface water modelling approach to address mine interception of rainfall and overland flow is outlined in Section 2.6.1.3 of Karim et al. (2018).

At the initial qualitative modelling workshop, the following receptor impact variables were chosen: riparian trees, and algae and/or invertebrates. The second receptor impact variable was specified further on the initial day of the second receptor impact modelling workshop in Brisbane in October 2016. The decision was taken to use a species of mayfly (order Ephemeroptera) in the genus *Offadens* of the family Baetidae (Webb and Suter, 2011). The identification of the genus is based on expert feedback from Phil Suter, La Trobe University, Wodonga, Victoria (Dr Phil Suter, 26 Oct 2016, pers. comm.).

The mayfly in the genus *Offadens* was chosen as the invertebrate receptor impact variable for a number of reasons, specifically: (i) data were available for the species from sampling locations in the upper Burdekin river basin (i.e. the Cape and Campaspe rivers), north-east of the zone of potential hydrological change (Blanchette, 2012); and (ii) the species requires fast-flowing streams. It was deemed that a suitable receptor impact variable needed to respond to flow and to be impacted by water drying up.

The species can recolonise within 1 to 2 days of flows but is challenged by low-flow periods of greater than 14 days. Water depth in riffles is assumed to be more than 2 cm. Turbidity is not a driver for this species. There is no legacy effect in terms of how mayflies respond to changing flow conditions.

The hydrological factors identified by the participants in the qualitative modelling workshops have been interpreted as a set of hydrological response variables. The hydrological response variables are summary statistics that: (i) reflect these hydrological factors, and (ii) can be extracted from BA's numerical surface water and groundwater models during the reference-, short- and long-assessment intervals defined previously. The hydrological factors and associated hydrological response variables for the streams landscape groups are summarised in Table 14. The precise definition of the receptor impact variable, typically a species or group of species represented by a qualitative model node, was determined during the receptor impact modelling workshop.

Using this interpretation of the hydrological response variables, and the receptor impact variable definitions derived during the receptor impact modelling workshop, the relationships identified in the qualitative modelling workshop were formalised into two receptor impact models (Table 15).

**Table 14 Summary of hydrological response variables used in receptor impact models for the streams landscape groups in the Galilee subregion zone of potential hydrological change, and the corresponding variables for the signed directed graphs**

| Hydrological response variable | Definition of hydrological response variable | Notation used for corresponding signed digraph variable |
|---|---|---|
| dmaxRef | Maximum difference in drawdown under the baseline future or under the coal resource development pathway future relative to the reference period (1983 to 2012) | MDWGW |
| tmaxRef | The year that the maximum difference in drawdown relative to the reference period (1983 to 2012) occurs | MDWGW |
| EventsR2.0 | The mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in flood events with a return period of 2.0 years as defined from modelled baseline flow in the reference period (1983 to 2012)). This metric is designed to be approximately representative of the number of overbank flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development. | SW |
| LQD | The number of days per year with low flow (<10 ML/day), averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development. | SW |
| LME | The maximum length of spells (in days per year) with low flow, averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development. | SW |

**Table 15 Summary of the two receptor impact models developed for the streams landscape groups in the Galilee subregion zone of potential hydrological change**

| Relationship being modelled | Receptor impact variable (with associated sample units) | Hydrological response variables |
|---|---|---|
| Response of woody riparian vegetation to changes in flow regime and groundwater | Annual mean percent foliage cover of woody riparian vegetation (target species include *Eucalyptus camaldulensis* and *Melaleuca* spp.) in a transect 10 to 15 m wide and 100 m long covering the stream channel to the top of the stream bank | dmaxRef<br>LQD<br>EventsR2.0 |
| Response of high-flow macroinvertebrates to changes in flow regime | Annual mean density (30 years, >33 sites/year) of the mayfly *Offadens* (family Baetidae), 3 months after the wet season in a 2 m × 0.5 m (1 $m^2$) area of riffle habitat | LQD<br>LME |

Hydrological response variables are defined in Table 14.

### *2.7.4.4 Receptor impact models*

#### 2.7.4.4.1 Percent foliage cover

***Elicitation scenarios***

Table 16 summarises the elicitation design matrix for the percent foliage cover in the streams landscape groups. The first three design points (design point identifiers 1, 2 and 3) address the current variability in the number of low-flow days that these two landscape groups experience. During the assessment years the model assumes that there is no groundwater drawdown due to coal resource development, and the mean annual number of days with peak daily streamflow exceeding the EventsR2.0 reference value is by definition fixed at one in 2 years.

Design points identifiers 26, 28, 48, 15, 36 and 52 capture the extremes and intermediate values of the hydrological response variables in the short-future period (2042), and identifiers 86, 61, 73, 57, 92 and 108 perform the same role for the long-future period (2102). Note that the design point identifiers are simply index variables that identify the row of the elicitation design matrix. They are included here to maintain an auditable path between analysis and reporting.

In the future-assessment periods (short, 2013 to 2042, and long, 2073 to 2102), the maximum decrease in groundwater levels has been set at 10 m following advice received from the groundwater modelling team. In these assessment years the design matrix allows for the smallest possible (zero) and a very large (356) number of annual low-flow days. The number of flood events that exceed the peak daily flow in flood events with a return period of 2 years as defined from modelled flow in the reference period (1983 to 2012) – EventsR2.0 – is varied from a very low value of one flood event every 20 years to a very high value of approximately three flood events of this magnitude every 2 years.

The reference value (Yref) in the future-assessment years spans the receptor impact model estimates of the 10th and 90th percentiles of percent foliage cover (see also the top row of Figure 22), based on the experts' responses to the design points in the reference year. These design point values were selected by the receptor impact model software during the receptor impact modelling workshop; as soon as the experts had responded to design points 1, 2 and 3 the points were automatically included within the design for the elicitations at the subsequent design points.

**Table 16 Elicitation design matrix for percent foliage cover in the streams landscape groups in the Galilee subregion zone of potential hydrological change**

| Design point identifier | dmaxRef | LQD | EventsR2.0 | Yref | Year |
|---|---|---|---|---|---|
| 1 | 0 | 177 | 0.50 | na | 2012 |
| 2 | 0 | 0 | 0.50 | na | 2012 |
| 3 | 0 | 354 | 0.50 | na | 2012 |
| 26 | 2.8 | 356 | 1.65 | 0.19 | 2042 |
| 28 | 0.2 | 0 | 0.05 | 0.32 | 2042 |
| 48 | 10 | 0 | 1.65 | 0.32 | 2042 |
| 15 | 10 | 178 | 0.85 | 0.19 | 2042 |
| 36 | 10 | 356 | 0.05 | 0.32 | 2042 |
| 52 | 0.2 | 356 | 1.65 | 0.32 | 2042 |
| 86 | 2.8 | 178 | 0.05 | 0.32 | 2102 |
| 61 | 0.2 | 356 | 0.05 | 0.19 | 2102 |
| 73 | 0.2 | 0 | 1.65 | 0.19 | 2102 |
| 57 | 10 | 0 | 0.05 | 0.19 | 2102 |
| 92 | 2.8 | 0 | 0.85 | 0.32 | 2102 |
| 108 | 10 | 356 | 1.65 | 0.32 | 2102 |

Design points for Yref in the future (short- and long-assessment periods) were calculated during the receptor impact modelling elicitation workshop using elicited values for the receptor impact variable in the reference period. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling. na = not applicable, hydrological response variables are as defined in Table 14.
Data: Bioregional Assessment Programme (Dataset 4)

### *Receptor impact model*

The receptor impact variable is the percent foliage cover of *Eucalyptus camaldulensis* and *Melaleuca* spp. in the streams landscape groups. The sample unit is a 100 m length transect along the stream reach extending from the stream channel to the top of the bank. The width is at least 10 m increasing to 15 m in areas where more than a single row of river red gum is present during the reference period. This sample frame is invariant for predictions in future periods.

The receptor impact modelling methodology allows for a very flexible class of statistical models to be fitted to the values of the receptor impact variable elicited from the experts at each of the 1010 design points (for details see companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)).

The model fitted to the experts' elicited values is summarised in Table 17 and Figure 22. The fitted model takes the form:

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \sum_{j=1}^{3} \beta_{h_j} x_{h_j} \quad (1)$$

where $x_0$ is an intercept term (a vector of ones), $x_f$ is a binary indicator variable scored 1 for the case of an assessment in the short- or long-assessment year, $x_l$ is a binary indicator variable scored 1 for the case of an assessment in the long-assessment year, $x_r$ is a continuous variable that represents the value of the receptor impact variable in the reference year (Yref, set to zero for the case of an assessment in the reference year), and $x_{h_j}$ $j = 1..3$ are the (continuous or integer) values of the three hydrological response variables (dmaxRef, LQD and EventsR2.0).

**Table 17 Mean, 10th and 90th percentile of the coefficients of the receptor impact model percent foliage cover in the streams landscape groups in the Galilee subregion zone of potential hydrological change**

| | Mean | q10 | q90 |
|---|---|---|---|
| (Intercept) | –0.682 | –1.07 | –0.294 |
| future1 | –0.17 | –0.578 | 0.237 |
| long1 | –0.0243 | –0.372 | 0.323 |
| dmaxRef | –0.0276 | –0.0784 | 0.0233 |
| EventsR2.0 | 0.084 | –0.207 | 0.375 |
| LQD | –0.00376 | –0.00498 | –0.00254 |

Future is a binary variable scored 1 if the analysis case is in a short- or long-assessment period. Long is a binary variable scored 1 if the analysis case is in the assessment year. dmaxRef, LQD and EventsR2.0 are as described in Table 14.
Data: Bioregional Assessment Programme (Dataset 4)

Note that the modelling framework provides for more complex models, including quadratic value of, and interactions between, the hydrological response variables but in this instance the simple linear model (Equation 1) was identified as the most parsimonious representation of the experts' responses.

The model estimation procedure adopts a Bayesian approach. The model coefficients $\beta_0, \beta_f, \beta_l, \beta_r, \beta_{h_j}$ are assumed to follow a multivariate normal distribution. The Bayesian estimation procedure quantifies how compatible different values of the parameters of this distribution are with the data (the elicited expert opinion) under the model. The (marginal) mean and 80% central credible intervals of the three hydrological response variable coefficients (holding all other variables at their median values) are summarised in partial regression plots in Figure 22, whereas Table 17 shows the (jointly estimated) mean and 80% central credible interval (defined by the 10th and 90th percentiles) for all seven model coefficients.

Interestingly, the coefficient for Yref is not referenced in the best selected model (Table 17), which indicates that the current value of percent foliage cover is not a major predictor of future values. This is at odds with the predictions for equivalent receptor impact variables in other bioregions where the coefficient for percent foliage cover in the assessment year typically is important. It is critical to recognise, however, that percent foliage cover in the streams landscape groups starts from a very low base – the 90th percentile is approximately 30% with a mean value of about 22%. It is also important to recognise that the relatively modest changes highlighted in the summary above may still be ecologically important given the relatively low baseline condition. The model indicates that the experts' opinion provides strong evidence that of the three hydrological response variables only LQD has a major (Bayesian credible intervals do not span zero) influence on the mean percent foliage cover in the streams landscape groups (Table 17). In the short- and long-assessment years, the model predicts that if all other model variables are held at their median values, and the groundwater depth decreases by 5 m, then the mean percent foliage cover will decrease by approximately 5% with some large uncertainty that is even larger in the long-assessment year (middle and bottom row, left column, Figure 22).

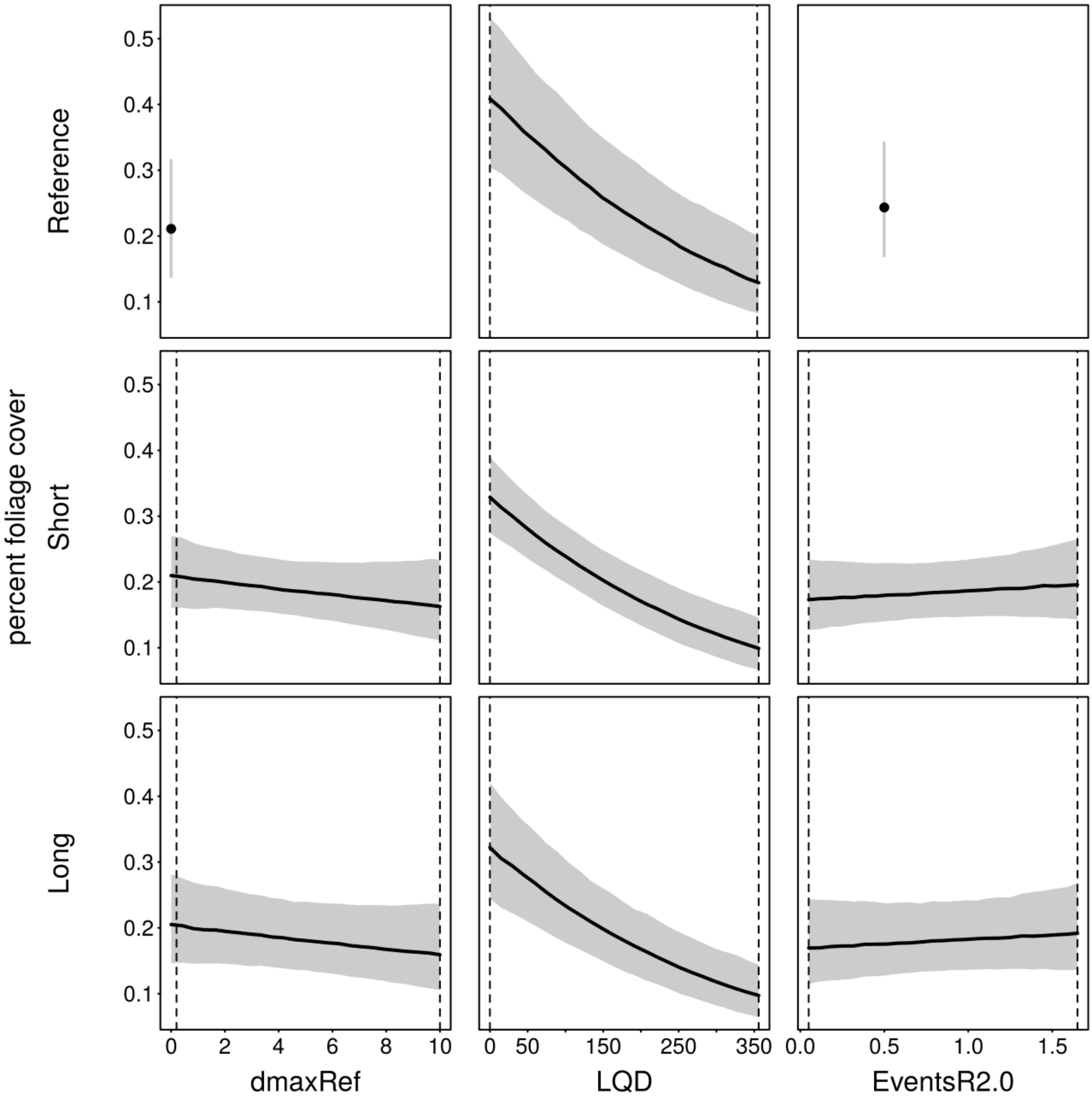


**Figure 22 (Top row) Predicted mean (black dot or line) and 80% central credible interval (grey line or polygon) of percent foliage cover under reference hydrological conditions. (Middle and bottom rows) Predicted future effects (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on percent foliage cover**

In the middle and bottom rows, the uncertainty in the percent foliage cover in the reference year has been integrated out, and all other hydrological response variables are held constant at the midpoint of their elicitation range (during the risk estimation process all hydrological response variables vary simultaneously). The dashed vertical lines show range of hydrological response variables used in the elicitation workshop. Reference = period from 1983 to 2012, Short = assessment period 2013 to 2042, Long = assessment period 2073 to 2102. dmaxRef, LQD and EventsR2.0 are as described in Table 14.The range of the y axis is from just below 10% to just above 50%. The numbers on the y-axis range from 0 to 1 as the receptor impact model was constructed using the proportion for the statistical modelling. They should be interpreted as a percent foliage cover ranging from 0 to 100%.
Data: Bioregional Assessment Programme (Dataset 4)

If all other model variables are held at their median values, the model predicts a somewhat more dramatic decrease of approximately 10% in mean percent foliage cover if the number of low-flow days increases by 100 days/year from a mid-value of 177 days/year to 277 days/year. Again, the uncertainty associated with these predictions appears to increase slightly (larger credible interval) in the long-assessment year (middle and bottom row, middle column, Figure 22).

Finally, the model suggests that if all other model variables are held at their median values, the mean percent foliage cover should increase as the number of flood events with peak daily flow exceeding the 1983 to 2012 2-year return period increases. The magnitude of the mean increase in foliage cover will be a few percent. There is, however, a large amount of uncertainty associated with this prediction as indicated by the relatively broad credible intervals in Figure 22 and the order of magnitude difference between the 10th and 90th percentiles of the Events2.0 coefficient in Table 17.

#### 2.7.4.4.2 Density of baetids

***Elicitation scenarios***

Table 18 summarises the elicitation design matrix for the mean density of baetids (*Offadens*) in the streams landscape groups of the Galilee subregion. Here, the first six design points (design point identifiers 1 to 6) address the current variability in the number of low-flow days, and mean maximum spell duration (in days) per year with low streamflow, that the streams landscape groups experience.

Design points identifiers 7, 21, 41, 9 and 11 capture the extremes and intermediate values of the hydrological response variables in the short-future period (2042), and identifiers 22, 17 and 18 perform the same role for the long-future period (2102). Note that the design point identifiers are simply index variables that identify the row of the elicitation design matrix. They are included here to maintain an auditable path between analysis and reporting. Note also that the design points are the minimum required to estimate the coefficients of a linear model that allows for a quadratic relationship between hydrological response variables and receptor impact variables, and for interactions between hydrological response variables, in the reference and future assessment periods (Section 5.2, companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)). The absence of any particular combination of hydrological response variables (for example, LQD = 0 and LME = 0) in any particular year (for example 2102) does not imply that this scenario cannot occur or is not modelled. The purpose of the receptor impact modelling is to enable the analysis to extrapolate across what is an infinite set of possible combinations.

Again, the reference value (Yref) in the future assessment years spans the receptor impact model estimates of the 10th and 90th percentiles of density of baetids (see also the top row of Figure 23), based on the experts' responses to the design points in the reference year.

**Table 18 Elicitation design matrix for density of baetids (*Offadens*) in the streams landscape groups in the Galilee subregion zone of potential hydrological change**

| Design point identifier | LQD | LME | Yref | Year |
|---|---|---|---|---|
| 3 | 343 | 15.3 | na | 2012 |
| 1 | 0 | 0 | na | 2012 |
| 6 | 354 | 201 | na | 2012 |
| 4 | 177 | 101 | na | 2012 |
| 5 | 354 | 101 | na | 2012 |
| 2 | 177 | 0.90 | na | 2012 |
| 7 | 0 | 0 | 240 | 2042 |
| 21 | 178 | 0.95 | 30 | 2042 |
| 41 | 178 | 115 | 30 | 2042 |
| 9 | 343 | 16 | 240 | 2042 |
| 11 | 356 | 115 | 240 | 2042 |
| 22 | 178 | 115 | 240 | 2102 |
| 17 | 356 | 115 | 30 | 2102 |
| 18 | 356 | 230 | 30 | 2102 |

Design points for Yref in the future (short- and long-assessment periods) were calculated during the receptor impact modelling elicitation workshop using elicited values for the receptor impact variable in the reference period. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling. na = not applicable, LQD and LME are as described in Table 14.
Data: Bioregional Assessment Programme (Dataset 4)

### *Receptor impact model*

The receptor impact variable is the density of mayfly nymphs (order Ephemeroptera) in the genus *Offadens* of the family Baetidae (Webb and Suter, 2011). The measurement unit for the receptor impact variable is the number of mayfly nymphs per $m^2$. Density would be measured in a 2 m by 0.5 m quadrat in flowing water. The measurement period would be 3 months after the end of the wet season.

The model fitted to the experts' elicited values is summarised in Table 19 and Figure 23. The fitted model takes the form:

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \sum_{j=1}^{2} \beta_{h_j} x_{h_j} \quad (2)$$

where $x_0$ is an intercept term (a vector of ones), $x_f$ is a binary indicator variable scored 1 for the case of an assessment in the short- or long-assessment year, $x_l$ is a binary indicator variable scored 1 for the case of an assessment in the long-assessment year, $x_r$ is a continuous variable that represents the value of the receptor impact variable in the reference year (Yref, set to zero for the case of an assessment in the reference year), and $x_{h_j}$ $j = 1..2$ are the values of the two continuous hydrological response variables (LQD and LME).

**Table 19 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for density of baetids (*Offadens*) in the streams landscape groups in the Galilee subregion zone of potential hydrological change**

| | Mean | q10 | q90 |
|---|---|---|---|
| **(Intercept)** | 5.26 | 3.92 | 6.6 |
| **future1** | 0.0112 | –1.13 | 1.15 |
| **long1** | 0.0241 | –1.47 | 1.52 |
| **LQD** | –0.00365 | –0.00853 | 0.00123 |
| **LME** | –0.00319 | –0.0118 | 0.00544 |

Future is a binary variable scored 1 if the analysis case is in a short- or long-assessment period. Long is a binary variable scored 1 if the analysis case is in the assessment year. LQD and LME are as described in Table 14.
Data: Bioregional Assessment Programme (Dataset 4)

Again, the modelling framework provides for more complex models, including quadratic value of, and interactions between, the hydrological response variables but in this instance the simple linear model (Equation 2) was identified as the most parsimonious representation of the experts' responses.

The model indicates that the experts' opinion provides no strong evidence that either the number of low-flow days or the mean maximum spell of low-flow days have a significant effect on mean baetid density.

The model also predicts that baetid density under reference conditions does not influence outcomes under the different low-flow conditions in the future assessment years (Table 19). This conclusion is consistent with receptor impact model predictions for other relatively short-lived species (such as Hydropyschidae larvae) in other bioregions.

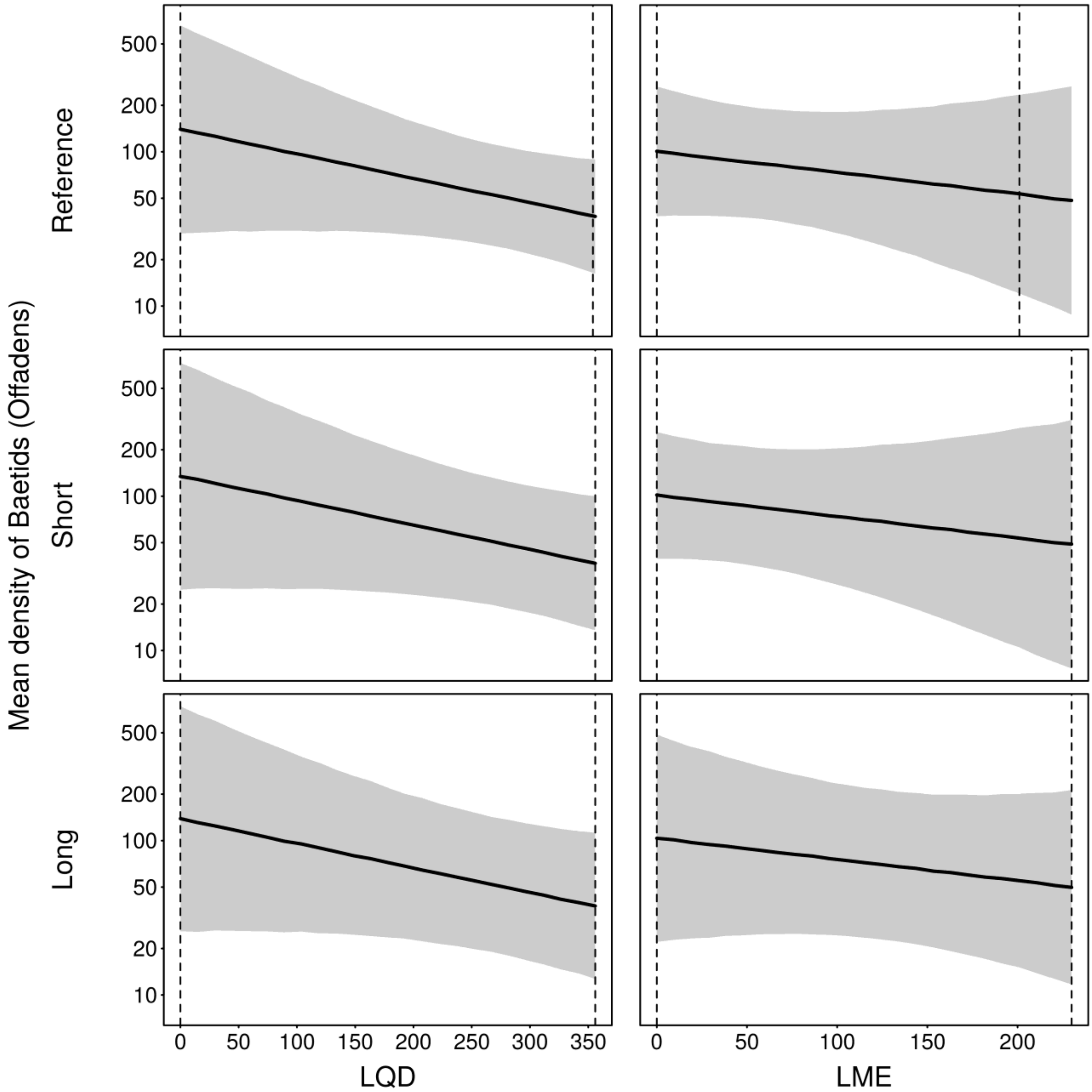


**Figure 23 Predicted mean (black line) and 80% central credible interval (grey polygon) of density of baetids (*Offadens*) under reference hydrological conditions. (Middle and bottom rows) Predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on density of baetids in the Galilee subregion zone of potential hydrological change**

In the middle and bottom rows, all other hydrological response variables are held constant at the midpoint of their elicitation range (during the risk estimation process all hydrological response variables vary simultaneously). The dashed vertical lines show range of hydrological response variables used in the elicitation workshop. Reference = period from 1983 to 2012, Short = assessment period 2013 to 2042, Long = assessment period 2073 to 2102. LQD and LME are as described in Table 14.
Data: Bioregional Assessment Programme (Dataset 4)

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## 2.7.5 'Floodplain, terrestrial groundwater-dependent ecosystem' landscape group


***Summary***

The 'Floodplain, terrestrial groundwater-dependent ecosystem (GDE)' landscape group contains two landscape classes within the zone of potential hydrological change of the Galilee subregion: 'Terrestrial GDE, remnant vegetation' and 'Terrestrial GDE'. The zone contains 2358 $km^2$ of 'Terrestrial GDE, remnant vegetation' compared to 75.2 $km^2$ of 'Terrestrial GDE'. The vegetation in this landscape group depends on the subsurface expression of groundwater on a permanent or intermittent basis to maintain growth or avoid water stress and adverse impacts on condition. The landscape classification does not distinguish between artesian and non-artesian groundwater sources.

The physical environment of the 'Floodplain, terrestrial GDE' landscape group is described here along with descriptions of vegetation assemblages, threatened flora and fauna and threatened ecological communities. The water requirements and the degree of groundwater dependency of the vegetation focus here on rooting depth and depth to watertable. It identifies two variables – groundwater and surface water – as the key hydrological elements. These variables influence trees that support a woodland community, and create local conditions and a microclimate (i.e. shade, leaf litter and soil moisture) that favours mesic vegetation and suppresses xeric vegetation. Qualitative analyses of the four signed digraph models developed generally indicate a negative or ambiguous response prediction for all biological variables within the floodplain ecosystem.

Key ecological relationships identified through the qualitative mathematical modelling of the 'Floodplain, terrestrial GDE' landscape group were formalised into a receptor impact model that related the response in annual foliage cover to changes in maximum drawdown (dmaxRef) and overbank flood events (EventsR2.0). The model indicates that the experts' opinion provides evidence that foliage cover may decrease as groundwater drawdown increases due to additional coal resource development. There is, however, considerable uncertainty in these predictions across both the short-assessment period (2013-2042) and the long-assessment period (2073-2102).

The receptor impact modelling also indicates that there is evidence in the experts' responses for overbank flood events (Events R2.0) to have a major quadratic effect on percent foliage cover. The frequency of overbank flood events will generally have a positive effect on average percent foliage cover, unless that frequency becomes too high. When values of Events R2.0 exceed 1 there will be a negative effect on percent foliage cover.


### *2.7.5.1 Description*

#### 2.7.5.1.1 Overview

The 'Floodplain, terrestrial GDE' landscape group contains two landscape classes within the zone of potential hydrological change of the Galilee subregion: 'Terrestrial GDE' and 'Terrestrial GDE, remnant vegetation’ (see Section 2.3.3 of companion product 2.3 for the Galilee subregion (Evans et al., 2018b)). The first landscape class comprises non-remnant vegetation whereas the second landscape class comprises remnant vegetation. The classification does not distinguish between artesian and non-artesian groundwater sources. The zone contains 2358 $km^2$ of ‘Terrestrial GDE, remnant vegetation’ compared to 75.2 $km^2$ of ‘Terrestrial GDE’ (Figure 24). These two landscape classes are type three GDEs following the typology of Richardson et al. (2011). These are terrestrial GDEs that rely on the subsurface expression of groundwater on a permanent or intermittent basis to maintain growth or to avoid water stress and adverse impacts on condition (Eamus et al., 2006; Richardson et al., 2011).

In the landscape classification adopted here, these landscape classes would be broadly defined as groundwater-dependent vegetation assemblages (mostly woodlands or shrublands) that occur on floodplains but are not associated with palustrine, lacustrine or riparian wetlands. Floodplains are broadly defined as a collection of landscape and ecological elements exposed to inundation or flooding along a river system (Rogers, 2011). Within 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, 2012). Patterns of flooding and drying are a key driver of spatial and temporal variability in vegetation in these areas (Capon et al., 2016).

Companion product 2.3 for the Galilee subregion (Evans et al., 2018b) identified two high-level conceptual models relevant to this landscape group: GDEs: alluvia – lower catchment; and GDEs: alluvia – closed drainage systems (Figure 25). These conceptual models are presented and discussed in more detail in DSITI (2015). Here, a brief description is given for context. The floodplains are commonly underlain by sediments deposited in fluvial (riverine) environments. The alluvial aquifers that support these groundwater-dependent landscape classes are formed from particles such as sand, silt and/or clay deposited within channels or on floodplains as a result of highly intermittent flooding processes. Floodplains in the lower parts of catchment areas tend to be much wider and deeper than alluvial floodplains that occur in higher parts of the catchments.

Climatically, areas occupied by the ‘Floodplain, terrestrial GDE’ landscape group are water limited, annual rainfall is low (about 300 mm/year) and evaporation is high (greater than 2000 mm/year) (companion product 1.1 for the Galilee subregion (Evans et al., 2014)). Low and sporadic rainfall coupled with high evaporative demand suggest that groundwater may be a more reliable source of water for the landscape group than surface water (Eamus et al., 2006). Several processes, acting either individually or in combination, control recharge into these alluvial aquifers including direct infiltration of rainfall, inundation by floodwaters or discharge from surrounding water-bearing rock types (Figure 25).

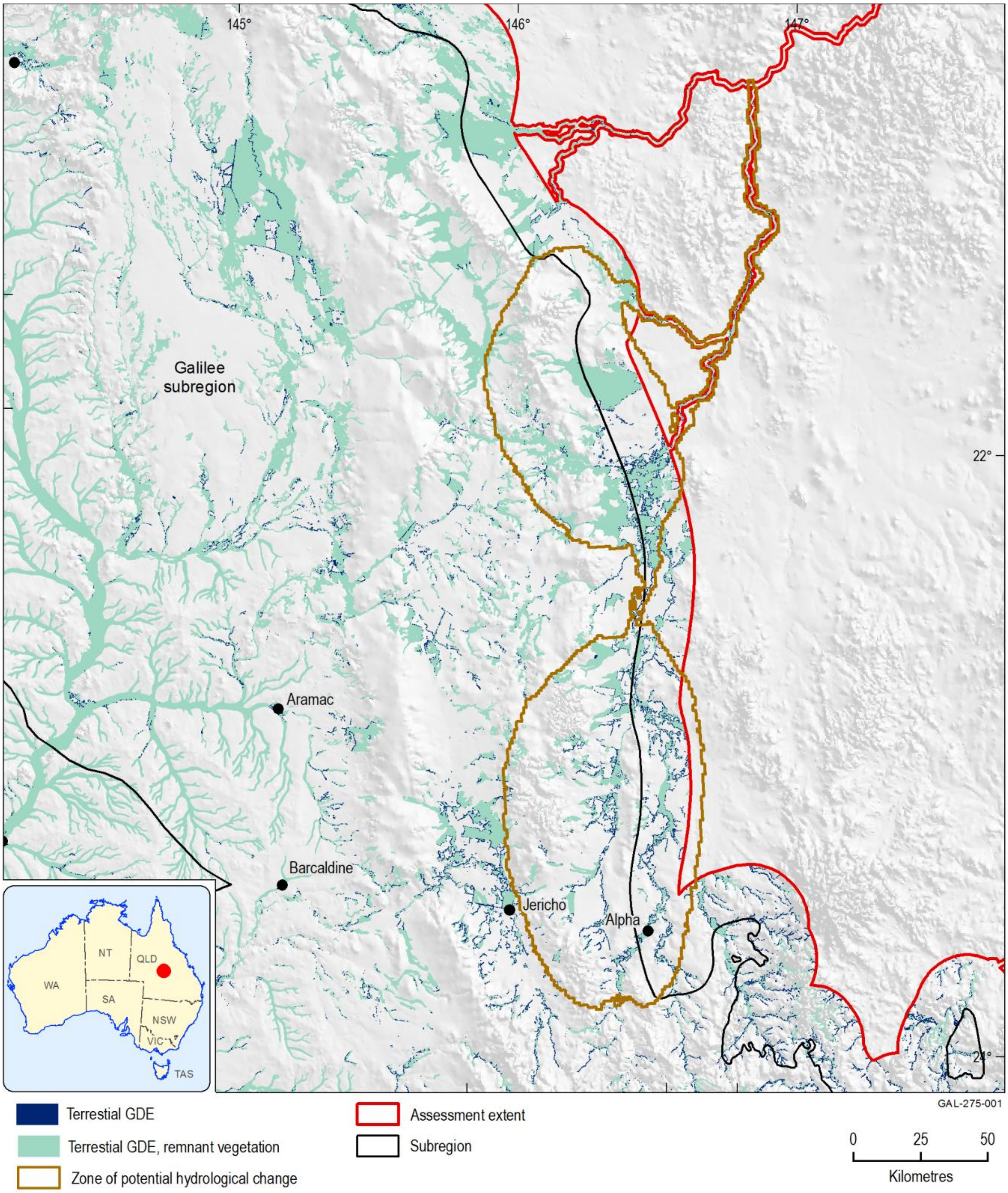


**Figure 24 Distribution of landscape classes in the 'Floodplain, terrestrial GDE' landscape group within the Galilee assessment extent**

GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 1)

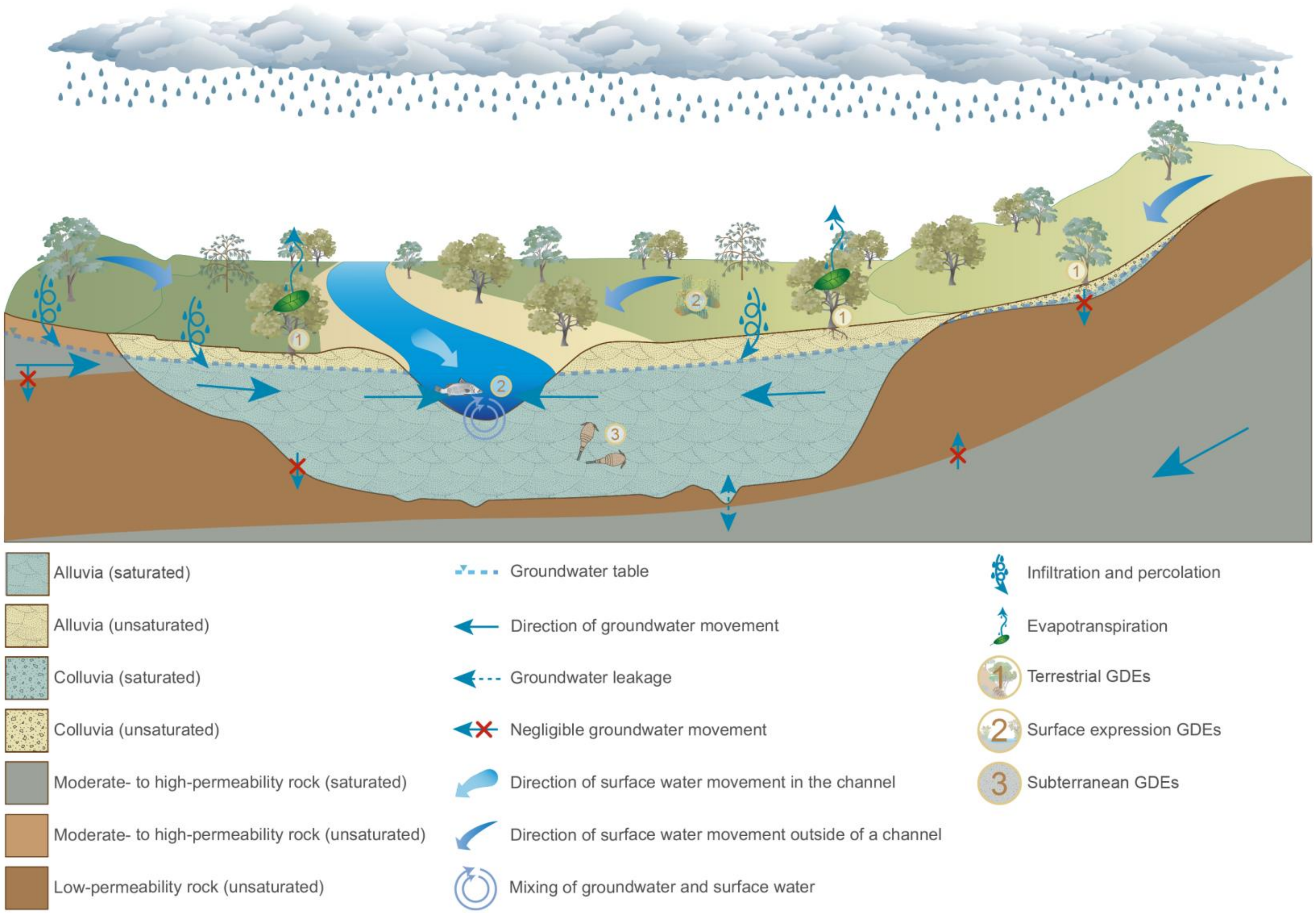


**Figure 25 Pictorial conceptual model of the potential interactions between ecosystems and groundwater within alluvial aquifers**

GDE = groundwater-dependent ecosystem

Source: adapted from Queensland Department of Science, Information Technology and Innovation (Dataset 2), © The State of Queensland (Department of Science, Information Technology and Innovation) 2015

### 2.7.5.1.2 Hydrological regimes and connectivity

Understanding the connectivity of groundwater in the zone of potential hydrological change is complicated both because the Galilee subregion contains a series of stacked groundwater systems and by a paucity of data in some areas. The groundwater systems are described in detail in companion product 2.1-2.2 (Evans et al., 2018a) and Section 2.3.2 of companion product 2.3 (Evans et al., 2018b) for the Galilee subregion and are summarised below to provide context.

Shallow groundwater systems in alluvial sediments that underlie floodplains may take the form of perched aquifer systems isolated from the regional watertable, or in groundwater systems that are connected with deeper aquifers that are not in the alluvial sediments. The degree of connection between deeper aquifers and shallow aquifers in alluvial sediments is governed by a number of factors including variations in hydraulic head (pressure) in the different aquifer systems, and whether sedimentary layers in alluvial deposits impede upward groundwater movement from underlying aquifers. If there is sufficient hydraulic head in underlying aquifers and a connective pathway exists, then groundwater may discharge from underlying aquifers into overlying aquifers in alluvial sediments. This may occur if there is not a sufficiently competent aquitard (e.g. thick clay-rich layers) to impede upwards groundwater flow. Aquifers that may have potential to discharge to overlying alluvial sediments in the zone of potential hydrological change (within the Burdekin river basin) include the: Clematis Group, Dunda beds (the more permeable upper part of the Rewan Group), upper Permian coal measures and Joe Joe Group.

Potentiometric mapping of different aquifer systems outlined in companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a) suggests that areas where there is potential for discharge from deeper aquifers to overlying alluvium include where the:

- Clematis Group and Dunda beds aquifers occur near-surface under shallow cover of the Moolayember Formation, or where these units directly underlie alluvium in the Carmichael River valley (e.g. in the vicinity and downstream of the Doongmabulla Springs complex)
- Belyando River floodplain is underlain by the upper Permian coal measures and/or the Joe Joe Group, in particular in the vicinity of the confluence of the Carmichael River and the Belyando River (this includes the Mellaluka Springs complex and Albro Springs).

Further information about the variability of the depth to the watertable in the zone of potential hydrological change (i.e. the standing water level observed in groundwater bores) is provided in Section 3.4.1 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018).

Connection between surface water features and shallow groundwater in floodplain environments will vary depending on local geological conditions (e.g. distribution of sand-rich sediments in the floodplain), hydrogeological characteristics (e.g. flow system dynamics), and climatic events. For instance, after high rainfall events groundwater levels can rise to a point resulting in temporary discharge to streams. During drier periods groundwater levels can fall to a point where the reverse process may occur, with surface water recharging shallow groundwater.

Regardless of aquifer configuration and connectivity, vegetation can draw from groundwater if the watertable, or capillary zone that can form above the watertable, comes within reach of a plant's root system (generally within 20 m of the surface). The majority of vegetation that forms the

'Floodplain, terrestrial GDE' landscape group is likely to source groundwater from alluvium and Cenozoic sediments. As a result, GDEs connected to regional groundwater systems within the zone of potential hydrological change may be impacted by changes in groundwater due to additional coal resource development (for example, from drawdown or reduced recharge) across a broad area.

#### 2.7.5.1.3 Ecological processes

The water requirements and the degree of groundwater dependency of the vegetation that occupies the 'Floodplain, terrestrial GDE' landscape group will depend on a number of factors including:

- age and rooting distribution of plants and how this enables access to the watertable
- depth to the watertable, and any spatial and temporal (seasonal) variation in watertable levels
- groundwater quality.

Vegetation within the 'Floodplain, terrestrial GDE' landscape group will typically use deep roots to access groundwater in the capillary zone above the watertable via capillary action or hydraulic lift. A baseline assumption with the physiology of Australian plants is that they can access groundwater to a depth to 10 m (D Eamus, 2016, pers. comm.). This value is supported by research that found the mean maximum rooting depth across 11 species of sclerophyllous trees to be 12.6 m ± 3.4 m (standard error) (Canadell et al., 1996). However, some tree species have roots that can access water at much greater depths. As an example of the potential of eucalypt roots to access water at depth, *Eucalyptus marginata* roots in south-western Australia are reported to reach depths of 40 m by Dell et al. (1983).

It is generally assumed that groundwater dependency of vegetation will change seasonally with rainfall and be greatest at times of seasonal rainfall deficit. There is empirical support for this viewpoint. For example, in eucalypt woodland along the Condamine River, southern Queensland, the frequency of deep subsurface water use was greatest in the late dry season (Gow et al., 2016).

The depth to the watertable is an important factor in determining the volume of water discharged through GDEs. In the Galilee subregion, the average depth to standing water level of 250 bores in the 'Terrestrial GDE, remnant vegetation' landscape class is 20.9 m below surface, with a wide range of 152.5 to 3.3 m depth below surface. The bores from which the measurements were taken cover a variety of aquifer systems including: alluvial sediments (49 bores); Paleogene sediments (43 bores); other types of Cenozoic sediments (25 bores); Hooray Sandstone (20 bores); Clematis Group aquifer (7 bores); upper Permian coal measures (9 bores); Wallumbilla Formation (24 bores); and Winton-Mackunda Formation aquifer (40 bores). In the 'Terrestrial GDE' landscape class (i.e. non-remnant vegetation GDEs) the average depth to groundwater across 17 bores is 33 m below surface, with a range of 90 to 4 m depth below surface.

Currently, there is little published information on either the amount of water used by GDEs or the physiology of GDEs. Similarly, there is a knowledge gap in terms of information on root depth of vegetation within GDEs and on responses to changes in depth-to-groundwater (Eamus et al., 2015). This information, if it were available, would be invaluable in assessing the potential impacts of groundwater drawdown on GDEs.

#### 2.7.5.1.4 Vegetation

Within the Galilee subregion’s zone of potential hydrological change, the ‘Floodplain, terrestrial GDE’ landscape group supports over 85 regional ecosystems (REs). There is considerable uncertainty related to the water regime required to support many of these REs. However, the nature of the dependency on groundwater is likely to vary among and within vegetation communities, as a function of groundwater availability, depth and quality (companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)).

The distribution of the most widespread vegetation assemblages, represented by REs, within the ‘Floodplain, terrestrial GDE’ landscape group is shown in Figure 26. The majority of these REs have *Eucalyptus* or *Corymbia* or *Acacia* species as dominant/co-dominant in the upper storey. Specifically, eucalypt woodlands dominate the alluvial river and creek-flat land zone. *Eucalyptus brownii* or *E. coolabah* woodlands and open woodlands dominate the alluvial plains. *Acacia* woodlands, including *A. cambagei* are also common on the alluvial plains. Smaller areas of *Corymbia* woodlands are associated with alluvial plains. The most widespread REs in the ‘Floodplain, terrestrial GDE’ landscape group within the zone listed in order of decreasing area (expressed as a percentage of the zone) (Figure 26) are:

- RE 10.3.28 ‘Eucalyptus melanophloia or E. crebra woodland to open woodland on sandy alluvial fans’ (4.31%)
- RE 10.3.6 ‘Eucalyptus brownii woodland to open woodland on alluvial plains’ (2.89%)
- RE 11.3.3 ‘Eucalyptus coolabah woodland on alluvial plains’ (1.90%)
- RE 11.3.5 ‘Acacia cambagei woodland on alluvial plains’ (1.68%)
- RE10.3.27 ‘Eucalyptus populnea woodland to open woodland on alluvial plains’ (1.47%)
- RE 11.3.2 ‘Eucalyptus populnea woodland on alluvial plains’ (0.97%)
- RE 11.3.10 ‘Eucalyptus brownii woodland on alluvial plains’ (0.91%)
- RE 11.3.7 ‘Corymbia spp. woodland on alluvial plains’ (0.42%)
- RE 10.3.14 ‘Eucalyptus camaldulensis and/or E. coolabah woodland to open woodland along channels and on floodplains’ (0.34%)
- RE 10.3.4 ‘Acacia cambagei low open woodland to low woodland on alluvial plains’ (0.31%)
- RE 10.3.3 ‘Acacia harpophylla and/or Eucalyptus cambageana low open woodland to open woodland on alluvial plains’ (0.26%).

Canopy cover in these woodlands and open woodlands tends to be sparse, with sparse or scattered understories, dominated by grasses such as *Aristida* spp. and *Triodia* spp.

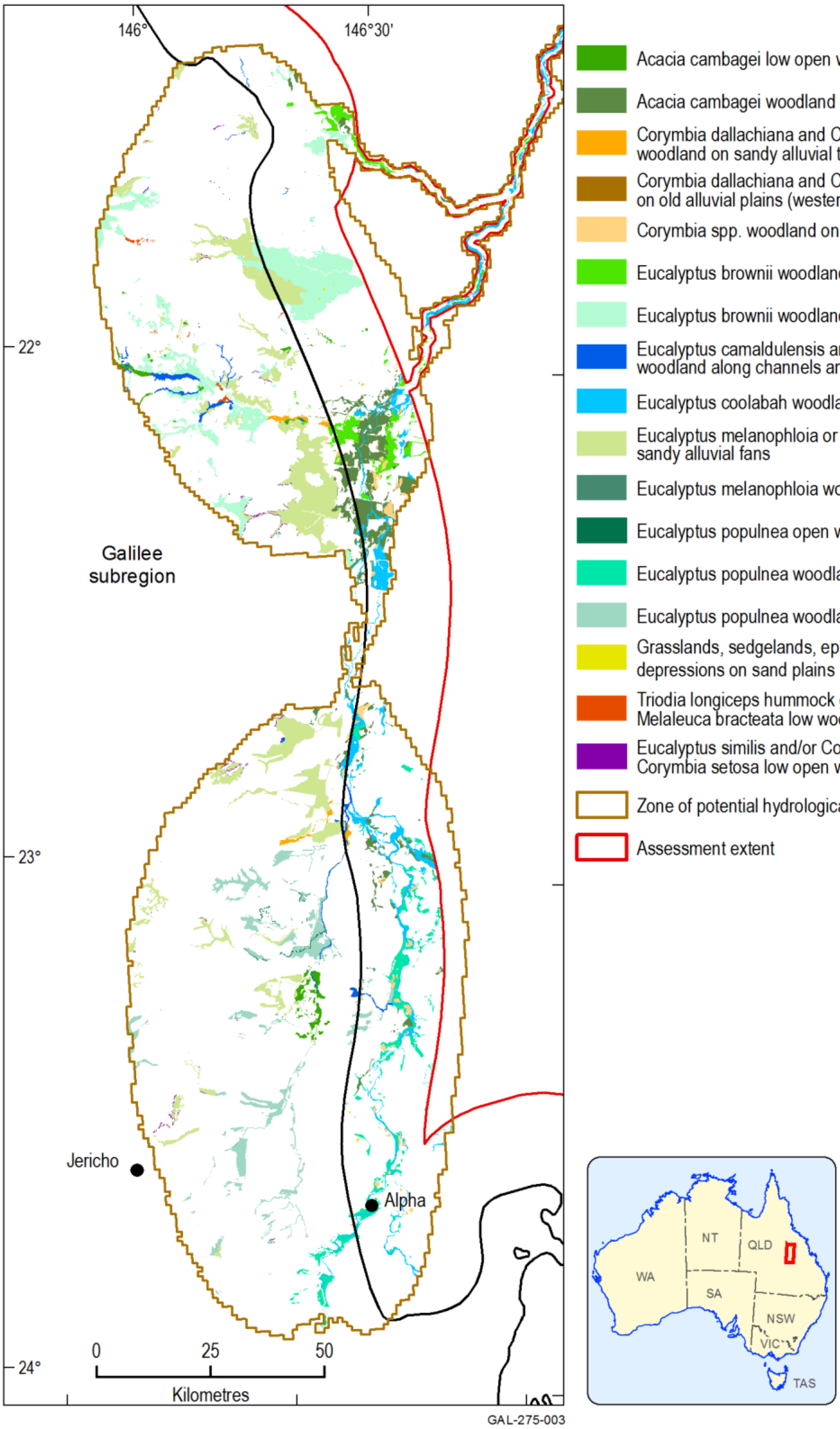


**Figure 26 Vegetation assemblages (regional ecosystems) in the 'Floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change**

GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 1, Dataset 3)

Two threatened ecological communities occur within the ‘Floodplain, terrestrial GDE’ landscape group. ‘Brigalow (Acacia harpophylla dominant and co-dominant)’ is listed under the Commonwealth’s *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) as an ‘Endangered’ ecological community. This ecological community is predicted to occur widely in the eastern half of the Galilee subregion zone of potential hydrological change (Department of the Environment and Energy, 2017a). The vegetation types that make up the brigalow ecological community mostly occur on acidic and salty clay soils. Within the zone these are mostly on deep cracking clay soils. Gilgai may be present in these areas. The dominant landform on which this ecological community occurs is flat to gently undulating clay plains that are not associated with recently deposited alluvium. It is also present on gently undulating areas on fine-grained sedimentary rocks.

‘Weeping Myall Woodlands’ is listed under the EPBC Act as an ‘Endangered’ ecological community. The ecological community is predicted to occur widely in the south-eastern section of the zone (Department of the Environment and Energy, 2017b). It occurs on flat areas or shallow depressions on alluvial plains. Such areas are not associated with river channels and are rarely flooded. The soils are black, brown, red-brown or grey clay or clay loam (Commonwealth of Australia, 2009). The ‘Weeping Myall Woodlands’ ecological community is likely to be present in the ‘Floodplain, terrestrial GDE’ landscape group within the zone.

### 2.7.5.1.5 Flora and fauna

The ‘Floodplain, terrestrial GDE’ landscape group provides potential habitat for a range of threatened plant and animal species. These are detailed below.

The potential habitat of the koala (*Phascolarctos cinereus*) occurs within the zone of potential hydrological change. Koalas that occur in Queensland, NSW and the ACT are considered as a combined management unit that is listed nationally as ‘Vulnerable’ under the EPBC Act (Department of the Environment and Energy, 2017c). Koalas in the remainder of Australia are not listed as threatened. The koala is also listed as ‘Vulnerable’ under Queensland’s *Nature Conservation Act 1992* (Nature Conservation Act). Within the zone of potential hydrological change of the Galilee subregion, koala habitat occurs in the ‘Floodplain, terrestrial GDE’ landscape group. Koalas in semi-arid environments, including the zone, inhabit forest and woodland dominated by *Eucalyptus* species in riparian and non-riparian areas. Important food and habitat trees for koalas in semi-arid Queensland include *Eucalyptus camaldulensis*, *E. populnea*, *E. crebra*, *E. tereticornis*, *E. melanophloia*, *E. tessellaris* and *Melaleuca bracteata* (Gordon et al., 1988; Ellis et al., 2002). Apart from *E. camaldulensis*, which is largely restricted to the riverine landscape groups, many of the other important food and habitat trees of koalas are dominant components of the regional ecosystems within the ‘Floodplain, terrestrial GDE’ landscape group (*E. populnea*, *E. tereticornis*, *E. melanophloia*).

The ornamental snake (*Denisonia maculata*) occurs within the Galilee subregion zone of potential hydrological change. The species is listed as ‘Vulnerable’ under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017d). Within the zone, it occupies the ‘Floodplain, terrestrial GDE’ landscape group. The ornamental snake is considered to be water-dependent as it feeds almost exclusively on frogs. It occurs in riparian vegetation along watercourses, on the margins of wetlands including lakes and swamps and in terrestrial vegetation that is likely to be groundwater-dependent. The latter category includes woodland and open woodland of coolibah (*Eucalyptus coolabah*), poplar box (*E. populnea*), brigalow (*Acacia harpophylla*), gidgee (*A. cambagei*) and blackwood (*A. argyrodendron*) (Department of the

Environment and Energy, 2017d). The REs in which it has been found all have clay soils. These REs include 11.4.3, 11.4.6, 11.4.8 and 11.4.9 (Department of the Environment and Energy, 2017d).

Dunmall's snake (*Furina dunmalli*) potentially occurs within the zone. The species is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017e). In Queensland, the range of Dunmall's snake is mostly within the Brigalow Belt region to the east of the zone. Dunmall's snake inhabits terrestrial vegetation. The two main types of environment in which it occurs are:

- forest and woodland on black alluvial cracking clay and clay loams dominated by brigalow (*Acacia harpophylla*), other acacias (*A. brownii, A. deanei, A. leiocalyx*), cypress (*Callitris* spp.) or bulloak (*Allocasuarina luehmannii*)
- open forest and woodland on sandstone-derived soils dominated by blue spotted gum (*Corymbia citriodora*), ironbarks (*Eucalyptus crebra* and *E. melanophloia*), white cypress (*Callitris glaucophylla*) and bulloak (*Allocasuarina luehmannii*).

The species seems unlikely to be water-dependent. The potential range of the species within the Galilee subregion zone of potential hydrological change includes the 'Floodplain, terrestrial GDE' landscape group.

The yakka skink (*Egernia rugosa*) is a threatened lizard that occurs within the Galilee subregion zone of potential hydrological change. It is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017f). The species occurs in woodland and open forest dominated by a range of trees including *Acacia*, *Eucalyptus*, *Casuarina* and *Callitris*. Yakka skinks are burrowing animals that occur in colonies or small groups (Chapple, 2003). Within the zone the yakka skink is likely to occupy sand plains, clay and clay loam plains, sandstone rises and minor pediments and vegetation fringing watercourses and stream channels and on alluvial plains. Therefore, it is expected to occupy all the landscape groups within the zone with the exception of the 'Springs' landscape group. The water-dependency of the species is poorly understood.

The southern subspecies of the squatter pigeon (*Geophaps scripta scripta*) is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017g). It is a granivorous bird that occurs through much of the zone. It was recorded during surveys as part of the environmental impact statements for five of the proposed coal mine developments in the zone. From north to south these are China Stone, Carmichael, Kevin's Corner, Alpha, and China First. The squatter pigeon (southern) forages and breeds in a range of open-forest, woodland and open-woodland vegetation types that have a grassy understory. It depends on surface water as it needs to drink on a daily basis and, as a consequence, foraging and nesting sites are located within 3 km of a water source. Water sources used by the species include rivers, lakes and artificial sources such as farm dams (Department of the Environment and Energy, 2017g). Therefore, the squatter pigeon uses water available in the 'Floodplain, terrestrial GDE' landscape group.

The red goshawk (*Erythrotriorchis radiatus*) is listed as 'Vulnerable' nationally (EPBC Act) and 'Endangered' in Queensland (Nature Conservation Act). The range of this species includes small areas of the Galilee subregion zone of potential hydrological change. The species can be considered to be water-dependent because of the nest sites it uses. Nests are constructed in tall trees (mean height of 31 m) that are located within 1 km of, and often beside, permanent water. Water sources include rivers, swamps and pools (DERM, 2012). Given this nesting preference, the red goshawk is mostly likely to occur within the riverine landscape groups and the ‘Floodplain, terrestrial GDE’ landscape group within the zone.

The southern subspecies of the black-throated finch (*Poephila cincta cincta*) is classified as ‘Endangered’ nationally (EPBC Act) and in Queensland (Nature Conservation Act). This threatened species occurs throughout the Galilee subregion zone of potential hydrological change and adjacent areas (Vanderduys et al., 2016). The black-throated finch was located during surveys as part of environmental impact statements and subsequent surveys at Carmichael (nine locations) and China Stone (eight locations) coal mine developments. The black-throated finch occupies grassy woodland within the zone. It is surface water dependent. The finch feeds mostly on the ground on a range of grass seeds. It occupies several vegetation assemblages within the ‘Floodplain, terrestrial GDE’ and ‘Non-floodplain, terrestrial GDE’ landscape groups. Important Res for the black-throated finch in the zone are listed below (based on GHD, 2012; Vanderduys et al., 2016):

- RE 10.3.6 ‘Eucalyptus brownii woodland to open woodland on alluvial plains’
- RE 10.3.28 ‘Eucalyptus melanophloia or E. crebra woodland to open woodland on sandy alluvial fans’
- RE 10.5.1 ‘Eucalyptus similis and/or Corymbia brachycarpa and/or Corymbia setosa low open woodland on sand plains’
- RE 10.5.5 ‘Eucalyptus melanophloia woodland to open woodland on sand plains’. This is the dominant RE where the black-throated finch occurs on the Carmichael mine lease (GHD, 2012)
- RE 10.7.11 ‘Eucalyptus melanophloia low open woodland on ferricrete’.

The species also occurs in non-remnant vegetation (GHD, 2012).

### 2.7.5.2 Qualitative mathematical model

As part of this bioregional assessment (BA), a qualitative mathematical model was developed for the 'Floodplain, terrestrial GDE' landscape group. This model focused on the influence that surface water and groundwater hydrology had on trees that support a woodland community, creating local conditions and a microclimate (i.e. shade, leaf litter and soil moisture) that favours mesic vegetation and suppresses xeric vegetation (Figure 27). Trees connected to groundwater are maintained by a specific regime where the rate of drawdown in groundwater and its maximum depth does not outstrip the ability of the trees’ rate and extent of root growth to maintain contact with groundwater stores. Moreover, deep-rooted trees have the potential to draw groundwater to the surface where it can become available to shallow-rooted mesic vegetation. The strength or existence of this effect, however, was deemed to be uncertain. Seasonal floods are generally shown to suppress xeric vegetation in the floodplain, to favour trees and mesic species, and to support a (as yet unspecified) floodplain community. Seasonal floods are important contributors to the recharging of groundwater, but excessive groundwater recharge could potentially contribute to saturated soil conditions where an anoxic root zone suppresses deep-rooted vegetation (i.e. trees connected to groundwater (TCGW) and mesic non-tree deep roots (MNTDR), Figure 27). It is uncertain, however, whether these floodplains could develop anoxic soil conditions, and existence of this link was also uncertain.

In summary, two uncertainties exist in the qualitative modelling. First, whether deep-rooted trees have the potential to draw groundwater to the surface where it can become available to shallow-rooted mesic vegetation. Second, whether there is a link between groundwater and the anoxic root zone. As a consequence of these uncertainties, four alternative models were developed (Figure 27, Figure 28, Figure 29 and Figure 30). In the first model (Figure 27, Table 21), both links are present. The second model (Figure 28, Table 22) lacks the link between trees drawing groundwater to the surface, but the link indicating the potential for groundwater to contribute to anoxic soils is present. In the third model (Figure 29, Table 23) the link between trees drawing groundwater to the surface is present but the link indicating the potential for groundwater to contribute to anoxic soils is not. In the fourth model (Figure 30, Table 24) neither link occurs.

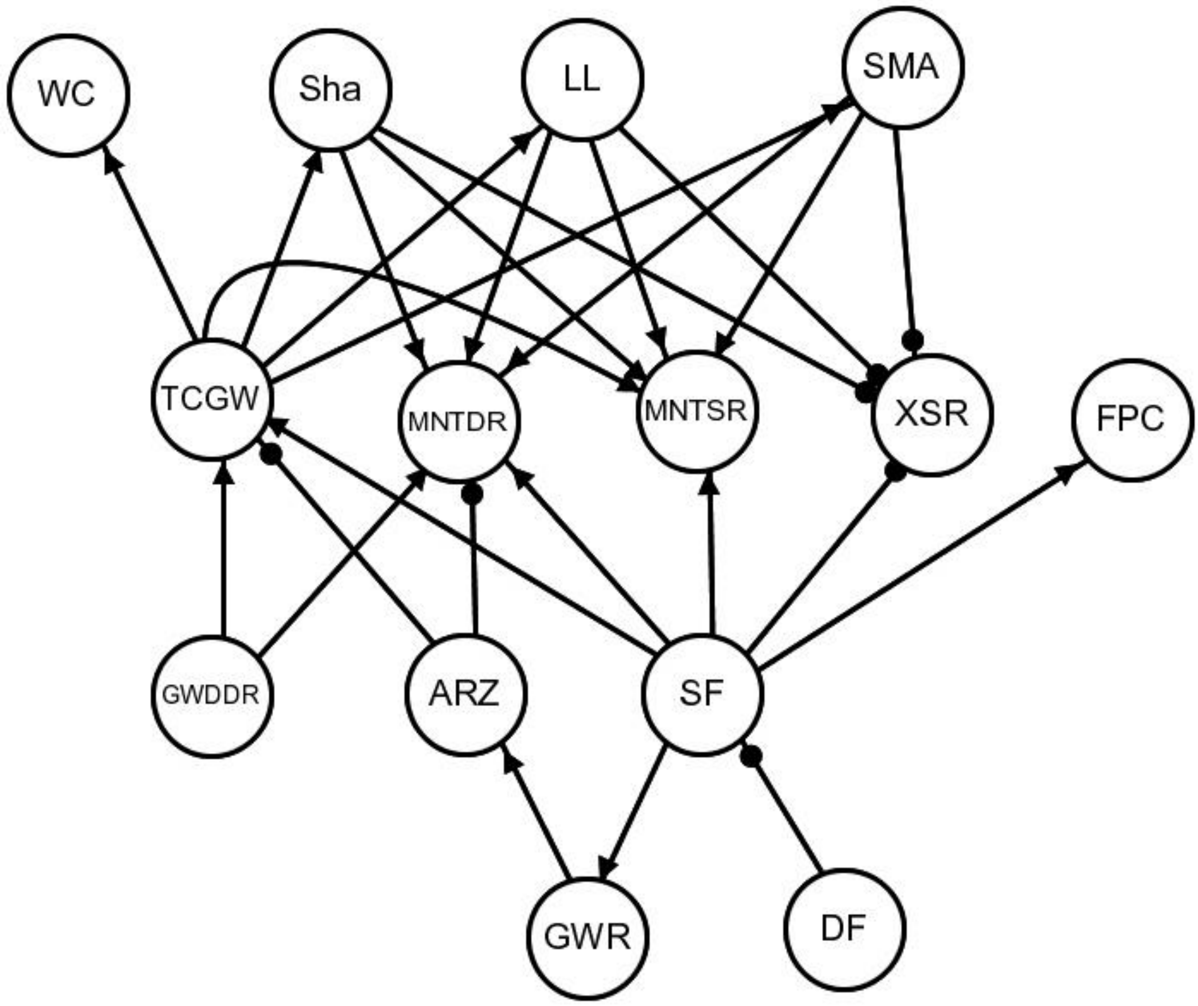


**Figure 27 Signed digraph model (Model 1) of the floodplain vegetative community associated with the 'Floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change**

Model variables are: anoxic root zone (ARZ), floodplain community (FPC), groundwater depth and drawdown rate (GWDDR), decreased floods (DF), groundwater recharge (GWR), leaf litter (LL), mesic non-tree deep roots (MNTDR), mesic non-tree shallow roots (MNTSR), seasonal floods (SF), shade (Sha), soil moisture availability (SMA), trees connected to groundwater (TCGW), woodland community (WC), xeric shallow roots (XSR). A link ending in an arrowhead denotes a positive direct effect; a link ending in a filled circle denotes a negative direct effect. GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

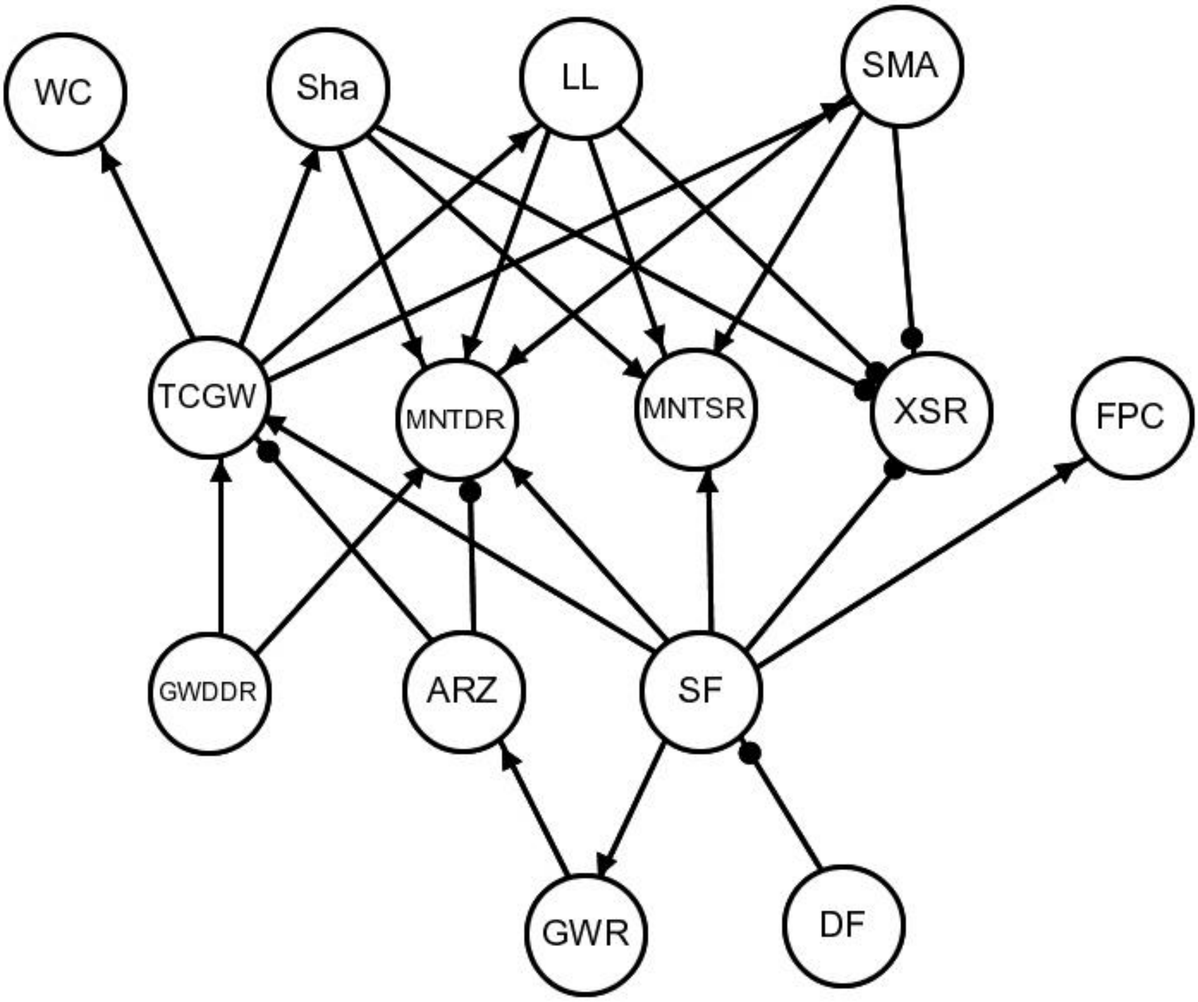


**Figure 28 Signed digraph model (Model 2) of the floodplain vegetative community associated with the 'Floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change**

Model variables are: anoxic root zone (ARZ), floodplain community (FPC), groundwater depth and drawdown rate (GWDDR), decreased floods (DF), groundwater recharge (GWR), leaf litter (LL), mesic non-tree deep roots (MNTDR), mesic non-tree shallow roots (MNTSR), seasonal floods (SF), shade (Sha), soil moisture availability (SMA), trees connected to groundwater (TCGW), woodland community (WC), xeric shallow roots (XSR). A link ending in an arrowhead denotes a positive direct effect; a link ending in a filled circle denotes a negative direct effect. GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

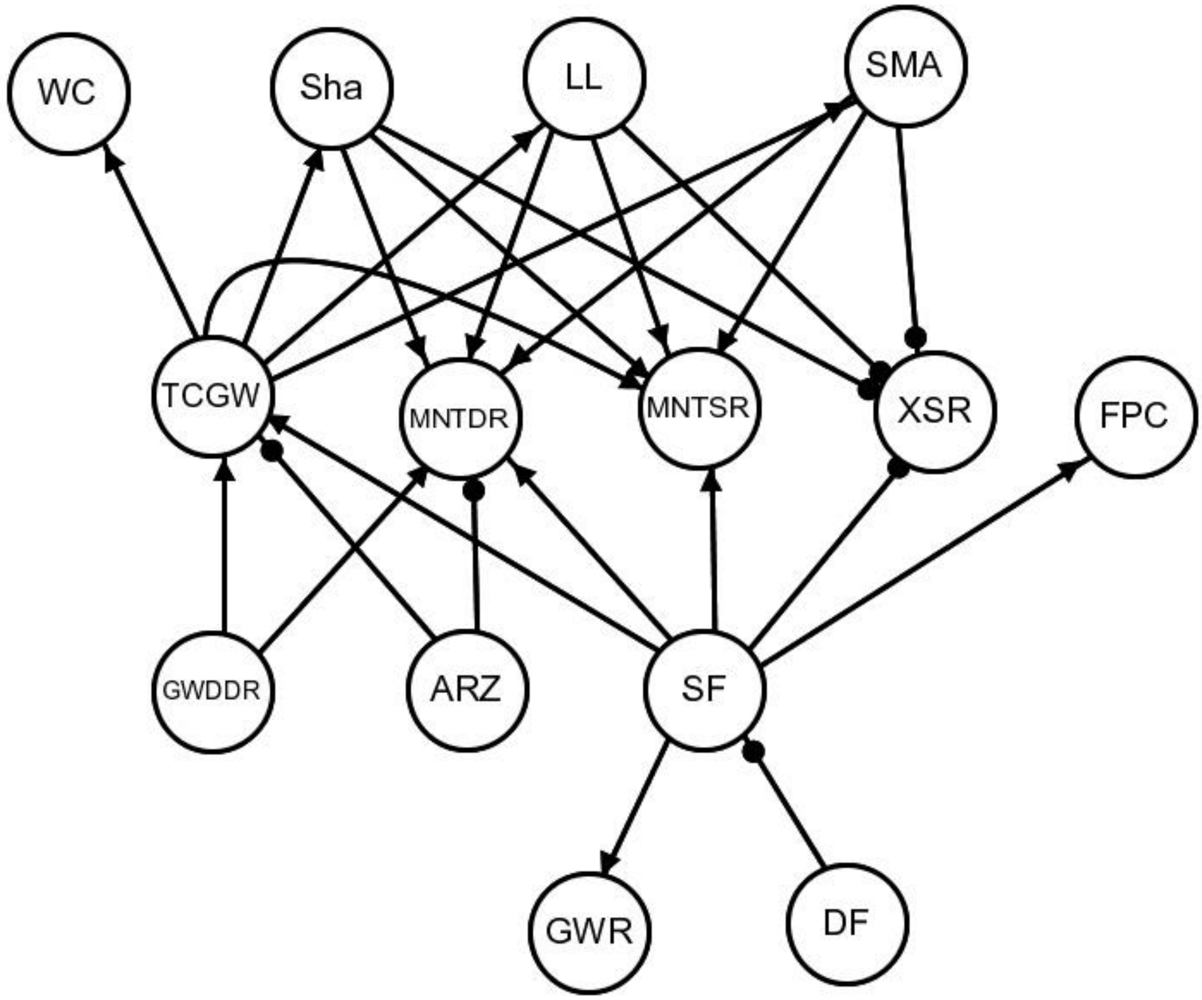


**Figure 29 Signed digraph model (Model 3) of the floodplain vegetative community associated with the 'Floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change**

Model variables are: anoxic root zone (ARZ), floodplain community (FPC), groundwater depth and drawdown rate (GWDDR), decreased floods (DF), groundwater recharge (GWR), leaf litter (LL), mesic non-tree deep roots (MNTDR), mesic non-tree shallow roots (MNTSR), seasonal floods (SF), shade (Sha), soil moisture availability (SMA), trees connected to groundwater (TCGW), woodland community (WC), xeric shallow roots (XSR). A link ending in an arrowhead denotes a positive direct effect; a link ending in a filled circle denotes a negative direct effect. GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

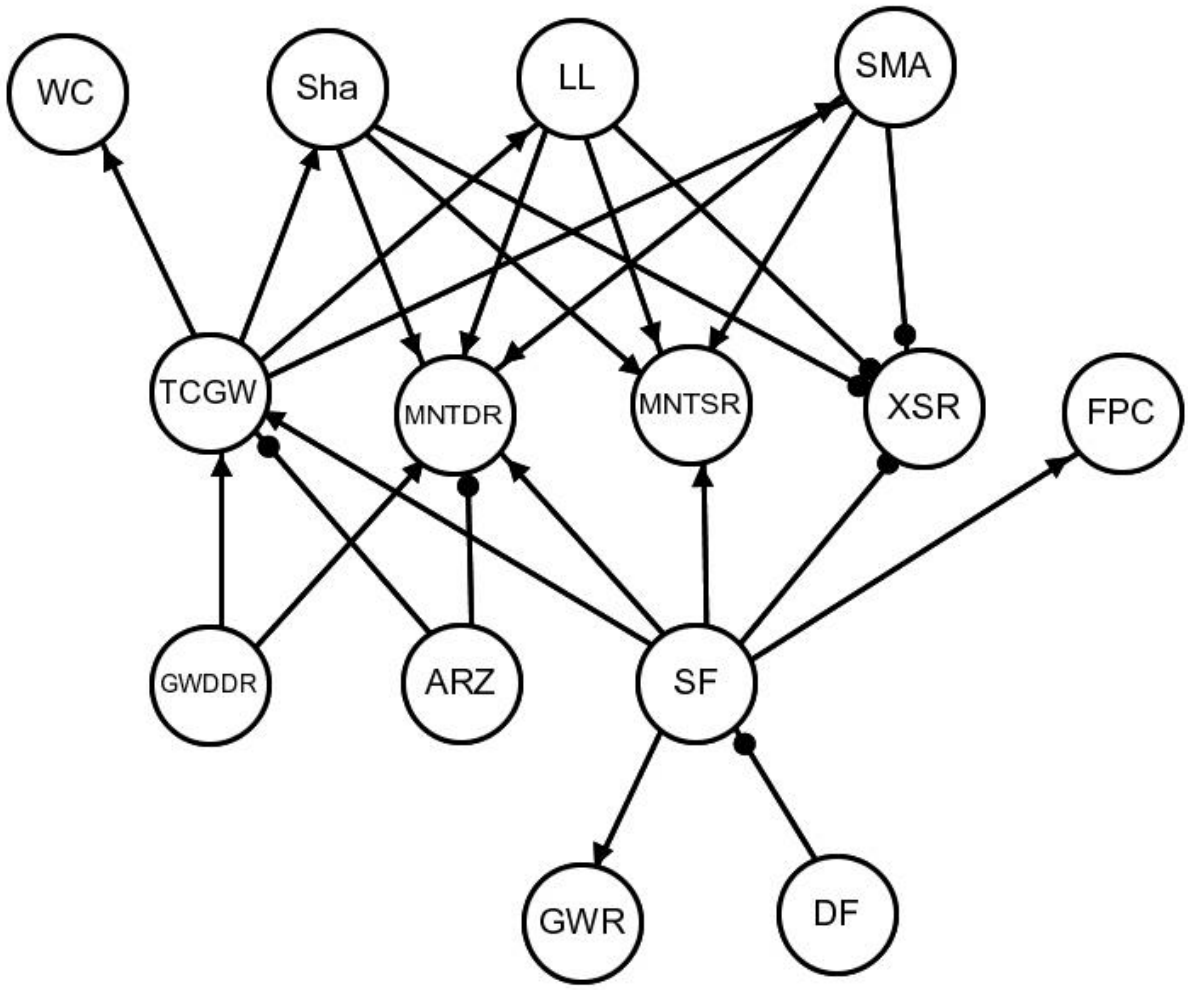


**Figure 30 Signed digraph model (Model 4) of the floodplain vegetative community associated with the ‘Floodplain, terrestrial GDE’ landscape group in the Galilee subregion zone of potential hydrological change**

Model variables are: anoxic root zone (ARZ), floodplain community (FPC), groundwater depth and drawdown rate (GWDDR), decreased floods (DF), groundwater recharge (GWR), leaf litter (LL), mesic non-tree deep roots (MNTDR), mesic non-tree shallow roots (MNTSR), seasonal floods (SF), shade (Sha), soil moisture availability (SMA), trees connected to groundwater (TCGW), woodland community (WC), xeric shallow roots (XSR). A link ending in an arrowhead denotes a positive direct effect; a link ending in a filled circle denotes a negative direct effect. GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

Surface and groundwater modelling indicate potential impacts of coal mining to the regime for groundwater depth and drawdown rate (i.e. such that trees can maintain contact with groundwater through root growth), and decreased flood events. These projected changes may be ecologically meaningful. Based on all combinations of these impacts, three cumulative impact scenarios were developed for qualitative analysis of response predictions (Table 20).

Qualitative analyses of the four signed digraph models (Figure 27, Figure 28, Figure 29 and Figure 30) generally indicate a negative or ambiguous response prediction for all biological variables within the floodplain ecosystem (Table 21, Table 22, Table 23 and Table 24, respectively). The only variable that was predicted to respond positively to any of the cumulative impact scenarios was xeric vegetation with shallow roots. Response predictions for models 3 and 4, which lacked the link between groundwater and anoxic conditions in the root zone of the floodplain, generally had a higher level of sign determinacy for impacts that included a decrease in floods (i.e. impact scenarios C2 and C3, Table 23 and Table 24).

**Table 20 Summary of the cumulative impact scenarios (CISs) for the 'Floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change**

| CIS | GWDDR | DF |
|---|---|---|
| C1 | – | 0 |
| C2 | 0 | + |
| C3 | – | + |

Pressure scenarios are determined by combinations of no-change (0), increase (+) or a decrease (–) in the following signed digraph variables: groundwater depth and drawdown rate (GWDDR), and decreased flood events (DF). Scenario C3 shows the expected impacts under the modelled coal resource development pathway in the Galilee subregion. GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

**Table 21 Predicted response of the signed digraph variables (Model 1) in the 'Floodplain, terrestrial GDE' landscape group to (cumulative) changes in hydrological response variables**

| Signed digraph variable (full name) | Signed digraph variable (short form) | C1 | C2 | C3 |
|---|---|---|---|---|
| Seasonal floods | SF | 0 | – | – |
| Groundwater recharge | GWR | 0 | – | – |
| Floodplain community | FPC | 0 | – | – |
| Groundwater depth and drawdown rate | GWDDR | – | 0 | – |
| Decreased floods | DF | 0 | + | + |
| Trees connected to groundwater | TCGW | – | ? | ? |
| Mesic non-tree deep roots | MNTDR | – | ? | ? |
| Mesic non-tree shallow roots | MNTSR | – | ? | (–) |
| Xeric shallow roots | XSR | + | ? | (+) |
| Woodland community | WC | – | ? | ? |
| Shade | Sha | – | ? | ? |
| Leaf litter | LL | – | ? | ? |
| Soil moisture availability | SMA | – | ? | ? |
| Anoxic root zone | ARZ | 0 | – | – |

Qualitative model predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

**Table 22 Predicted response of the signed digraph variables (Model 2) in the 'Floodplain, terrestrial GDE' landscape group to (cumulative) changes in hydrological response variables**

| Signed digraph variable (full name) | Signed digraph variable (short form) | C1 | C2 | C3 |
|---|---|---|---|---|
| Seasonal floods | SF | 0 | – | – |
| Groundwater recharge | GWR | 0 | – | – |
| Floodplain community | FPC | 0 | – | – |
| Groundwater depth and drawdown rate | GWDDR | – | 0 | – |
| Decreased floods | DF | 0 | + | + |
| Trees connected to groundwater | TCGW | – | ? | ? |
| Mesic non-tree deep roots | MNTDR | – | ? | ? |
| Mesic non-tree shallow roots | MNTSR | – | ? | (–) |
| Xeric shallow roots | XSR | + | ? | (+) |
| Woodland community | WC | – | ? | ? |
| Shade | Sha | – | ? | ? |
| Leaf litter | LL | – | ? | ? |
| Soil moisture availability | SMA | – | ? | ? |
| Anoxic root zone | ARZ | 0 | – | – |

Qualitative model predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

**Table 23 Predicted response of the signed digraph variables (Model 3) in the ‘Floodplain, terrestrial GDE’ landscape group to (cumulative) changes in hydrological response variables**

| Signed digraph variable (full name) | Signed digraph variable (short form) | C1 | C2 | C3 |
|---|---|---|---|---|
| Seasonal floods | SF | 0 | – | – |
| Groundwater recharge | GWR | 0 | – | – |
| Floodplain community | FPC | 0 | – | – |
| Groundwater depth and drawdown rate | GWDDR | – | 0 | – |
| Decreased floods | DF | 0 | + | + |
| Trees connected to groundwater | TCGW | – | – | – |
| Mesic non-tree deep roots | MNTDR | – | – | – |
| Mesic non-tree shallow roots | MNTSR | – | – | – |
| Xeric shallow roots | XSR | + | + | + |
| Woodland community | WC | – | – | – |
| Shade | Sha | – | – | – |
| Leaf litter | LL | – | – | – |
| Soil moisture availability | SMA | – | – | – |
| Anoxic root zone | ARZ | 0 | 0 | 0 |

Qualitative model predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

**Table 24 Predicted response of the signed digraph variables (Model 4) in the 'Floodplain, terrestrial GDE' landscape group to (cumulative) changes in hydrological response variables**

| Signed digraph variable (full name) | Signed digraph variable (short form) | C1 | C2 | C3 |
|---|---|---|---|---|
| Seasonal floods | SF | 0 | – | – |
| Groundwater recharge | GWR | 0 | – | – |
| Floodplain community | FPC | 0 | – | – |
| Groundwater depth and drawdown rate | GWDDR | – | 0 | – |
| Decreased floods | DF | 0 | + | + |
| Trees connected to groundwater | TCGW | – | – | – |
| Mesic non-tree deep roots | MNTDR | – | – | – |
| Mesic non-tree shallow roots | MNTSR | – | – | – |
| Xeric shallow roots | XSR | + | + | + |
| Woodland community | WC | – | – | – |
| Shade | Sha | – | – | – |
| Leaf litter | LL | – | – | – |
| Soil moisture availability | SMA | – | – | – |
| Anoxic root zone | ARZ | 0 | 0 | 0 |

Qualitative model predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

### 2.7.5.3 *Temporal scope, hydrological response variables and receptor impact variables*

The temporal scope for the floodplain ecosystem is the same as that described for the other landscape classes of the Galilee subregion. For groundwater variables the reference assessment interval is defined as the 30 years preceding 2012 (i.e. 1983 to 2012). For groundwater, maximum drawdown (metres) and time to maximum drawdown are considered across the full 90-year assessment period (i.e. 2013 to 2102). At the time of the workshop, it was uncertain whether the time of maximum drawdown would vary in that 90-year window. The elicitation was thus conditioned on that variable as well.

For the floodplain ecosystem, the qualitative modelling workshop identified two variables – groundwater and surface water – as the key hydrological elements.

The hydrological variables were interpreted as a set of hydrological response variables that can be modelled (Table 25), and the receptor impact variable was formally defined during the receptor impact modelling workshop. As a result, the relationships identified in the qualitative modelling workshop were formalised into a receptor impact model. The model related the response of annual mean percent foliage cover in a 0.01 $km^2$ (1 ha) plot to changes in dmaxRef (maximum drawdown) and EventsR2.0 (overbank flood events).

**Table 25 Summary of hydrological response variables used in receptor impact models for the 'Floodplain, terrestrial GDE' landscape group, and the corresponding variables for the signed directed graphs**

| Hydrological response variable | Definition of hydrological response variable | Notation used for corresponding signed digraph variable |
|---|---|---|
| dmaxRef | Maximum difference in drawdown under the baseline future or under the coal resource development pathway future relative to the reference period (1983 to 2012) | GWDDR |
| tmaxRef | The year that the maximum difference in drawdown relative to the reference period (1983 to 2012) occurs | GWDDR |
| EventsR2.0 | The mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in flood events with a return period of 2.0 years as defined from modelled baseline flow in the reference period (1983 to 2012)). This metric is designed to be approximately representative of the number of overbank flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development. | DF |

GDE = groundwater-dependent ecosystem

### *2.7.5.4 Receptor impact models*

#### 2.7.5.4.1 Percent foliage cover

***Elicitation scenarios***

Table 26 summarises the elicitation design matrix for the percent foliage cover of trees in the 'Floodplain, terrestrial GDE' landscape group. The first design point (design point identifier 1) set the variability in percent foliage cover under the reference conditions (no drawdown).

The remaining design points represent hydrological scenarios that span the uncertainty in the values of the hydrological response variables in the relevant time period of hydrological history associated with the short-assessment (2013 to 2042) and long-assessment (2073 to 2102) periods.

Design point identifiers 3 through to 33 (as listed in Table 26) represent combinations of the two hydrological response variables (dmaxRef, EventsR2.0, Table 25), together with high and low values of Yref. The high and low values for Yref were calculated during the receptor impact modelling workshop following the experts' response to the first design point, and then automatically included within the design for the elicitations at the subsequent design points.

**Table 26 Elicitation design matrix for receptor impact model of percent foliage cover in 'Floodplain, terrestrial GDE' landscape group**

| Design point identifier | dmaxRef | EventsR2.0 | Yref | Year |
|---|---|---|---|---|
| 1 | 0 | 0.50 | na | 2012 |
| 13 | 0.2 | 0.85 | 0.2 | 2042 |
| 17 | 2.8 | 1.65 | 0.2 | 2042 |
| 9 | 10 | 1.65 | 0.075 | 2042 |
| 3 | 10 | 0.05 | 0.075 | 2042 |
| 23 | 2.8 | 0.85 | 0.075 | 2102 |
| 33 | 10 | 0.85 | 0.2 | 2102 |
| 25 | 0.2 | 1.65 | 0.075 | 2102 |
| 28 | 0.2 | 0.05 | 0.2 | 2102 |

Design points for Yref in the future (short- and long-assessment periods) are calculated during the receptor impact modelling elicitation workshop using elicited values for the receptor impact variable in the reference period. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling. dmaxRef and EventsR2.0 are as in Table 25. na = not applicable, GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

### *Receptor impact model*

The model fitted to the elicited values of mean percent foliage cover takes the form

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \sum_{j=1}^{2} \beta_{h_j} x_{h_j} \quad (3)$$

where $x_0$ is an intercept term (a vector of ones), $x_f$ is a binary indicator variable scored 1 for the case of an assessment in the short- or long-assessment year, $x_l$ is a binary indicator variable scored 1 for the case of an assessment in the long-assessment year, $x_r$ is a continuous variable that represents the value of the receptor impact variable in the reference year (Yref, set to zero for the case of an assessment in the reference year), and $x_{h_j}, j = 1 \dots 2$ are the (continuous or integer) values of the two hydrological response variables (dmaxRef, EventsR2.0). Note that the modelling framework provides for more complex models, including the quadratic value of, and interactions between, the hydrological response variables but in this instance the simple linear model above was identified as the most parsimonious representation of the experts' responses.

The (marginal) mean and 80% central credible intervals of the two hydrological response variable coefficients are summarised in the partial regression plot in Figure 31, while Table 27 summarises the same information for all six model coefficients.

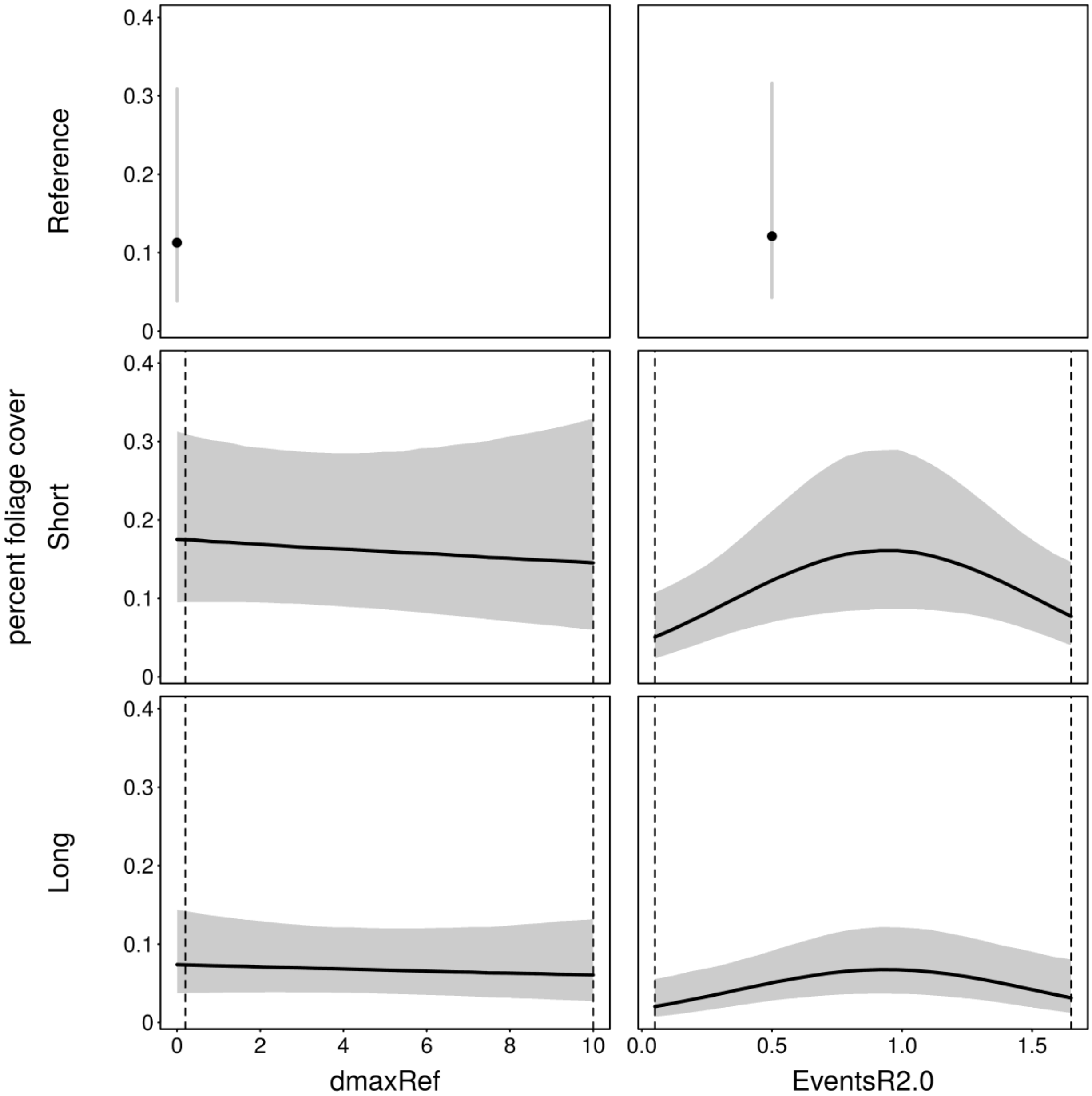


**Figure 31 (Top row) Predicted mean (black dot) and 80% central credible interval (grey line) of percent foliage cover under reference hydrological conditions. (Middle and bottom rows) Predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on percent foliage cover in the Galilee subregion zone of potential hydrological change**

In the middle and bottom rows, all other hydrological response variables are held constant at the midpoint of their elicitation range (during the risk estimation process all hydrological response variables vary simultaneously). The dashed vertical lines show range of hydrological response variables used in the elicitation workshop. Reference = period from 1983 to 2012, Short = assessment period 2013 to 2042, Long = assessment period 2073 to 2102. dmaxRef and EventsR2.0 are as in Table 25. The numbers on the y-axis range from 0 to 1 as the receptor impact model was constructed using the proportion for the statistical modelling. They should be interpreted as a percent foliage cover ranging from 0 to 100%.
Data: Bioregional Assessment Programme (Dataset 4)

The model indicates that the experts' opinion provides evidence for dmaxRef having a very small negative effect on average percent foliage cover. This suggests that percent foliage cover may decrease as groundwater drawdown increases due to coal resource development. The model predicts that (holding all other hydrological response variables constant at the mid-point of their elicitation range) the mean of the average percent foliage cover will drop from approximately 10% without any change in groundwater level, to about 7% if the levels decrease by 6 m relative to the reference level in 2012. There is, however, considerable uncertainty in these predictions, with an 80% chance that the foliage cover will lie somewhere between approximately 24% and less than 1% on the short-assessment period, and somewhere between roughly 17% and less than 1% in the long-assessment period, with a 6 m drop in groundwater level.

**Table 27 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for percent foliage cover in the ‘Floodplain, terrestrial GDE’ landscape group**

| | Mean | q10 | q90 |
|---|---|---|---|
| **(Intercept)** | –3.08 | –4.4 | –1.76 |
| **future1** | 0.0937 | –1.12 | 1.3 |
| **long1** | –0.923 | –1.72 | –0.131 |
| **dmaxRef** | –0.0205 | –0.112 | 0.0715 |
| **EventsR2.0** | 2.89 | 0.575 | 5.21 |
| **I(EventsR2.0$^2$)** | –1.54 | –2.8 | –0.291 |

Future is a binary variable scored 1 if the analysis case is in a short- or long-assessment period. Long is a binary variable scored 1 if the analysis case is in the assessment year. dmaxRef and EventsR2.0 are as in Table 25. GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

The fitted model suggests that there is evidence in the experts’ responses for EventsR2.0 having a major quadratic effect on percent foliage cover. The 80% credible interval for this hydrological response variable’s coefficient lies wholly within the positive or negative parts of the real line (Table 27). If all other hydrological response variables are held at the midpoint of their elicitation range, the model suggests that the frequency of overbank flows will have a positive effect on average percent foliage cover unless that frequency becomes too high – the predicted increase in the average frequency of overbank flood events, from 0.05 in the 30 years preceding the reference year, to an average value of 0.9 over the future period, causes the average percent foliage cover to increase by almost 10%. However, large values of EventsR2.0 (above 1) will have a negative effect on percent foliage cover.

The summary statistics for the marginal distribution of the model coefficients (Table 27) for the two remaining model coefficients (future1 and long1) indicate that there is insufficient information in the expert-elicited data to determine the effect of the future coefficient, whereas the long coefficient is identified as having a negative effect.

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## 2.7.6 'Non-floodplain, terrestrial groundwater-dependent ecosystem' landscape group

***Summary***

The 'Non-floodplain, terrestrial groundwater-dependent ecosystem (GDE)' landscape group contains two landscape classes within the zone of potential hydrological change: 'Non-floodplain, terrestrial GDE', which occupies an area of 5.5 $km^2$; and 'Non-floodplain, terrestrial GDE, remnant vegetation', which occupies an area of 1184 $km^2$. The vegetation in this landscape group depends on the subsurface expression of groundwater on a permanent or intermittent basis to maintain growth or avoid water stress and adverse impacts on condition.

The physical environment of the 'Non-floodplain, terrestrial GDE' landscape group is described here along with a description of vegetation assemblages and threatened flora and fauna. The water requirements and the degree of groundwater dependency of the vegetation are discussed with a focus on rooting depth and depth to watertable.

A qualitative model was developed for the 'Non-floodplain, terrestrial GDE' landscape group. The model focused on recruitment dynamics associated with groundwater-dependent native tree species, with the primary production associated with tree canopies providing a range of (as yet unspecified) ecosystem roles.

A receptor impact model was designed that focused on the response of mean annual percent foliage cover of woody vegetation to changes in groundwater. The quantitative modelling, based on expert elicitation of response values, indicated that the reference year had a positive effect on average percent foliage cover. This suggests that given a set of hydrological response variable values in the future, a site with higher foliage cover at the 2012 reference point is more likely to have a higher foliage cover in the future than a site with a lower foliage cover value at this reference point.

The model also indicates that the expert's responses suggest that a 10 m groundwater drawdown will have almost no effect on average percent foliage cover.

### *2.7.6.1 Description*

#### 2.7.6.1.1 Overview

The 'Non-floodplain, terrestrial GDE' landscape group contains two landscape classes: 'Non-floodplain, terrestrial GDE', which occupies an area of 5.5 $km^2$; and 'Non-floodplain, terrestrial GDE, remnant vegetation', which occupies an area of about 1184 $km^2$ (Figure 32). The classification of these two landscape classes does not specify the source of groundwater (see Section 2.3.3 of companion product 2.3 for the Galilee subregion (Evans et al., 2018b)). These two landscape classes are examples of the third type of GDE defined in the typology of Richardson et al. (2011). These ecosystems are terrestrial GDEs that rely on the subsurface expression of groundwater on a permanent or intermittent basis to maintain growth or avoid water stress and adverse impacts on condition (Eamus et al., 2006; Richardson et al., 2011). In the landscape classification adopted here, these would be broadly defined as groundwater-dependent vegetation assemblages that are not on floodplains and are not associated with palustrine, lacustrine or riparian wetlands.

The Galilee subregion occurs in an area where the annual rainfall is low and unpredictable. Climatically, areas occupied by the ‘Non-floodplain, terrestrial GDE’ landscape group are water-limited. Annual rainfall is low at approximately 300 mm/year and evaporation is high at greater than 2000 mm/year (companion product 1.1 for the Galilee subregion (Evans et al., 2014)). Low and sporadic rainfall coupled with high evaporative demand suggest that groundwater may be a more reliable source of water for this landscape group than surface water (Eamus et al., 2006). Much of the vegetation, in particular trees, relies on accessing groundwater from shallow unconfined aquifers. Groundwater is needed for trees to persist in areas where evapotranspiration exceeds rainfall. The presence of a shallow watertable enables the roots of trees to obtain a relatively consistent supply of water irrespective of aboveground conditions (Eamus et al., 2015).

A high level conceptual model for unconfined, permeable rock aquifers is relevant to this landscape group (Figure 33). In the model, groundwater stored in one or more unconfined permeable rock aquifers is transmitted through intergranular pore spaces, fractures and/or weathered zones in the rock strata (DSITI, 2015). Near-surface discharge can occur where there is a change in geology (e.g. at a geological contact between a sandstone layer and an underlying shale layer) or at footslopes at the base of hills or ranges (Figure 33). Here, unconfined aquifers can discharge groundwater to terrestrial vegetation. Groundwater may then move laterally downslope to within reach of the capillary zone of the terrestrial vegetation.

Sediments that comprise Cenozoic to Quaternary loamy and sandy plains readily store and transmit groundwater in shallow, local aquifers. Here, terrestrial vegetation may source groundwater up-gradient of the contact between the plains and elevated areas such as mesas and raised ironstone outcrops. Terrestrial GDEs in these areas are likely to support regional ecosystems (REs) dominated by *Corymbia* spp. (DSITI, 2015). Medium- to coarse-grained sedimentary rocks may store and transmit groundwater through fractures, residual porosity and weathered zones. These local, bedrock aquifers occur in rock that is otherwise of relatively low porosity (DSITI, 2015). Here, terrestrial vegetation may source groundwater where it discharges along footslopes within sandstone ranges. A rarer type of permeable rock aquifer occurs in basalts which store and transmit groundwater through vesicles, fractures and weathered zones. Terrestrial vegetation that occurs in areas of basaltic rock may source groundwater at the edge of basalt plains and hills.

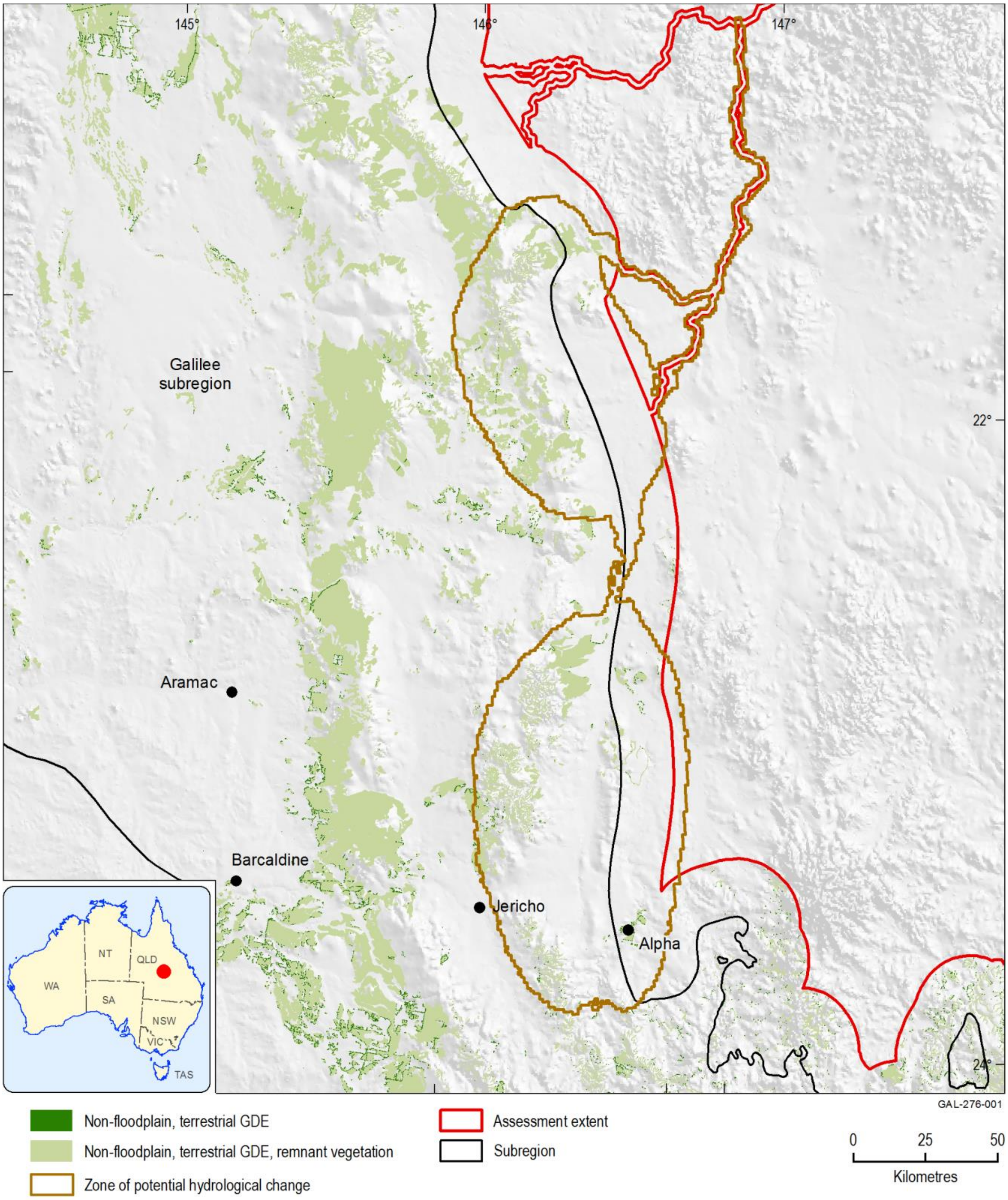


**Figure 32 Distribution of the landscape classes in the 'Non-floodplain, terrestrial GDE' landscape group within the Galilee subregion zone of potential hydrological change**

GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 1)

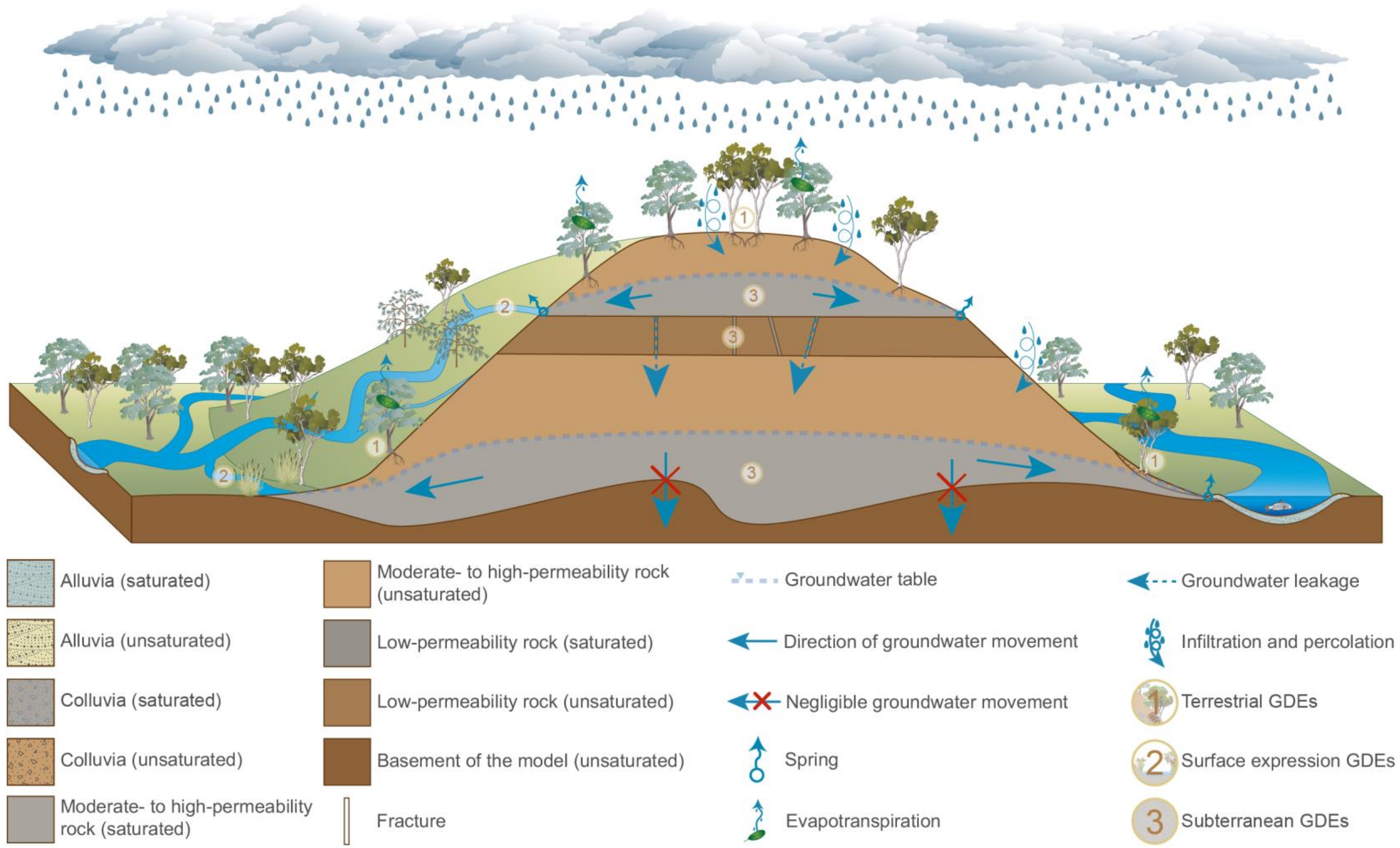


**Figure 33 Conceptual model of a permeable rock aquifer**

GDE = groundwater-dependent ecosystem
Source: adapted from Queensland Department of Science, Information Technology and Innovation (Dataset 2), © The State of Queensland (Department of Science, Information Technology and Innovation) 2015

### 2.7.6.1.2 Hydrological regimes and connectivity

Understanding the connectivity of groundwater in the zone of potential hydrological change is challenging because the Galilee subregion contains a series of stacked groundwater systems. These are described in detail in companion product 2.1-2.2 (Evans et al., 2018a) and Section 2.3.2 of companion product 2.3 (Evans et al., 2018b) for the Galilee subregion, and are summarised below to provide context. The paragraph below focuses on the Galilee Basin groundwater system in which the Rewan Group and Clematis Group occur. These are the most likely sources of groundwater for the 'Non-floodplain, terrestrial GDE' landscape group within the zone. Further information about the variability of the depth to the watertable in the zone (i.e. the standing water level observed in groundwater bores) is provided in Section 3.4.1 of companion product 3-4 for the Galilee subregion (Lewis et al., 2018).

Potential sources of groundwater for vegetation that forms the 'Non-floodplain, terrestrial GDE' landscape group are:

- shallow perched aquifers in weathered Cenozoic sediments. Groundwater may come near or discharge to the surface on footslopes or where percolating groundwater becomes perched upon a relatively impermeable layer such as clay or shale, the result of which redirects groundwater flow to near surface
- groundwater flow in unconfined parts of aquifers coming within the capillary zone of plants or discharging near surface. This could occur in any weathered sedimentary rock unit which is dominated by sandstone (e.g. Clematis Group, Dunda beds (the upper and more permeable part of the Rewan Group), Colinlea Sandstone, and sandstone beds in the Joe Joe Group).

Some shallow groundwater flow could be part of a regional groundwater system. The GDEs that are connected to the regional groundwater systems within the zone of potential hydrological change would be impacted by changes in groundwater (for example, from drawdown or reductions in recharge) across a broad area. However, not all GDEs are connected to the regional watertable. Those that aren't are unlikely to be impacted by broader-scale changes.

### 2.7.6.1.3 Ecological processes

The water requirements and the degree of groundwater dependency of the vegetation that is in the 'Non-floodplain, terrestrial GDE' landscape group will depend on a number of factors including:

- age and rooting distribution of plants, and how this enables access to the watertable
- depth to the watertable and spatial and temporal (seasonal) variation in the watertable level
- groundwater quality.

Vegetation within the 'Non-floodplain, terrestrial GDE' landscape group will typically use deep roots to access groundwater in the capillary zone above the watertable via capillary action or hydraulic lift. A baseline assumption with the physiology of Australian plants is that they can access groundwater to a depth of about 10 m (D Eamus, 2016, pers. comm.). This value is supported by research that found the mean maximum rooting depth across 11 species of sclerophyllous trees to be 12.6 m ± 3.4 m standard error (Canadell et al., 1996). However, some tree species have roots that can access water at greater depths. *Eucalyptus marginata* roots have been reported at depths of 40 m by Dell et al. (1983). This work found that only fine roots (less than 1 mm diameter) were able to penetrate the clay matrix of the soil and reach these depths.

The dependency of vegetation on groundwater may vary seasonally. It is generally assumed that water dependency will change with rainfall and be greatest at times of seasonal rainfall deficit. There is empirical support for this view. For example, in eucalypt woodland along the Condamine River, southern Queensland, the frequency of deep subsurface water use was greatest in the late dry season (Gow et al., 2016).

The depth to the watertable is an important factor in determining the volume of water discharged through GDEs. In the zone of potential hydrological change, the depth to standing water in the 98 bores in the ‘Non-floodplain, terrestrial GDE’ landscape group averaged 37.3 m below surface. The range varied widely however, from a maximum depth of 156.7 m to a minimum depth of 0.3 m below surface.

Currently, there is little published information on either the amount of water used by GDEs or the physiology of GDEs. Similarly, there is a knowledge gap in terms of information on root depth of vegetation within GDEs and on responses to changes in depth-to-groundwater (Eamus et al., 2015). This information, if it were available, would be invaluable in assessing the impacts of groundwater drawdown on GDEs.

#### 2.7.6.1.4 Vegetation

The landscape classes within the zone of potential hydrological change span two of the Interim Biogeographic Regionalisation for Australia (IBRA) regions: Desert Uplands and Brigalow Belt. The Desert Uplands are characterised by upland landforms dominated by sandstone ranges and sandplains. In contrast, the Brigalow Belt is characterised by undulating ranges to alluvial plains (Bastin et al., 2008). Underlying geology and land zone contribute to a complex mosaic of vegetation communities, including eucalypt and acacia woodlands, shrublands and grasslands.

Within the ‘Non-floodplain, terrestrial GDE’ landscape group there are 90 regional ecosystems (REs). There is considerable uncertainty related to the water regime required to support many of these REs. However, the nature of the dependency on groundwater is likely to vary among and within vegetation communities, as a function of groundwater availability, depth and quality (companion product 2.1-2.2 for the Galilee subregion (Evans et al., 2018a)).

The distribution of the most widespread vegetation assemblages, represented by REs, within the ‘Non-floodplain, terrestrial GDE’ landscape group is shown in Figure 34. The majority of these REs have *Eucalyptus* and/or *Corymbia* species as dominant/co-dominant in the upper storey. A smaller number of REs have *Acacia* and/or *Melaleuca* species as dominant/co-dominant. The 10 most widespread REs in the ‘Non-floodplain, terrestrial GDE’ landscape group in order of decreasing area (expressed as a percentage of the zone) are:

- RE 10.5.5 ‘Eucalyptus melanophloia woodland to open woodland on sand plains’ (3.68%)
- RE 10.7.2 ‘Eucalyptus persistens or Corymbia dallachiana low open woodland or Triodia pungens hummock grassland on ferricrete above scarps’ (1.00%)

- RE 10.7.11 'Eucalyptus melanophloia low open woodland on ferricrete' (0.74%)
- RE 10.7.7 'Melaleuca spp. and/or Acacia leptostachya shrubland on ferricrete (eastern)' (0.56%)
- RE 10.10.4 'Eucalyptus exilipes and/or Corymbia leichhardtii open woodland on sandstone ranges' (0.39%)
- RE 10.7.3 'Acacia shirleyi woodland or A. catenulata low woodland at margins of plateaus' (0.28%)
- RE 10.10.1 'Acacia shirleyi woodland or A. catenulata low open woodland on sandstone ranges' (0.26%)
- RE 11.5.3 'Eucalyptus populnea +/- E. melanophloia +/- Corymbia clarksoniana woodland on Cainozoic sand plains and/or remnant surfaces' (0.19%)
- RE 10.5.2 'Corymbia plena with or without C. dallachiana or C. terminalis open woodland on sand plains' (0.11%)
- RE 10.7.12 'Eucalyptus drepanophylla or E. crebra open woodland on ferricrete' (0.11%).

'Brigalow (Acacia harpophylla dominant and co-dominant)', which is listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) as an 'Endangered' ecological community, occurs within this landscape group. The ecological community is predicted to occur widely in the eastern half of the Galilee subregion zone of potential hydrological change (Department of the Environment and Energy, 2017a). The vegetation types that make up the brigalow ecological community mostly occur on acidic and salty clay soils. Within the zone these are mostly on deep cracking clay soils.

'Weeping Myall Woodlands', which is listed under the EPBC Act as an 'Endangered' ecological community, occurs within this landscape group. The ecological community is predicted to occur widely in the south-eastern part of the Galilee subregion zone of potential hydrological change (Department of the Environment and Energy, 2017b). It occurs on flat areas or shallow depressions on alluvial plains. Such areas are not associated with river channels and are rarely flooded. The soils are black, brown, red-brown or grey clay or clay loam (Commonwealth of Australia, 2009).

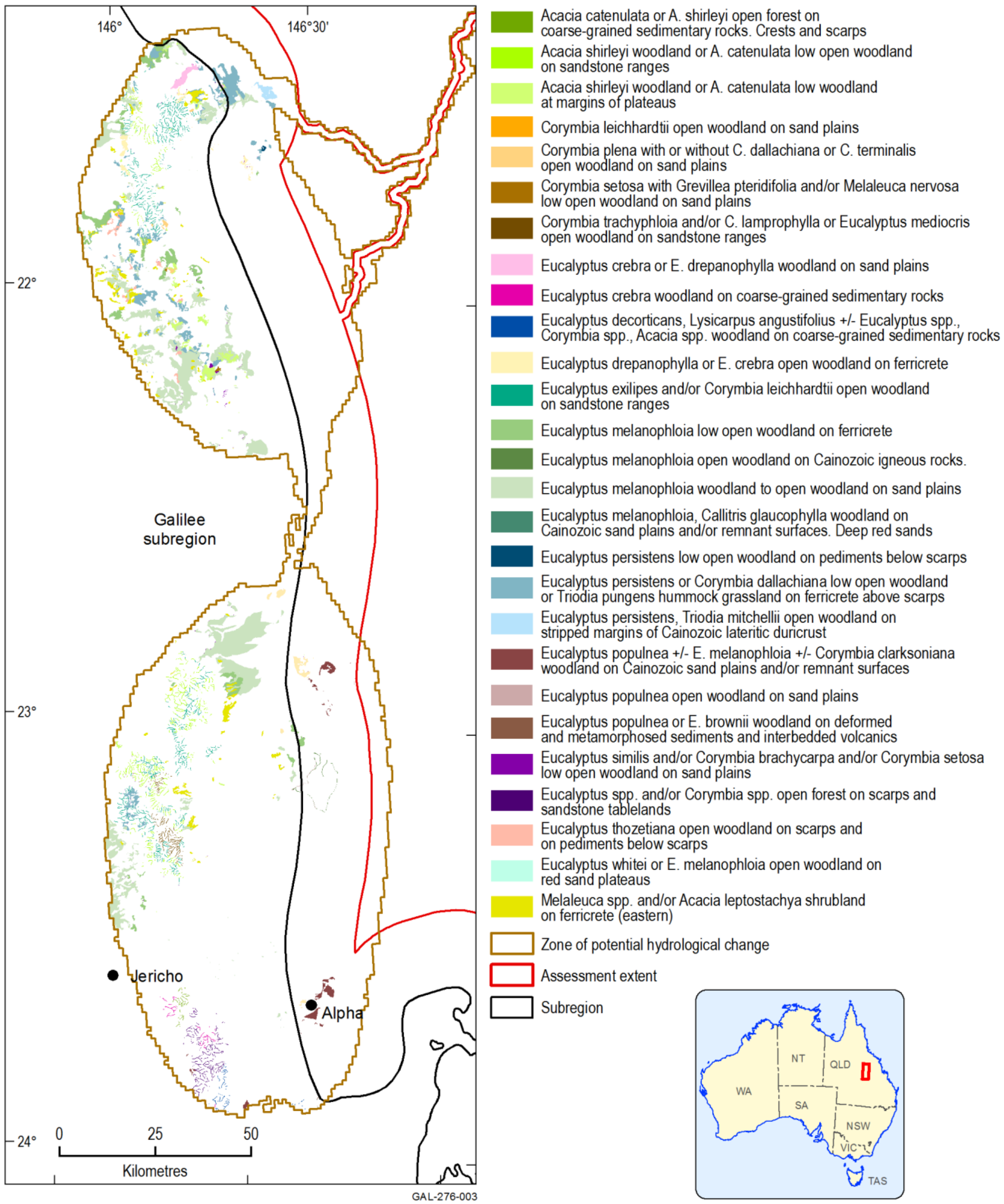


**Figure 34 Vegetation assemblages (regional ecosystems) in the 'Non-floodplain, terrestrial GDE' landscape group within the Galilee subregion zone of potential hydrological change**

GDE = groundwater-dependent ecosystem

Data: Bioregional Assessment Programme (Dataset 1, Dataset 3)

### 2.7.6.1.5 Flora and fauna

The 'Non-floodplain, terrestrial GDE' landscape group provides potential habitat for a range of threatened animal species. These are detailed below.

The koala (*Phascolarctos cinereus*) potentially occurs within the 'Non-floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change. Koalas in Queensland are listed as 'Vulnerable' nationally (EPBC Act) and under Queensland's *Nature Conservation Act 1992* (Nature Conservation Act). Koalas in semi-arid environments, including within the zone, inhabit forest and woodland dominated by *Eucalyptus* species with important food and habitat trees including *Eucalyptus camaldulensis*, *E. populnea*, *E. crebra*, *E. tereticornis*, *E. melanophloia*, *E. tessellaris* and *Melaleuca bracteata* (Gordon et al., 1988; Ellis et al., 2002).

The ornamental snake (*Denisonia maculata*) occurs within the zone of potential hydrological change of the Galilee subregion and potentially occupies the 'Non-floodplain, terrestrial GDE' landscape group. The species is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017c). The ornamental snake is considered to be water-dependent as it feeds almost exclusively on frogs. It occurs in riparian vegetation along watercourses, on the margins of wetlands including lakes and swamps and in terrestrial vegetation that is likely to be groundwater-dependent. The latter category includes woodland and open woodland of coolibah (*Eucalyptus coolabah*), poplar box (*E. populnea*), brigalow (*Acacia harpophylla*), gidgee (*A. cambagei*) and blackwood (*A. argyrodendron*) (Department of the Environment and Energy, 2017c). The REs in which it has been found all have clay soils.

Dunmall's snake (*Furina dunmalli*) potentially occurs within the zone and, if it does, it is likely to occupy the 'Non-floodplain, terrestrial GDE' landscape group. The species is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017d). In Queensland, the range of Dunmall's snake is mostly within the Brigalow Belt region to the east of the zone. Dunmall's snake occurs in terrestrial vegetation. The species seems unlikely to be water-dependent.

The yakka skink (*Egernia rugosa*) is a threatened lizard that occurs within the zone of potential hydrological change of the Galilee subregion. It is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017e). The species occurs in woodland and open forest dominated by a range of trees including *Acacia*, *Eucalyptus*, *Casuarina* and *Callitris*. Yakka skinks are burrowing animals that occur in colonies or small groups (Chapple, 2003). Within the zone the yakka skink is likely to occupy sand plains, clay and clay loam plains, sandstone rises and minor pediments and vegetation fringing watercourses and stream channels and on alluvial plains. Therefore, it is expected to occur in the 'Non-floodplain, terrestrial GDE' landscape group. The water dependency of the species is poorly understood.

The southern subspecies of the squatter pigeon (*Geophaps scripta scripta*) is listed as 'Vulnerable' under both the EPBC Act and the Nature Conservation Act (Department of the Environment and Energy, 2017f). It is a granivorous bird that occurs through much of the Galilee subregion zone of potential hydrological change. It was recorded during surveys as part of the environmental impact statements for five of the proposed major coal mine developments in the zone. From north to south these are China Stone, Carmichael, Kevin's Corner, Alpha, and China First. The squatter pigeon (southern) forages and breeds in a range of open-forest, woodland and open-woodland vegetation types that have a grassy understory. It depends on surface water as it needs to drink on a daily basis and, as a consequence, foraging and nesting sites are located within 3 km of a water source. Water sources used by the species include rivers, lakes and artificial sources such as farm dams (Department of the Environment and Energy, 2017f). Therefore, the squatter pigeon is predicted to use water sources within the 'Non-floodplain, terrestrial GDE' landscape group.

The southern subspecies of the black-throated finch (*Poephila cincta cincta*) is classified as 'Endangered' nationally (EPBC Act) and in Queensland (Nature Conservation Act). It is a threatened species with a large potential distribution within and adjacent to the Galilee subregion zone of potential hydrological change (Vanderduys et al., 2016). The black-throated finch was located during surveys as part of environmental impact statements and subsequent surveys at the Carmichael (nine locations) and China Stone (eight locations) coal mine projects. The black-throated finch occupies grassy woodland within the zone. It is surface water dependent. The finch feeds mostly on the ground on a range of grass seeds. It occupies several vegetation assemblages within the 'Floodplain, terrestrial GDE' and 'Non-floodplain, terrestrial GDE' landscape groups. Important regional ecosystems for the black-throated finch in the zone are listed below (based on GHD, 2012; Vanderduys et al., 2016):

- RE 10.3.6 'Eucalyptus brownii woodland to open woodland on alluvial plains'
- RE 10.3.28 'Eucalyptus melanophloia or E. crebra woodland to open woodland on sandy alluvial fans'
- RE 10.5.1 'Eucalyptus similis and/or Corymbia brachycarpa and/or Corymbia setosa low open woodland on sand plains'
- RE 10.5.5 'Eucalyptus melanophloia woodland to open woodland on sand plains'. This is the dominant RE where the black-throated finch occurs on the Carmichael mine lease (GHD, 2012)
- RE 10.7.11 'Eucalyptus melanophloia low open woodland on ferricrete'.

The species also occurs in non-remnant vegetation (GHD, 2012).

### *2.7.6.2 Qualitative mathematical model*

A signed digraph model was developed for the vegetative community associated with the 'Non-floodplain, terrestrial GDE' landscape group. The model focused on recruitment dynamics associated with groundwater-dependent native tree species (referred to as full canopy (FC) in the models), with the primary production associated with tree canopies providing a range of (as yet unspecified) ecosystem roles. There was uncertainty in the extent to which native trees benefited native non-groundwater-dependent vegetation (i.e. canopy microclimate) or suppressed invasive non-groundwater-dependent vegetation, which led to the development of two alternative signed digraph models (Figure 35 and Figure 36).

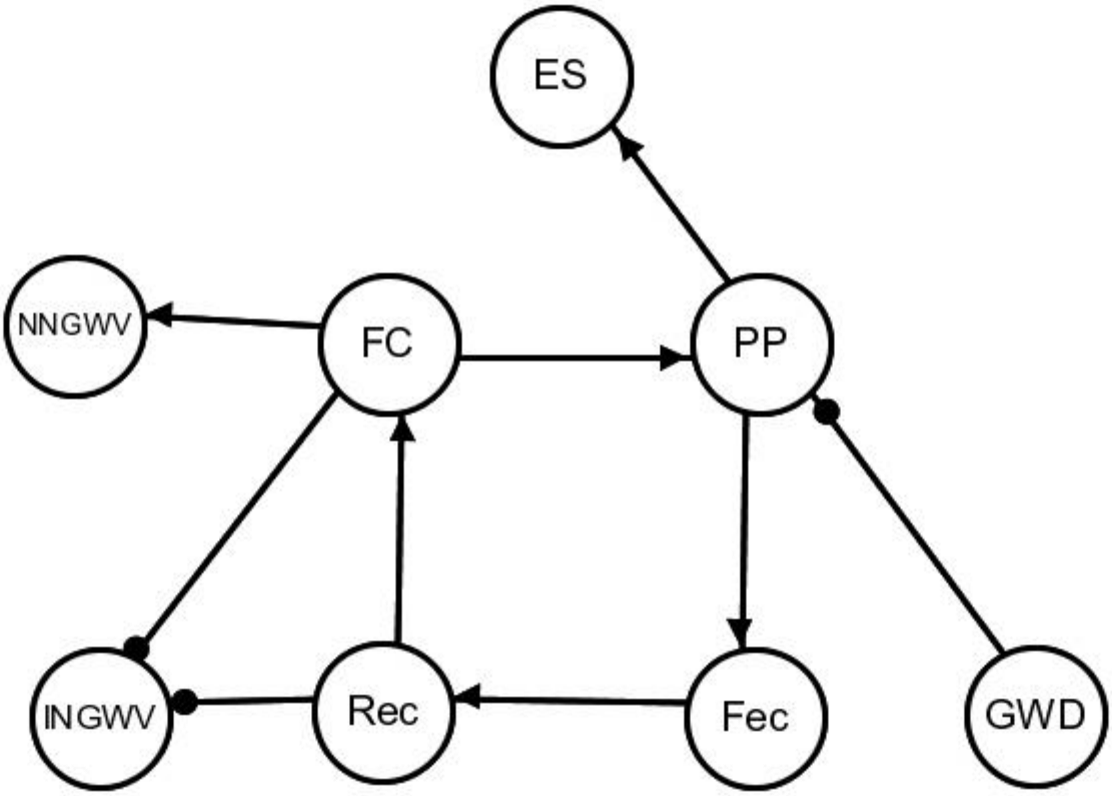


**Figure 35 Signed digraph model (Model 1) of the vegetative community associated with the 'Non-floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change**

Model variables are: ecosystem roles (ES), full canopy (FC), fecundity (Fec), groundwater depletion (GWD), invasive non-groundwater vegetation (INGWV), native non-groundwater vegetation (NNGWV), primary production (PP) and recruitment (Rec).
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

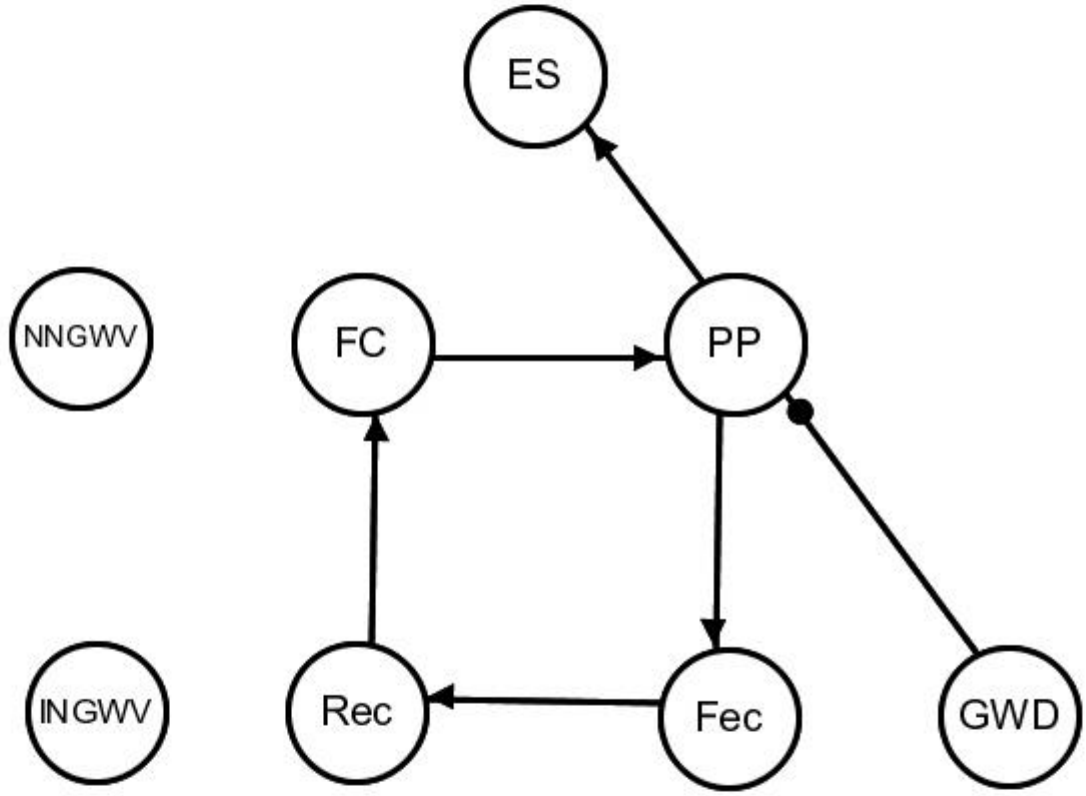


**Figure 36 Signed digraph model (Model 2) of the vegetative community associated with the ‘Non-floodplain, terrestrial GDE’ landscape group in the Galilee subregion zone of potential hydrological change**

Model variables are: ecosystem roles (ES), full canopy (FC), fecundity (Fec), groundwater depletion (GWD), invasive non-groundwater vegetation (INGWV), native non-groundwater vegetation (NNGWV), primary production (PP) and recruitment (Rec).
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

Conceptual modelling, coupled with surface water and groundwater numerical modelling for the Galilee subregion indicated the potential impact of coal mining to groundwater depletion, which was included as a cumulative impact scenario in Table 28.

**Table 28 Summary of the (cumulative) impact scenario (CIS) for the ‘Non-floodplain, terrestrial GDE’ landscape group in the Galilee subregion zone of potential hydrological change**

| CIS | GWD |
|---|---|
| C1 | + |

Pressure scenarios are determined by combinations of no-change (0), increase (+) or a decrease (–) in the signed digraph variable: groundwater depletion (GWD). Scenario C1 shows the expected impacts under the coal resource development pathway (CRDP).
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

Qualitative analysis of the signed digraph models (Figure 35 and Figure 36) indicates a negative response prediction for all biological variables (Table 29 and Table 30, respectively), except for invasive non-groundwater vegetation, which is predicted to increase in Model 1. In Model 2 (Table 30), native non-groundwater vegetation and invasive non-groundwater vegetation both have predictions of zero change, which is a consequence of not being connected to the rest of the system.

**Table 29 Predicted response of the signed digraph variables (Model 1) of 'Non-floodplain, terrestrial GDE' landscape group to (cumulative) changes in the hydrological response variable**

| Signed digraph variable | Signed digraph variable (short form) | C1 |
|---|---|---|
| Full canopy | FC | – |
| Primary production | PP | – |
| Fecundity | Fec | – |
| Recruitment | Rec | – |
| Ecosystem roles | ES | – |
| Native non-groundwater vegetation | NNGWV | – |
| Invasive non-groundwater vegetation | INGWV | + |
| Groundwater depletion | GWD | + |

Qualitative mathematical model predictions that are completely determined are shown without parentheses. GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

**Table 30 Predicted response of the signed digraph variables (Model 2) of 'Non-floodplain, terrestrial GDE' landscape group to (cumulative) changes in hydrological response variables**

| Signed digraph variable | Signed digraph variable (short form) | C1 |
|---|---|---|
| Full canopy | FC | – |
| Primary production | PP | – |
| Fecundity | Fec | – |
| Recruitment | Rec | – |
| Ecosystem roles | ES | – |
| Native non-groundwater vegetation | NNGWV | 0 |
| Invasive non-groundwater vegetation | INGWV | 0 |
| Groundwater depletion | GWD | + |

Qualitative mathematical model predictions that are completely determined are shown without parentheses. Zero denotes completely determined predictions of no change. GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

### *2.7.6.3 Temporal scope, hydrological response variable and receptor impact variables*

The temporal scope for the 'Non-floodplain, terrestrial GDE' landscape group is the same as that described for the other landscape groups or combinations of landscape groups of the Galilee subregion. For groundwater variables, the reference assessment interval is defined as the 30 years preceding 2012 (i.e. 1983 to 2012). For groundwater, maximum drawdown (metres) and time to maximum drawdown are considered across the full 90-year simulation window (2013 to 2102). At the time of the qualitative modelling workshop, it was uncertain whether the time of maximum drawdown would vary in that 90-year window. Thus, the elicitation was conditioned on that variable as well.

For non-floodplain ecosystems, the qualitative modelling workshop identified one variable – groundwater – as the key hydrological component.

This hydrological variable was interpreted as two hydrological response variables that can be modelled (Table 31). The receptor impact variable was formally defined during the receptor impact modelling workshop. Annual mean percent foliage cover was chosen as the receptor impact variable. At the workshop, leaf area index was discussed as an alternative receptor impact variable but percent foliage cover was considered preferable. The relationships identified in the qualitative mathematical modelling workshop were formalised into a receptor impact model that described the response (due to changes in dmaxRef and tmaxRef) of annual average percent foliage cover of non-floodplain tree species in a 0.0025 $km^2$ (0.25 ha) area (Table 31).

**Table 31 Summary of the hydrological response variables used in the receptor impact models, together with the signed digraph variables that they correspond to, for the 'Non-floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change**

| Hydrological response variable | Definition of hydrological response variable | Notation used for corresponding signed digraph variable |
|---|---|---|
| dmaxRef | Maximum difference in drawdown under the baseline future or under the coal resource development pathway future relative to the reference period (1983 to 2012) | GWD |
| tmaxRef | The year that the maximum difference in drawdown relative to the reference period (1983 to 2012) occurs | GWD |

GDE = groundwater-dependent ecosystem

### *2.7.6.4 Receptor impact models*

#### 2.7.6.4.1 Percent foliage cover

***Elicitation scenarios***

Table 32 summarises the elicitation design matrix for the percent foliage cover of trees in the 'Non-floodplain, terrestrial GDE' landscape group. The first design point (design point identifier 1) sets the variability in percent foliage cover under the reference conditions (no drawdown).

The remaining design points represent hydrological scenarios that span the uncertainty in the values of the hydrological response variables in the relevant time period of hydrological history associated with the short-assessment (2013 to 2042) and long-assessment (2073 to 2102) periods.

Design point identifiers 2 through to 32 (as listed in Table 32) represent combinations of the two hydrological response variables (dmaxRef, tmaxRef), together with high and low values of Yref. The high and low values for Yref were calculated during the receptor impact modelling workshop following the experts' response to the first design point, and then automatically included within the design for the elicitations at the subsequent design points.

**Table 32 Elicitation design matrix for receptor impact model of annual percent canopy cover in the 'Non-floodplain, terrestrial GDE' landscape group**

| Design point identifier | dmaxRef | Yref | Year | tmaxRef |
|---|---|---|---|---|
| 1 | 0 | na | 2012 | 0 |
| 18 | 10 | 0.60 | 2042 | 2102 |
| 13 | 0 | 0.60 | 2042 | 2060 |
| 2 | 5 | 0.35 | 2042 | 2019 |
| 6 | 10 | 0.35 | 2042 | 2060 |
| 25 | 0 | 0.35 | 2102 | 2102 |
| 32 | 5 | 0.60 | 2102 | 2060 |
| 30 | 10 | 0.60 | 2102 | 2019 |
| 19 | 0 | 0.35 | 2102 | 2019 |

Design points for Yref in the future (short- and long-assessment periods) are calculated during the receptor impact modelling elicitation workshop using elicited values for the receptor impact variable in the reference period. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling. dmaxRef and tmaxRef are as in Table 31. na = not applicable, GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

### ***Receptor impact model***

The model fitted to the elicited values of mean percentage foliage cover takes the form:

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \sum_{j=1}^{2} \beta_{h_j} x_{h_j} \quad (4)$$

where $x_0$ is an intercept term (a vector of ones), $x_f$ is a binary indicator variable scored 1 for the case of an assessment in the short- or long-assessment year, $x_l$ is a binary indicator variable scored 1 for the case of an assessment in the long-assessment year, $x_r$ is a continuous variable that represents the value of the receptor impact variable in the reference year (Yref, set to zero for the case of an assessment in the reference year), and $x_{h_j}, j = 1 \dots 2$ are the (continuous or integer) values of the two hydrological response variables (dmaxRef, tmaxRef). Note that the modelling framework provides for more complex models, including the quadratic value of, and interactions between, the hydrological response variables but in this instance the simple linear model above was identified as the most parsimonious representation of the experts' responses.

The (marginal) mean and 80% central credible intervals of the two hydrological response variable coefficients are summarised in the partial regression plot in Figure 37, whereas Table 33 summarises the same information for all six model coefficients.

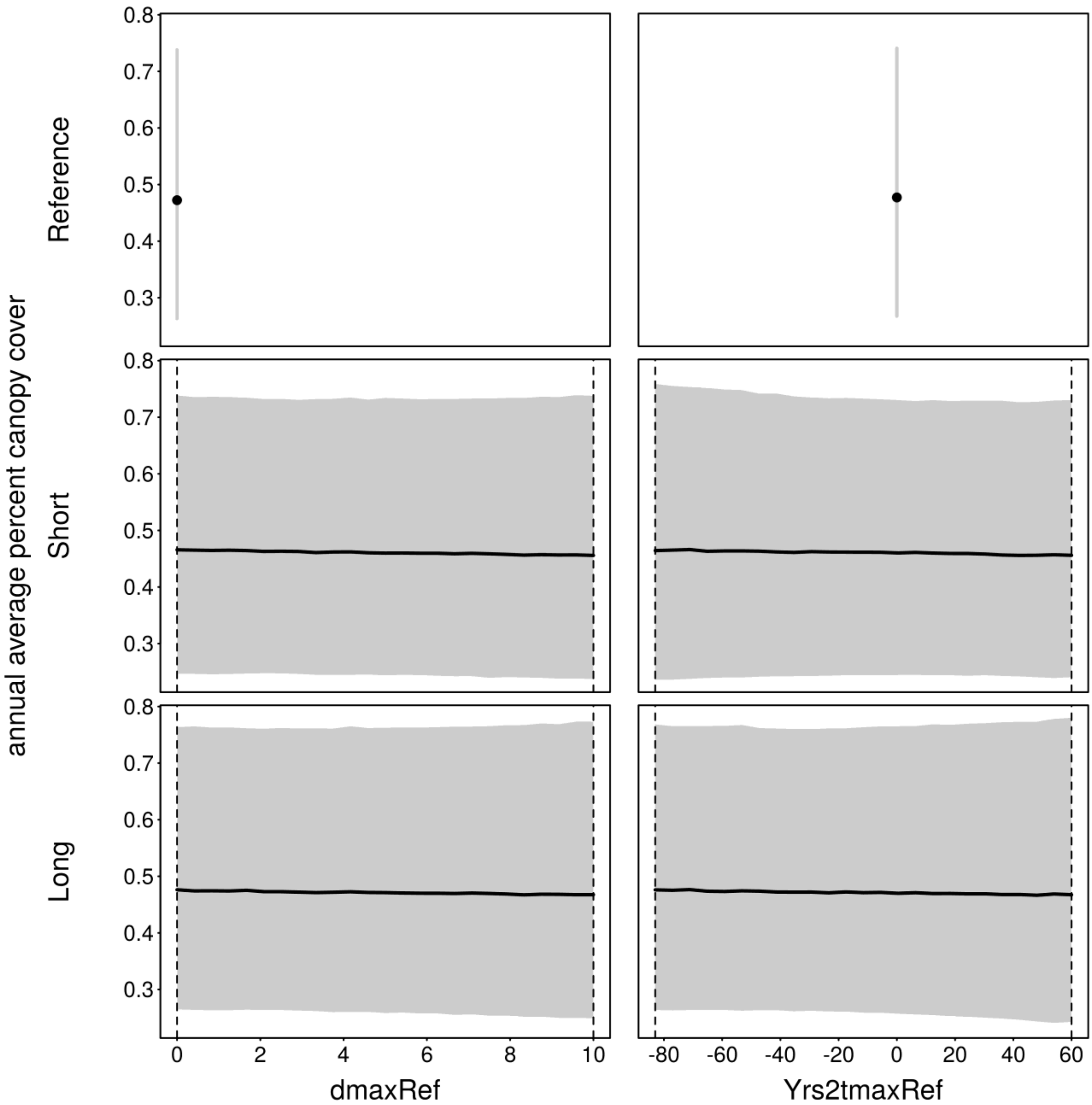


**Figure 37 (Top row) Predicted mean (black dot) and 80% central credible interval (grey line) of percent foliage cover under reference hydrological conditions. (Middle and bottom rows) Predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on percent foliage cover**

In the middle and bottom rows, all other hydrological response variables are held constant at the midpoint of their elicitation range (during the risk estimation process all hydrological response variables vary simultaneously). The dashed vertical lines show range of hydrological response variables used in the elicitation workshop. Reference = period from 1983 to 2012, Short = assessment period 2013 to 2042, Long = assessment period 2073 to 2102. dmaxRef is as in Table 31. Yrs2tmaxRef is the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102). The numbers on the y-axis range from 0 to 1 as the receptor impact model was constructed using the proportion for the statistical modelling. They should be interpreted as a percent foliage cover ranging from 0 to 100%.
Data: Bioregional Assessment Programme (Dataset 4)

**Table 33 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for annual average percent canopy cover in the 'Non-floodplain, terrestrial GDE' landscape group in the Galilee subregion zone of potential hydrological change**

| | Mean | q10 | q90 |
|---|---|---|---|
| (Intercept) | –0.435 | –1.16 | 0.285 |
| future1 | 0.408 | –0.34 | 1.16 |
| long1 | 0.0578 | –0.264 | 0.379 |
| Yref | 1.04 | 0.717 | 1.37 |
| dmaxRef | –0.00232 | –0.0315 | 0.0268 |
| Yrs2tmaxRef | –0.000204 | –0.00342 | 0.00301 |

Future is a binary variable scored 1 if the analysis case is in a short- or long-assessment period. Long is a binary variable scored 1 if the analysis case is in the assessment year. Yref is the value of the receptor impact variable in the reference assessment year; set to zero if case is in the reference assessment year. dmaxRef is as in Table 31. Yrs2tmaxRef is the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102). GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 4)

The model indicates that the experts' opinion provides strong evidence for Yref having a positive effect on average percent foliage cover. This suggests that given a set of hydrological response variable values in the future, a site with higher foliage cover at the 2012 reference point is more likely to have a higher foliage cover in the future than a site with a lower foliage cover value at this reference point. This reflects the lag in the response of foliage cover to changes in hydrological response variables that would be expected of mature trees with long life spans.

The model also indicates that the experts' opinion provides evidence for dmaxRef and Yrs2tmaxRef having an almost negligible effect on average percent foliage cover (over the 10 m range in groundwater drawdown considered in the receptor impact modelling workshop). The model predicts that (holding all other hydrological response variables constant at the mid-point of their elicitation range) the mean of the average percent foliage cover will drop from roughly just under 48% without any change in groundwater level, to about 47% if the levels decrease by 10 m relative to the reference level in 2012. This may indicate that the groundwater dependency of the 'Non-floodplain, terrestrial GDE' landscape group is not well represented in the model. However, there is considerable uncertainty in these predictions, with an 80% chance that the foliage cover is between approximately 72% and 25% (Figure 37).

The summary statistics for the marginal distribution of the model coefficients (Table 33) for the two remaining model coefficients (future1 and long1) indicate that there is insufficient information in the expert-elicited data to determine the effect of either the future coefficient or the long coefficient. This situation is indicated by the opposite signs for the 10th and 90th percentiles for their respective coefficients in Table 33. These results are not surprising, as they suggest that the variation in the elicited values of the receptor impact variables can be adequately described by the other hydrological response variables.

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### *Datasets*

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## 2.7.7 Limitations and gaps


**Summary**

The prediction of receptor impact variables at assessment units occurs in companion product 3-4 for the Galilee subregion (Lewis et al., 2018). Several gaps and limitations to the development of receptor impact models for the Galilee subregion are identified. Important limitations include the availability of experts with local knowledge for some landscape classes and elicitations, the inability to construct a receptor impact model for the potentially important 'Springs' landscape group, important knowledge gaps surrounding the connectivity between groundwater and surface water systems (both connectivity within landscape classes and groups of classes, as well as between ecosystems) in different parts of the subregion, and constraints to the availability of surface water modelling across the assessment extent.


### *2.7.7.1 Prediction of receptor impact variables*

The receptor impact modelling workflow applied in the bioregional assessment (BA) of the Galilee subregion is summarised in Figure 3 in Section 2.7.1.2, starting from the identification of the landscape classes within the zone of potential hydrological change that may be impacted, through to the prediction of receptor impact variables at assessment units. This product then presents the construction and interpretation of the qualitative mathematical models and receptor impact models developed for four landscape groups, and the relationship between the receptor impact variable and one or more hydrological response variables used in the modelling. While this approach allows some assessment of the sensitivity of the response to the hydrological response variables, it needs to be stressed that these should not be interpreted as risk predictions. Importantly, the prediction of receptor impact variables at assessment units occurs in companion product 3-4 for the Galilee subregion (Lewis et al., 2018), where the hydrological response variables are propagated through the receptor impact models to produce a range (or distribution) of the predicted receptor impact variable response at different time points and for the two futures considered in BA. These distributions reflect the uncertainty in the hydrological response variables, the uncertainty the experts have in the potential ecosystem response to those hydrological response variables, and the spatial heterogeneity across the landscape group.

### *2.7.7.2 Limitations of the receptor impact modelling approach*

The strengths and limitations of the expert elicitation process used in the BAs for building qualitative ecosystem models and quantitative receptor impact models are described in some detail in Section 2.7.1 and in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018). There is no need to revisit these here, except to acknowledge that the qualitative models and receptor impact models that were developed to represent the landscape classes (aggregated to landscape groups) in the zone of potential hydrological change for the Galilee subregion reflect the subjectivity and bias inherent in the knowledge base of the experts (e.g. in defining the scope of the model; its components and connections; the ecologically important hydrological variables; representative receptor impact variables; and magnitude and uncertainty of responses to change). Thus, each model represents 'a view' of a landscape group or ecosystem; a view that might brook argument about some of the specific aspects of these models, but one that would generally be accepted as an adequate high-level conceptualisation of the important components of the ecosystem(s) it represents. Importantly, given the regional-scale nature of the BA, the inherent complexity that naturally exists within each landscape group is simplified in the receptor impact modelling, although experts are encouraged to consider as fully as possible the system-level heterogeneity of each landscape group during the elicitation process. Further, Table 4 (Section 2.7.1) specifically acknowledges that the overall receptor impact modelling approach may create the potential to underestimate complex ecosystem function, and is something that needs to be considered and evaluated against observations (monitoring) in the future.

Important knowledge gaps and limitations specific to the receptor impact modelling undertaken for the Galilee subregion were identified at the expert elicitation workshops. These limit the assessment of potential impacts from hydrological changes due to additional coal resource development for some landscape groups, or components of landscape groups, within the zone of potential hydrological change. In other words, these gaps and limitations place some constraints on the comprehensiveness of the ecosystem analysis undertaken for this BA, and it is important to flag these so that further investigation can be better targeted to address these questions in the future.

Although some qualitative mathematical models include salinity and/or nutrient components, the expert elicitations to define the results for the receptor impact models are premised on changes in other types of hydrological parameters, for example, water availability or volume. Changes in water quality parameters that could potentially occur (for example, with a shift in the relative contributions of surface water runoff and groundwater contribution to streamflow, or due to enhanced connectivity between aquifers of differing water quality) are not represented. Thus, the potential ecological impacts due to additional coal resource development reported in companion product 3-4 for the Galilee subregion (Lewis et al., 2018) reflect the risk from hydrological changes that do not include water quality parameters. Consequently, the modelled impacts could differ if changes in key water quality parameters had been included in the model formulation.

The annual mean percent foliage cover of the woody vegetation, annual mean percent foliage cover of the woody riparian vegetation, and the annual mean density of the mayfly species (*Offadens* sp.) receptor impact variables were selected as indicators of terrestrial groundwater-dependent ecosystems (GDEs) and stream ecosystems. They have been identified as sensitive to changes in hydrology and can represent the response of other components of the ecosystem to changes in hydrology. The criteria for selecting the receptor impact variables are discussed in detail in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018). The receptor impact variables identified here reflect those criteria and the knowledge base of the ecological experts available at the workshops, but may benefit from testing and further consideration of their optimality over time. The extent to which the receptor impact variables are suitable indicators of ecosystem response for all terrestrial GDEs and stream ecosystems across the Galilee subregion has not been established. The interpretation of results of the receptor impact models presented in companion product 3-4 for the Galilee subregion

(Lewis et al., 2018) is couched in terms of risk to habitat, rather than risks to the receptor impact variables themselves.

A shortcoming of the ecological modelling process used for this BA is that it is assumed that there is sufficient hydrological modelling across the full distribution of a landscape class (or group of landscape classes) when the receptor impact models are elicited. In reality, surface water modelling particularly, is limited by the extent to which model simulation and calibration nodes exist and can be used to interpolate model output across the stream network. In the surface water zone of potential hydrological change of the Galilee subregion, there are large areas where the hydrological change to the stream network cannot be quantified. As an example, there is an absence of surface water model nodes along the upper parts of the Carmichael River and its tributary network (including Dyllingo Creek and Bimbah Creek). Similarly, there is no surface water modelling of extensive areas of Lagoon Creek and its tributary network in the southern mining cluster. The non-modelled stream network includes both the 'Streams, GDE' and 'Streams, non-GDE' landscape groups. This situation results in limited coverage of the stream network adjacent to some of the main coal mine developments both in the northern and southern parts of the zone. This limitation clearly hampers the assessment of potential risks across those parts of the landscape most affected from additional coal resource development.

A number of stream reaches in the modelled stream network of the Galilee assessment extent consist of multiple anabranches between surface water model nodes. This situation makes it difficult to reliably interpolate the surface water changes from model nodes to any particular anabranch. This is particularly the case for the Belyando River between model nodes 34 and 44 which consists of multiple anastomosing channels.

A clear knowledge gap for the Galilee subregion existed in relation to connectivity between groundwater and surface water systems. This relates both to connectivity within landscape classes and groups of classes and between ecosystems. Expert knowledge of potential surface water – groundwater interaction in the zone of potential hydrological change was limited. Similarly, there was limited understanding of the nature of groundwater interactions between riverine and terrestrial ecosystems. At the various workshops, the experts struggled with these aspects of the elicitation scenarios, in particular in relation to the 'Floodplain, terrestrial GDE' landscape group.

Climate change is not included directly in the receptor impact modelling, but a mid-range climate projection is used and potential changes to precipitation factored into the process through the surface water modelling of hydrological response variables.

A final shortcoming of the elicitation process was the absence of experts that had a strong knowledge of the local hydrological systems within the zone of potential hydrological change of the Galilee subregion. Most experts had not carried out field-based research within the main catchments of the zone, and had limited experience of the local hydrology and ecology. This situation resulted in multiple consequences for the receptor impact modelling process. Firstly, there were a limited number of suitable experts available for the elicitations. As an example, the elicitation process for the receptor impact variable for the 'Non-floodplain, terrestrial GDE' landscape group involved a single expert. Second, experts' decisions on the choice of receptor impact variables and potential hydrological response variables were generally extrapolated from their knowledge from other regions. In the 'best case' scenario this information came from geographic areas adjacent to the zone. For instance the 'high-flow macroinvertebrate' receptor impact model was developed based on expert knowledge of a mayfly species (*Offadens)* obtained for the Cape River and its tributary network. This area is adjacent to the northern boundary of the zone. Lastly, for the 'Springs' landscape group, there was a lack of expert knowledge available at the workshops for the main spring systems within the zone of potential hydrological change. This prevented the selection of a suitable receptor impact variable for springs and consequently, it was not possible to build a receptor impact model for the 'Springs' landscape group.

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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.

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

additional drawdown: the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development

annual flow (AF): the volume of water that discharges past a specific point in a stream in a year, commonly measured in GL/year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

analysis extent: the geographic area that encompasses all the possible areas that may be reported in the impact analysis of a bioregional assessment (BA), typically including the bioregion or subregion, the preliminary assessment extent (PAE) and the relevant groundwater and surface water model domains

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.

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. The assessment extent is created by revising the preliminary assessment extent on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

assessment unit: for the purposes of impact analysis, a geographic area that is used to partition the entire assessment extent into square polygons that do not overlap. The spatial resolution of the assessment units is closely related to that of the bioregional assessment groundwater modelling and is, typically, 1 x 1 km. Each assessment unit has a unique identifier. The partitioned data can be combined and recombined into any aggregation supported by the conceptual modelling, causal pathways and model data.

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.

baseflow: the portion of streamflow that comes from shallow and deep subsurface flow, and is an important part of the groundwater system

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

basement: the crust below the rocks of interest. In hydrogeology it means non-prospective rocks below accessible groundwater. Commonly refers to igneous and metamorphic rocks which are unconformably overlain by sedimentary beds or cover material, and sometimes used to indicate 'bedrock' (i.e. underlying or encasing palaeovalley sediments).

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

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).

dewatering: the process of controlling groundwater flow within and around mining operations that occur below the watertable. In such operations, mine dewatering plans are important to provide more efficient work conditions, improve stability and safety, and enhance economic viability of operations. There are various dewatering methods, such as direct pumping of water from within a mine, installation of dewatering wells around the mine perimeter, and pit slope drains.

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

dmax: maximum difference in drawdown, obtained by choosing the maximum of the time series of differences between two futures. For example, to calculate the difference in drawdown between the coal resource development pathway (CRDP) and baseline, use the equations dmax = max (dCRDP(t) – dbaseline(t)) where d is drawdown, or dmax = max (hbaseline(t) – hCRDP(t)) where h is groundwater level and t is time.

dmaxRef: maximum difference in drawdown under the baseline future or under the coal resource development pathway future relative to the reference period (1983 to 2012). This is typically reported as the maximum change due to additional coal resource development.

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).

EventsR2.0: the mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in flood events with a return period of 2.0 years as defined from modelled baseline flow in the reference period (1983 to 2012)). This metric is designed to be approximately representative of the number of overbank flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development.

fecundity: The reproductive capacity of an organism, i.e. the number of eggs that develop in a mated female over a specified period. It is usually calculated at the stage when this number is readily observable (i.e. in oviparous animals when eggs are laid and in viviparous animals when young are born), although strictly speaking it applies from the time that fertilization occurs. Sometimes the term 'fertility' is applied only to the production of fertilized eggs (ova), while 'fecundity' is used for the production of offspring, so excluding those embryos which fail to develop.

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

fractile: the value of a distribution below which some fraction of the sample lies. For example, the 0.95-fractile is the value below which there is a probability of 0.95 occurrence (or equivalently, 95% of the values lie below the 0.95-fractile).

Galilee subregion: The Galilee subregion is part of the Lake Eyre Basin bioregion and is entirely within Queensland. It extends westwards across the Great Dividing Range and into the Lake Eyre drainage basin. The subregion is sparsely populated, with most people living in towns and localities including Charleville, Barcaldine, Blackall and Hughenden. The subregion encompasses the headwaters of several major waterways including the Cooper Creek and the Diamantina, Belyando, Cape, Thomson, Barcoo, Flinders, Bulloo, and Warrego rivers. In addition to the river systems, the subregion has numerous wetlands, springs, waterholes and lakes, including the nationally important lakes Buchanan and Galilee. Some of these are home to diverse and unique plants and animals, many of which are listed as rare or threatened under Queensland and Commonwealth legislation. Native vegetation consists largely of grasslands in the west and open eucalyptus woodlands in the east. Cattle and sheep grazing on native pasture is the main land use and groundwater is of great importance.

groundwater: water occurring naturally below ground level (whether stored in or flowing through aquifers or within low-permeability aquitards), 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

groundwater zone of potential hydrological change: outside this extent, groundwater drawdown (and hence potential impacts) is very unlikely (less than 5% chance). It is the area with a greater than 5% chance of exceeding 0.2 m of drawdown due to additional coal resource development in the relevant aquifers.

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)

high-flow days (FD): the number of high-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (2013 to 2102). The threshold for high-flow days is the 90th percentile from the simulated 90-year period. In some early products, this was referred to as ‘flood days’.

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 flow 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 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.

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

interquartile range (IQR): the interquartile range in daily flow (ML/day); that is, the difference between the daily flow rate at the 75th percentile and at the 25th percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

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. Note that there is expected to be less heterogeneity in the response within a landscape class than between landscape classes. 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.

landscape group: for the purposes of bioregional assessments (BAs), a set of landscape classes grouped together based on common ecohydrological characteristics that are relevant for analysis purposes

length of low-flow spell (LLFS): the length (days) of the longest low-flow spell each year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

LME: the maximum length of spells (in days per year) with low flow, averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.

low-flow days (LFD): the number of low-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). The threshold for low-flow days is the 10th percentile from the simulated 90-year period.

low-flow days (averaged over 30 years) (LQD): the number of days per year with low flow (<10 ML/day), averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.

low-flow spells (LFS): the number of low-flow spells per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). A spell is defined as a period of contiguous days of flow below the 10th percentile threshold.

maximum zero-flow spell (ZME): the maximum length of spells (in days per year) with zero flow, averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.

model node: a point in the landscape where hydrological changes (and their uncertainty) are assessed. Hydrological changes at points other than model nodes are obtained by interpolation.

overbank flow: flood condition where water flows beyond and sub-parallel to the main channel of a river, but within the bounding floodplain

P01: the daily flow rate at the 1st percentile (ML/day). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

P99: the daily flow rate at the 99th percentile (ML/day). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

percentile: a specific type of quantile where the range of a distribution or set of runs is divided into 100 contiguous intervals, each with probability 0.01. An individual percentile may be used to indicate the value below which a given percentage or proportion of observations in a group of observations fall. For example, the 95th percentile is the value below which 95% of the observations may be found.

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

probability distribution: the probability distribution of a random variable specifies the chance that the variable takes a value in any subset of the real numbers. It allows statements such as 'There is a probability of x that the variable is between a and b'.

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

receptor impact model: a function that translates hydrological changes into the distribution or range of potential ecosystem outcomes that may arise from those changes. Within bioregional assessments, hydrological changes are described by hydrological response variables, ecosystem outcomes are described by receptor impact variables, and a receptor impact model determines the relationship between a particular receptor impact variable and one or more hydrological response variables. Receptor impact models are relevant to specific landscape classes, and play a crucial role in quantifying potential impacts for ecological water-dependent assets that are within the landscape class. In the broader scientific literature receptor impact models are often known as 'ecological response functions'.

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

return period: An event has a return period (or recurrence interval) of T years if its magnitude is equalled or exceeded once on average every T years. The reciprocal of the return period is the exceedance probability of the event, that is, the probability that the event is equalled or exceeded in any one year. For example, a flood with a return period of 10 years has a 0.1 or 10% chance of being exceeded in any one year and a flood with a return period of 50 years has a 0.02 or 2% chance of being exceeded in any one year. The actual number of years between floods of any given size varies a lot because of climatic variability.

riparian: An area or zone within or along the banks of a stream or adjacent to a watercourse or wetland; relating to a riverbank and its environment, particularly to the vegetation.

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.

sensitivity: the degree to which the output of a model (numerical or otherwise) responds to uncertainty in a model input

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

source dataset: a pre-existing dataset sourced from outside the Bioregional Assessment Programme (including from Programme partner organisations) or a dataset created by the Programme based on analyses conducted by the Programme for use in the bioregional assessments (BAs)

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

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

surface water zone of potential hydrological change: outside this extent, changes in surface water hydrological response variables due to additional coal resource development (and hence potential impacts) are very unlikely (less than 5% chance). The area contains those river reaches where a change in any one of nine surface water hydrological response variables exceeds the specified thresholds. For the four flux-based hydrological response variables (annual flow (AF), daily flow rate at the 99th percentile (P99), interquartile range (IQR) and daily flow rate at the 1st percentile (P01)), the threshold is a 5% chance of a 1% change in the variable. That is, if 5% or more of model runs show a maximum change in results under coal resource development pathway (CRDP) of 1% relative to baseline. For four of the frequency-based hydrological response variables (high-flow days (FD), low-flow days (LFD), length of longest low-flow spell (LLFS) and zero-flow days (ZFD)), the threshold is a 5% chance of a change of 3 days per year. For the final frequency-based hydrological response variable (low-flow spells (LFS)), the threshold is a 5% chance of a change of 2 spells per year.

tmax: year of maximum change

tmaxRef: the year that the maximum difference in drawdown relative to the reference period (1983 to 2012) occurs tenement: a defined area of land granted by a relevant government authority under prescribed legislative conditions to permit various activities associated with the exploration, development and mining of a specific mineral or energy resource, such as coal. Administration and granting of tenements is usually undertaken by state and territory governments, with various types related to the expected level and style of exploration and mining. Tenements are important mechanisms to maintain standards and safeguards relating to environmental factors and other land uses, including native title.

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

very unlikely: less than 5% chance

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)

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

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

Yrs2tmaxRef: the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102)

zero-flow days (ZFD): the number of zero-flow days per year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).

zero-flow days (averaged over 30 years) (ZQD): the number of zero-flow days per year, averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.

zone of potential hydrological change: outside this extent, hydrological changes (and hence potential impacts) are very unlikely (less than 5% chance). Each bioregional assessment defines the zone of potential hydrological change using probabilities of exceeding thresholds for relevant hydrological response variables. The zone of potential hydrological change is the union of the groundwater zone of potential hydrological change (the area with a greater than 5% chance of exceeding 0.2 m of drawdown due to additional coal resource development in the relevant aquifers) and the surface water zone of potential hydrological change (the area with a greater than 5% chance of exceeding changes in relevant surface water hydrological response variables due to additional coal resource development).

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