Australian Government

BIOREGIONAL ASSESSMENTS

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

Receptor impact modelling for the Gloucester subregion

Product 2.7 for the Gloucester subregion from the Northern Sydney 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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http://data.bioregionalassessments.gov.au/product/NSB/GLO/2.7.

Authorship is listed in relative order of contribution.

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Cover photograph

View of the Gloucester valley NSW with the Barrington River and associated riparian vegetation in the foreground and the township Gloucester in the distance looking south from the Kia Ora Lookout, 2013

Credit: Heinz Buettikofer, CSIRO

Australian Government
Department of the Environment and Energy
Bureau of Meteorology
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Executive summary

This product details the development of qualitative mathematical models and receptor impact models for the Gloucester 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. Using receptor impact models to investigate landscapes provides a better understanding of how changes in hydrology may result in changes in ecosystems.

A receptor impact model describes a 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, mean percent canopy cover of woody riparian vegetation).

Coal resource developments

Bioregional assessments consider two potential coal resource development futures in the Gloucester subregion:

- *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. The two baseline open-cut coal mines are Duralie Coal Mine in the south and Stratford Mining Complex in the north
- *coal resource development pathway (CRDP)*: a future that includes all coal mines and CSG fields that are in the baseline as well as the additional coal resource development (those that are expected to begin commercial production after December 2012). In this assessment the potential hydrological impacts of the expansion of the two baseline open-cut coal mines, Duralie and Stratford Mining Complex developments, and a new open-cut coal mine at Rocky Hill in the north of the Gloucester Basin, are modelled. AGL's proposed CSG development, the Gloucester Gas Project, is included because these futures were finalised in October 2015 before AGL withdrew from this project in February 2016. As per companion submethodology M04 for developing a coal resource development pathway, the CRDP was not revisited.

The difference in results between CRDP and baseline is the change that is primarily reported in a bioregional assessment. This change is due to additional coal resource development. Potential hydrological changes have been presented in companion product 2.6.1 (surface water) and companion product 2.6.2 (groundwater); the process of developing qualitative mathematical models and receptor impact models is summarised.

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 relevant ecological response data means the expert judgement, obtained through structured elicitation approaches, has a key role in the receptor impact modelling. It is involved in mapping ecological processes and key components (as signed digraphs), constructing qualitative models that record – as an increase, decrease or no change – landscape class response to sustained hydrological change, selecting ecological indicators (receptor impact variables) from the ecological components or processes and the hydrological regimes (hydrological response variables) that support them, and quantifying the potential response of those indicators to specific hydrological elicitation scenarios. The resulting statistical model quantifies how changes in hydrological response variables due to coal resource development may potentially impact the receptor impact variables in a short-term (2013 to 2042) and long-term (2073 to 2102) period within a landscape class.

Ecosystems

Landscape classes are used to categorise ecosystems into groups that are expected to respond similarly to changes in groundwater and surface water due to coal resource development for the receptor impact models in the Gloucester subregion. In the Gloucester subregion there are 25 landscape classes aggregated further into five landscape groups: (i) ‘Riverine’, (ii) ‘Groundwater-dependent ecosystem (GDE)’, (iii) ‘Non-GDE’, (iv) ‘Estuarine’, and (v) ‘Economic land use’.

A zone of potential hydrological change was defined to ‘rule out’ potential impacts. In the Gloucester subregion this zone is 250 km^2. Water-dependent landscapes and ecological assets outside of this zone are *very unlikely* (less than 5% chance) to experience hydrological change due to additional coal resource development. Within the zone, potential impacts are considered further using qualitative mathematical models and receptor impact models.

‘Riverine’ landscape group

Stream reaches in the ‘Riverine’ landscape group within the zone of potential hydrological change are almost entirely represented by two closely related landscape classes which are the focus of receptor impact modelling, ‘Perennial – gravel/cobble streams’ and ‘Intermittent – gravel/cobble streams’.

The qualitative mathematical model for the ‘Perennial – gravel/cobble streams’ landscape class indicates that potential changes in surface water and groundwater regimes due to coal resource development lead to negative effects across almost all processes and components of the system. Based on this knowledge, three receptor impact models were developed that show how a change in surface water or groundwater may cause a response in an ecological indicator. Examples of the output from the receptor impact models include:

- Percent canopy cover of woody riparian vegetation as an ecological indicator responding to a 6 m potential reduction in groundwater levels (from average conditions between 1983 and 2012), may lead to an approximate 20% decrease in percent canopy cover of woody riparian vegetation in both the short: 2013 to 2042 and long: 2073 to 2102 assessment years.

- Average density of net-spinning caddisfly larvae as an ecological indicator responding to a change in surface water flow (>200 zero-flow days per year) may drop to values <1 per m2 of riffle habitat in both the short: 2013 to 2042 and long: 2073 to 2102 assessment years. Noting that the qualitative model suggests that larvae density can vary substantially across the landscape class (<100 to 1000 per m2) under conditions of constant flow.
- Average density of the eel-tailed catfish as an ecological indicator responding to changes in surface water flow may see a decline from 5 individuals per 600 m2 transect under continuous flow, to less than 1 individual in two transects as flow becomes more intermittent.

The qualitative mathematical model for the 'Intermittent – gravel/cobble streams' landscape class reports a decrease or zero (no change) response in most of the model variables under three scenarios of hydrological change due to coal resource development. The receptor impact model built for this landscape class reports the response of the mean richness of hyporheic invertebrate taxa to changes in zero-flow days. Hyporheic taxa are organisms found where surface water and groundwater mix below the bed of a stream and is an ecological indicator because it can persist in intermittent rivers and streams but is sensitive to the length and frequency of zero-flow spells. Mean richness of hyporheic taxa may drop from 10 to 20 per sampling unit under conditions of constant flow to values between 1 and 8 under very intermittent flow conditions (>300 zero-flow days per year).

'Groundwater-dependent ecosystem (GDE)' landscape group

In the 'Groundwater-dependent ecosystem (GDE)' landscape group, qualitative mathematical models were developed for three landscape classes: (i) 'Forested wetlands', (ii) 'Wet sclerophyll forests', and (iii) 'Dry sclerophyll forests'. Receptor impact models, however, were not able to be developed for any of these landscape classes within the constraints of the workshop and due to availability of suitable experts.

The qualitative mathematical model for the 'Forested wetlands' landscape class focused on the role that forest canopies play as a food source and habitat and their response to a simultaneous decrease in shallow and deep groundwater. This model was also used as a basis for qualitative mathematical modelling of the 'Wet sclerophyll forests' and 'Dry sclerophyll forests' landscape classes. Outputs for all three landscape classes indicate an ambiguous or negative response for all the biological variables in the model with the exception of the zero (no change) response of ground-layer and mid-storey vegetation in the 'Dry sclerophyll forests' landscape class. Ambiguous responses arise from positive effects associated with the potential release from predation or competitive dominance, potentially being countered by negative effects resulting from reduced nectar production.

Ecosystems not modelled

No qualitative mathematical models or receptor impact models were developed for the 'Estuarine' landscape group, or the 'Freshwater wetlands' landscape class, located along the Karuah River estuary because they lay entirely outside the zone of potential hydrological change. No qualitative mathematical models or receptor impact models were developed for the landscape classes from the 'Non-GDE' landscape group because they lack a dependence on water other than rainfall and the ecological and economic assets within this group are not anticipated to be impacted by coal resource development through groundwater or surface water mediated pathways.

Bioregional assessments also consider risk to, and impacts on, 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 legislated make good provisions and cease-to-pump days. Potential impacts on sociocultural assets are limited to characterising the hydrological changes that may be experienced by those assets in the impact and risk analysis (product 3-4).

Future work

The receptor impact modelling described in this product guides how companion product 3-4 (impact and risk analysis) is framed. Companion product 3-4 will describe impacts on, and risks to, water-dependent assets in the Gloucester subregion.

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Figures

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This technical product was reviewed by several groups:

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- Independent reviewers: representatives of National Centre for Groundwater Research and Training (NCGRT).

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.

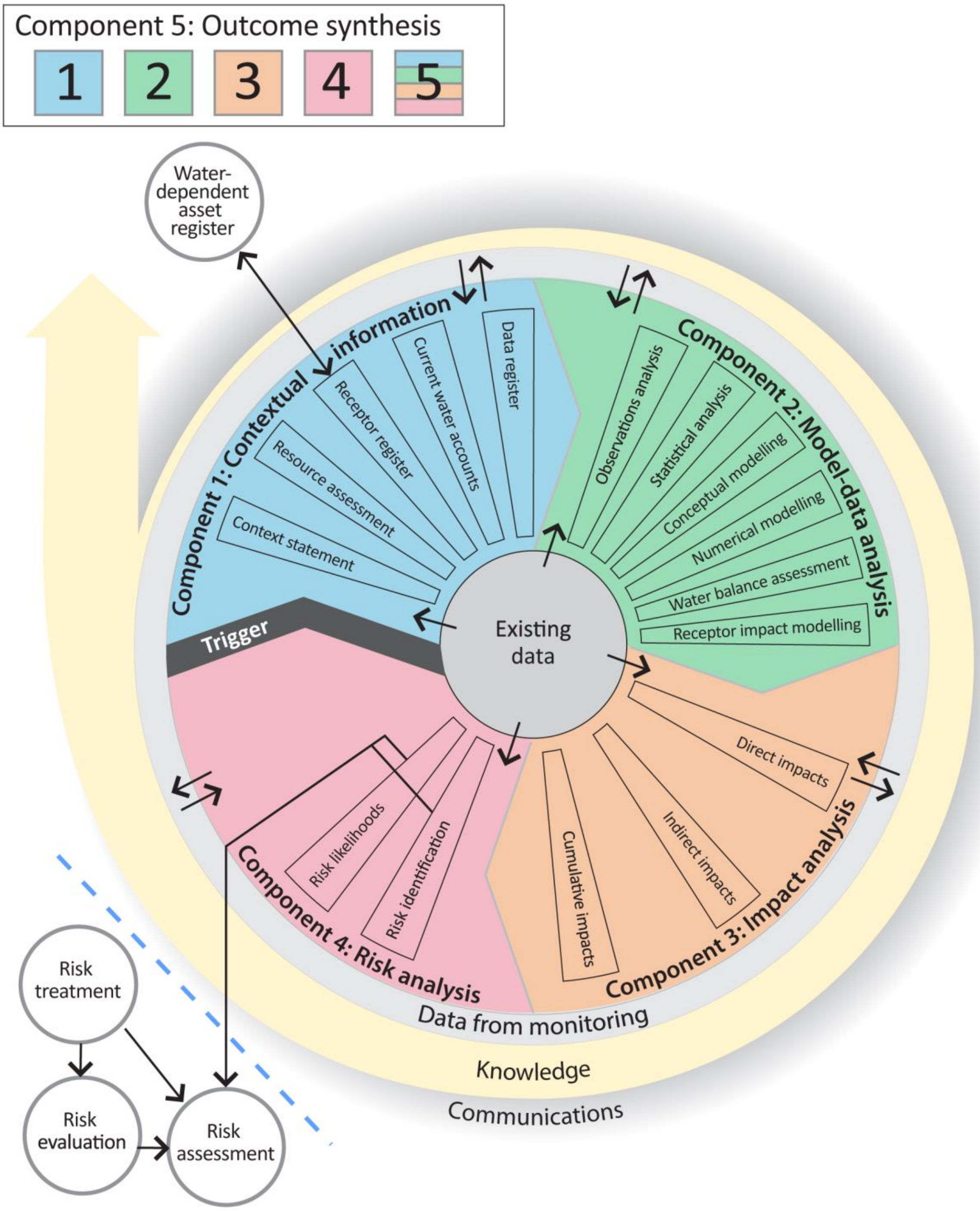

Figure 1 Schematic diagram of the bioregional assessment methodology

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.

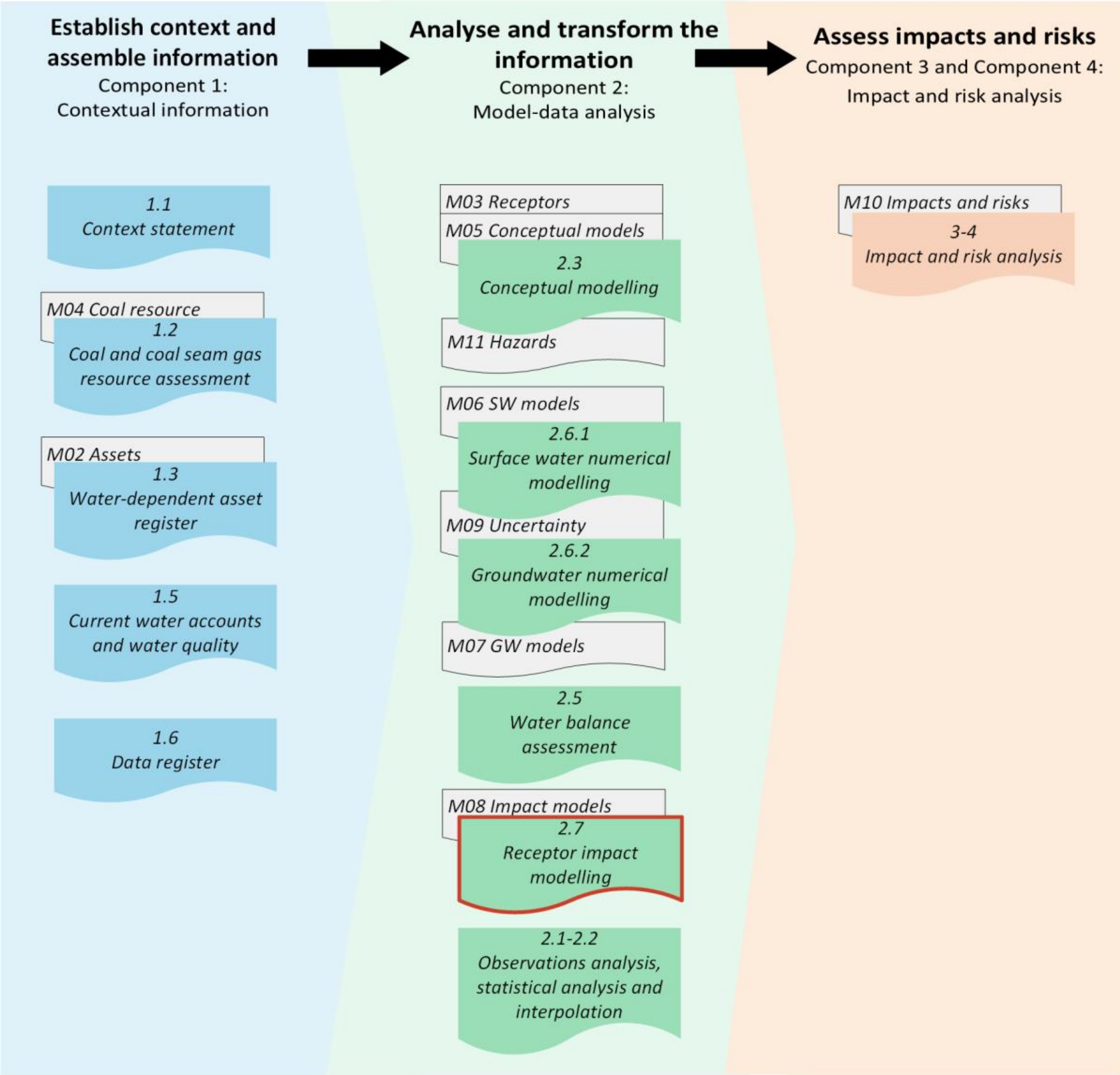

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Gloucester subregion

For each subregion in the Northern Sydney 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 Gloucester 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 Gloucester 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 Gloucester subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Gloucester 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 Northern Sydney 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 151.0° East for the Northern Sydney 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.

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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 4 May 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 Gloucester subregion

This product presents receptor impact modelling for the Gloucester 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 assessment (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 impact and risk 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 Gloucester 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

This section details the specific application to the Gloucester subregion of methods described in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018).

In bioregional assessments (BAs), receptor impact models are intended to characterise potential ecosystem changes that may result from a given hydrological change predicted in response to coal resource development. A receptor impact model is constructed for a specific landscape class, which 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. Only those landscape classes that intersect the zone of potential hydrological change are considered to be 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 used to elicit from independent experts and contain key components and processes of the landscape class ecosystems, and the hydrological variables that support them. They then are used to qualitatively predict (reported as an 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 selection of receptor impact variables from the ecological components or processes identified in the qualitative mathematical model and hydrological response variables to represent the hydrological regimes that support these components or processes. Thus the landscape classification and qualitative mathematical models form the bases for elicitations to quantify changes in receptor impact variables in response to simultaneous changes in hydrological response variables for subsequent model prediction.

The elicitation allows the BA team to construct 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 of coal resource development using predicted changes in hydrological response variables in a short-term (2013 to 2042) and long-term (2073 to 2102) 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

Receptor impact modelling attempts to capture the direct, indirect and cumulative impacts of coal seam gas (CSG) and coal mining development on the ecosystems within selected landscape classes. 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 stakeholders' 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 can lead to changes in hydrology are identified in companion product 2.3 for the Gloucester subregion (Dawes et al., 2018). The receptor impact models represent the subsequent pathways, which relate changes in hydrological response variables to potential impacts on water-dependent landscape classes and assets 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 groundwater bores, 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), and their predicted average conditions under the baseline and the CRDP in the short term (2013 to 2042) and longer term (2073 to 2012).

This product presents the receptor impact modelling for the Gloucester subregion. The modelling is described in detail in the companion submethodology M08 for receptor impact modelling (Hosack et al., 2018). Section 2.7.1.2 of this document describes how this methodology is applied to the Gloucester 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 submethodology M06 on surface water modelling (Viney, 2016) and companion submethodology 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 function that translates hydrological changes into the distribution or range of potential ecosystem outcomes that may arise from those changes; a receptor impact model predicts a relationship between a receptor impact variable (for example, annual mean percent canopy cover of woody riparian vegetation), and one or more hydrological response variables (for example, *dmax*, 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 has multiple landscape classes grouped into landscape groups.

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 (2, 3 and 5 in Figure 3), along with output from hydrological modelling (i.e. companion product 2.6.1 (Zhang et al., 2018) and companion product 2.6.2 (Peeters et al., 2018) for the Gloucester 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 also accessible to hydrological modelling. The expert elicitation data are available as a downloadable dataset from data.gov.au.

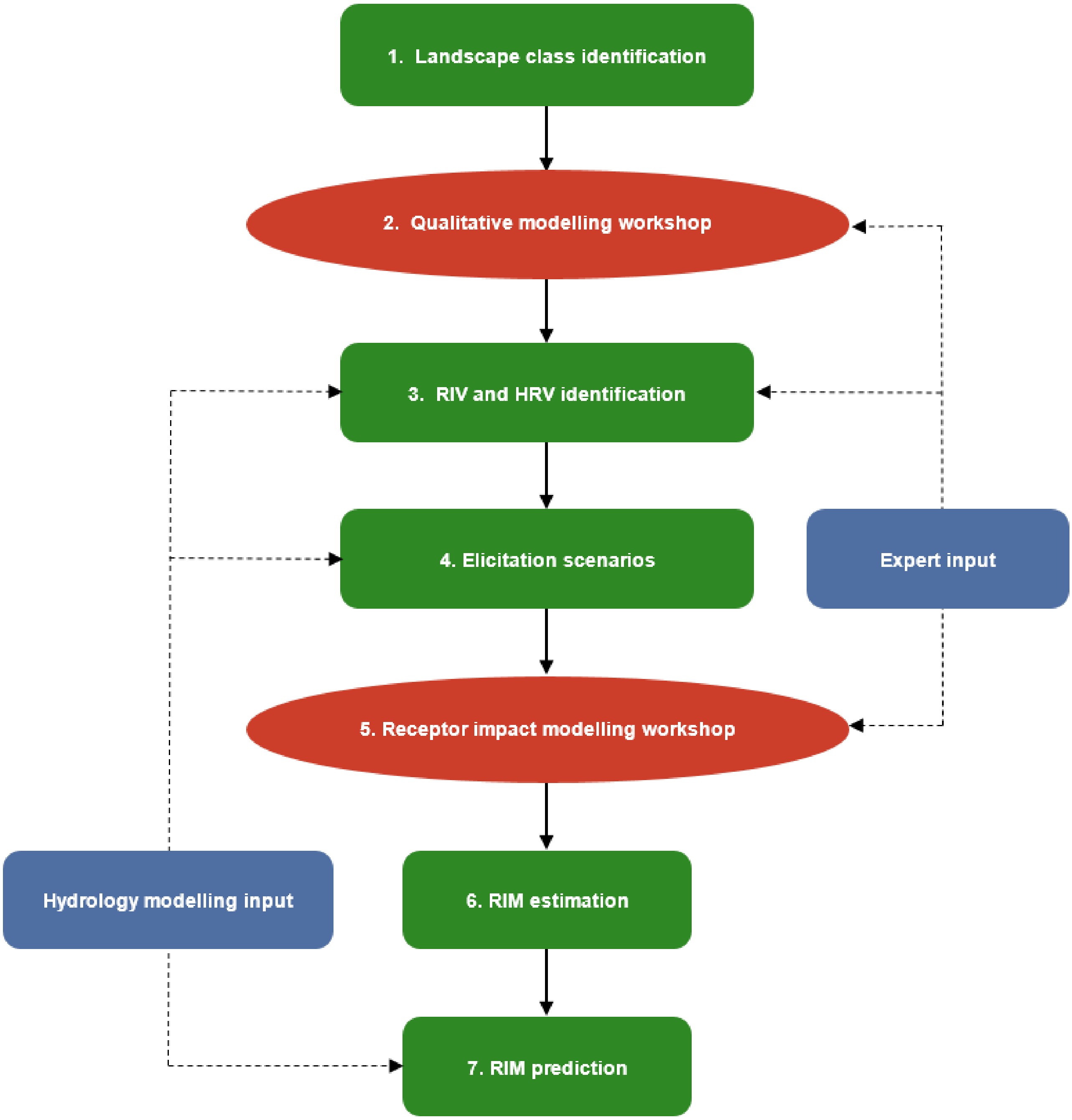

Figure 3 Outline of the ecological receptor impact workflow identifying (by stage) the contributions of external independent ecology experts, groundwater hydrology modelling and surface water hydrology modelling for the Gloucester subregion

The workflow leads to the construction of a receptor impact model (RIM) that predicts the response of a receptor impact variable (RIV) conditional on hydrological response variables (HRVs). The uncertainty encapsulated by the hydrology modelling is propagated through the RIM when predicting the RIV response to the choice of BA futures (baseline or coal resource development pathway) across a landscape class. Workshop steps are shown in red, ecology and hydrology expert input sources are shown in blue.

The workflow shown in Figure 3 leads to the construction of a receptor impact model 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.

2.7.1.2.1 Identification of landscape classes that are potentially impacted

BAs identify landscape classes that could be impacted by coal resource development as those landscape classes that lie wholly or partially within the zone of potential hydrological change. The zone of potential hydrological change is defined as the union of the groundwater and surface water zones of potential hydrological change. The groundwater zone of potential hydrological change is conservatively defined as the area with a greater than 5% chance of exceeding 0.2 m of drawdown in the relevant aquifers (see companion submethodology M10 (as shown in Table 1) for analysing impacts and risks (Henderson et al., 2018)). In the BA for the Gloucester subregion, the relevant aquifer is the regional watertable.

The surface water zone of potential hydrological change is defined in a similarly conservative manner. For the BA for the Gloucester subregion, it contains those river reaches where a change in at least one of eight surface water hydrological response variables exceeds its specified threshold. 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, with an additional threshold specified for P01 (see Table 5 in Post et al. (2018)). That is, if 5% or more of model runs show a maximum change in results under the CRDP of 1% relative to baseline. For three of the frequency-based hydrological response variables – high-flow days (FD), low-flow days (LFD) and length of low-flow spell (LLFS) – 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 (Viney, 2016).

It is important to recognise that the zone of potential hydrological change represents a conservative estimate of those parts of the landscape where there is a small chance of some minimal level of hydrological change attributable to coal resource development. The zone serves only to identify those landscape classes that should be taken to the next step of the receptor impact methodology from those landscape classes that should not (Stage 1 in Figure 3), 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

BA uses 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 experts familiar with the Gloucester subregion (Table 3; Stage 2 in Figure 3). In the workshop, ecological and hydrological experts were asked to describe how the key species and/or functional groups within the landscape class ecosystem interact with each other, and to identify the principal 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 and processes 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, which 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.

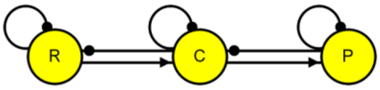

Figure 4 Signed digraph depicting a straight-chain system with a basal resource (R), consumer (C) and predator (P)

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 sudden disturbance to one of its population variables (i.e. pulse perturbation) it would be expected to return relatively quickly to its previous state or equilibrium.

Table 3 External experts who participated in the Gloucester subregion qualitative mathematical modelling (QMM) and receptor impact modelling (RIM) workshops

Organisation	Number of attendees QMM	Number of attendees RIM
University of Newcastle	1	1
NSW Department of Primary Industries	3	1
Cenwest Environmental Services and Charles Sturt University	1	1
Macquarie University	1	1
Consultant ecologist	1	1
NSW Office of Environment and Heritage	1	1
Birdlife Australia	1	
Department of the Environment	1	
University of Technology Sydney	1	1

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, 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.

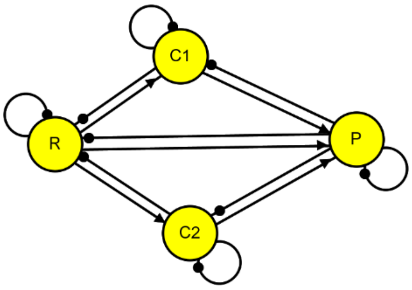

Figure 5 Signed digraph depicting a more complex system containing an additional consumer and a predator that feeds on more than one trophic level

Here the predicted response of R due to an increase in 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 the 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 P’s 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) describe a numerical simulation 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 BA, qualitative mathematical models are used to represent how ecosystems will respond qualitatively (increase, decrease, 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 hydrological variables that support the landscape class ecosystem. These variables are sometimes expressed as hydrological regimes, for example a surface water flow regime wherein overbank floods occur on average once every 3 years. The hydrological variables 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 by which BA identifies the way in which 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 these 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 Gloucester subregion (Zhang 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: 2013–2042 and 2073–2102 (e.g. mean number of overbank flows 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 (Zhang et al., 2018), which represent the maximum difference between the CRDP and baseline simulations over the 90-year (2013–2102) simulation period. 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.
- *It is something that the expertise available can provide an 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.
- *It is 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 about the response of a landscape class. Changes in the receptor impact variables imply changes to the ecology of the landscape class. For example, a decrease in percent canopy cover of woody riparian vegetation implies a reduction in the abundance and/or health of trees along river banks. A receptor impact variable may coincide with an ecological asset. For example, the abundance of a species listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999*, whose modelled 'Habitat (potential species distribution)' is an asset, might be selected as an indicator of overall ecosystem condition if experts thought its abundance were highly sensitive to hydrological change. Alternatively, a receptor impact variable that is not an asset, but which is highly sensitive to hydrological change, may be 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 to represent changes in water quality that might be expected to accompany changes in the relative contributions of surface runoff and groundwater to streamflow are not included in the models or the elicitations.

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 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

BA addresses 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. BA implements 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 group and the landscape classes and descriptions; and subsequently the finalised qualitative models; and, (iii) experts are given some 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 (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 criteria (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. 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 (Peeters et al., 2018) to give the predicted distribution of 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 class. Companion submethodology M09 (as listed in Table 1; Peeters et al., 2016) provides further details on how uncertainty is propagated through the models. Integrating across these 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 (impacts and risks) for the Gloucester subregion (Post et al., 2018). 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 legislation. Detailed site studies may give differing results due to the scale of modelling used.

2.7.1.2.6 Receptor impact modelling assumptions and implications

Companion submethodology M08 (as listed in Table 1) for receptor impact modelling (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 bioregional assessments

Assumptions of receptor impact modelling	Implications	Acknowledgement
Discretisation of continuous landscape surface	• provided a defined spatial scope for experts to focus upon • connections between landscape classes may be broken (i.e. connectivity is ignored) • 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 • prioritisation for qualitative mathematical models and receptor impact models may be affected • minimal effect on model development expected for receptor impact models.	• acknowledged issues with data in the impact and risk product (also done in the conceptual modelling product) • in the impact and risk analysis (product 3-4), 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 • 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
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 • 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

Assumptions of receptor impact modelling	Implications	Acknowledgement
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 • loss of within-landscape class predictive performance from the receptor impact models.	• identified as knowledge gaps where models do not represent some dependencies that are not captured by statistical dependencies with the chosen hydrological response variables • 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 also provided quantifiable predictions of the response of receptor impact variables to novel hydrological scenarios • expert availability affected the quality/utility of the qualitative mathematical model • 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 • identified as 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 • not all components and relationships are represented by receptor impact models.	• acknowledged that one or two receptor impact variables can underestimate complex ecosystem function • make assumptions clear • high-level interpretation of results • 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 • enables some simplification of complex systems • loss of local specificity in predictions of receptor impact variables.	• identified the need for local-scale information (in multiple places)
RIV selection (assumption that RIV 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 • focus on the quantified relationships within the landscape class.	• identified the need for local-scale information (in multiple places)

Assumptions of receptor impact modelling	Implications	Acknowledgement
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 • final model results sometimes extended beyond this preliminary range due to necessary changes in underlying hydrological modelling assumptions and assimilation of data • 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 Gloucester subregion (Post 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 under-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 receptor impact modelling (Hosack et al., 2018) • noted that many potential pulse perturbations are caused by accidents and managed by site-based processes • identified as a limitation or knowledge gap • noted that quantitative receptor impact models account for pulse perturbations.

BA = bioregional assessment, RIM = receptor impact model, RIV = receptor impact variable

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2.7.2 Prioritising landscape classes for receptor impact modelling

Summary

The zone of potential hydrological change for the Gloucester subregion is defined in Section 3.3 of companion product 3-4 (impact and risk analysis) for the Gloucester subregion (Post et al., 2018). All bioregional assessment (BA) landscape classes in the 'Economic land use' landscape group were present within the zone of potential hydrological change, as was the 'Native vegetation' landscape class in the 'Non-GDE' landscape group. These comprised the vast majority (98.6%) of the area inside the zone of potential hydrological change. Within the zone, there were also 3.5 km^2 of groundwater-dependent ecosystems (GDEs), which were classified either as wet or dry sclerophyll forests, rainforests or forested wetlands; and 242 km of river, which were overwhelmingly (88%) dominated by perennial and intermittent streams with a gravel/cobble substrate. Estuarine landscape classes were not present in the zone of potential hydrological change.

2.7.2.1 Potentially impacted landscape classes

All landscape classes are described in companion product 2.3 (Dawes et al., 2018) for the Gloucester subregion. Landscape classes potentially impacted by the additional coal resource development were identified as those that intersect the modelled zone of potential hydrological change. The zone of potential hydrological change was derived from the combination of a modelled groundwater drawdown zone and its downstream surface water network (see Section 3.3 of companion product 3-4 for the Gloucester subregion (Post et al., 2018)). The groundwater drawdown zone is defined as having a 5% probability of exceeding a 0.2m drawdown in the watertable aquifer. The surface water network downstream of this groundwater-drawdown zone was identified and a buffer of 150 m placed around it. A 150 m buffer was considered sufficient to capture any off-stream surface water impacts given the geomorphology of the Gloucester subregion. Any 500 m x 500 m assessment units (companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)) that intersect the groundwater drawdown zone or the buffered surface water network are included in the zone of potential hydrological change. The total area of the zone of potential hydrological change is 250 km^2. The zone of potential hydrological change is conservative and is designed to focus attention on those landscape classes that may be subject to hydrological changes, and at the same time identify areas and landscape classes beyond the zone where impacts are *very unlikely* (less than 5% chance).

All BA landscape classes in the 'Economic land use' landscape group are in the zone of potential hydrological change (Figure 6), as is the 'Native vegetation' landscape class in the 'Non-GDE' landscape group. These comprise the vast majority (98.6%) of the area inside the zone of potential hydrological change (Table 5). There are 3.5 km^2 of GDEs in the zone, classified as wet or dry sclerophyll forests, rainforests or forested wetlands (Table 5). There are 242 km of river within the zone of potential hydrological change, which are overwhelmingly (88%) dominated by perennial and intermittent streams with a gravel/cobble substrate (Table 5).

Table 5 Length or area of each landscape class within the zone of potential hydrological change in the Gloucester subregion

Also indicated are whether the landscape classes are represented in the qualitative model and the receptor impact model (RIM).

Landscape group	Landscape class	Extent in assessment extent	Extent in zone of potential hydrological change	Qualitative model	RIM
Riverine	Intermittent – gravel/cobble streams (km)	81	78	Intermittent gravel/cobble	Yes
	Intermittent – high gradient bedrock confined streams (km)	5	5	None	None
	Intermittent – lowland fine streams (km)	4	4	None	None
	Perennial – gravel/ cobble streams (km)	175	133	Perennial gravel/ cobble	Yes
	Perennial – high gradient bedrock confined streams (km)	28	9	None	None
	Perennial – lowland fine streams (km)	1	0	None	None
	Perennial – transitional fine streams (km)	17	13	None	None
Groundwater-dependent ecosystem (GDE)	Dry sclerophyll forests (km^2)	1.4	0.2	Dry sclerophyll forests	None
	Forested wetlands (km^2)	5.2	1.9	Forested wetlands	None
	Freshwater wetlands (km^2)	1.1	0	None	None
	Rainforests (km^2)	2.2	1.1	Wet sclerophyll forests	None
	Wet sclerophyll forests (km^2)	0.4	0.15	Wet sclerophyll forests	None
Estuarine	Barrier river (km)	33	0	None	None
	Saline wetlands (km^2)	5.4	0	None	None
Non-GDE	Native vegetation (km^2)	139	54	None	None
Economic land use	Dryland agriculture (km^2)	277	170	None	None
	Irrigated agriculture (km^2)	4.4	4.1	None	None
	Intensive uses (km^2)	20.9	14.2	None	None
	Plantation or production forestry (km^2)	3.2	1.0	None	None
	Water (km^2)	9.4	3.4	None	None

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

2.7.2.1.1 'Riverine' landscape group

Landscape classes in the 'Riverine' landscape group within the zone of potential hydrological change were identified and their lengths tabulated (Table 5). The total length of landscape classes within the 'Riverine' landscape group in the zone of potential hydrological change is approximately 242 km, the majority of which (88%) is either perennial or intermittent streams with gravel/cobble substrate. Hence, the receptor impact modelling described in Section 2.7.3 for the 'Riverine' landscape group focuses on the 'Perennial – gravel/cobble streams' and 'Intermittent – gravel/cobble streams' landscape classes. Rivers in the vicinity of coal resource development are intermittent in the north of the assessment extent and perennial in the south of the assessment extent (Figure 6).

The remaining streams within the non-estuarine region of the Gloucester subregion are a mixture of high gradient bedrock confined streams and transitional and lowland fine streams. High gradient bedrock confined streams are upstream of any development and lack a connection to the lowland regional groundwater aquifers; hence there is little potential for development to directly impact on these streams. Alterations to flow in the intermittent lowland streams could result in reduced opportunities for fish passage between lowland and upland streams (Thorncroft and Harris, 2000).

2.7.2.1.2 'Groundwater-dependent ecosystem (GDE)' landscape group

The total area of all landscape classes in the 'Groundwater-dependent ecosystem (GDE)' landscape group within the zone of potential hydrological change is 3.3 km^2, the majority of which (90%) is either 'Forested wetlands' or 'Rainforests' landscape classes. Rainforests are concentrated in the southern part of the assessment extent and are mainly associated with perennial streams while forested wetlands are concentrated in the northern part of the assessment extent and are mainly associated with intermittent streams. Rainforests are closely allied with wet sclerophyll forest. Wet sclerophyll forests are characterised by a tall, open, sclerophyllous tree canopy of *Eucalyptus* spp. and an understorey of soft-leaved shrubs, ferns and herbs, many of which are in common with rainforest species. More than 30% of crown cover of emergent, non-rainforest species (including eucalypts, brushbox and turpentine) results in a classification of wet sclerophyll forest rather than rainforest (DECC, 2007).

Qualitative mathematical models for the 'Dry sclerophyll forests' and 'Forested wetlands' and 'Wet sclerophyll forests' landscape classes are presented in Section 2.7.4. A qualitative model for rainforests was not developed owing to its small area within the subregion and lack of proximity to coal resource development.

2.7.2.1.3 'Estuarine' landscape group

Landscape classes in the 'Estuarine' landscape group were not present in the zone of potential hydrological change.

2.7.2.1.4 'Non-GDE' landscape group

A substantial area (54 km^2) of the zone of potential hydrological change is within the 'Native vegetation' landscape class of the 'Non-GDE' landscape group. As this class lacks a dependence on water other than rainfall, it was not expected to be impacted by development through groundwater or surface water mediated pathways, and no receptor impact model was developed for this landscape group.

2.7.2.1.5 'Economic land use' landscape group

In the 'Economic land use' landscape group, the majority of the zone of potential hydrological change is within the 'Dryland agriculture' landscape class (170 km^2). A further 23 km^2 is within the other landscape classes of the 'Economic land use' landscape group. Potential impacts on these landscape classes are not assessed.

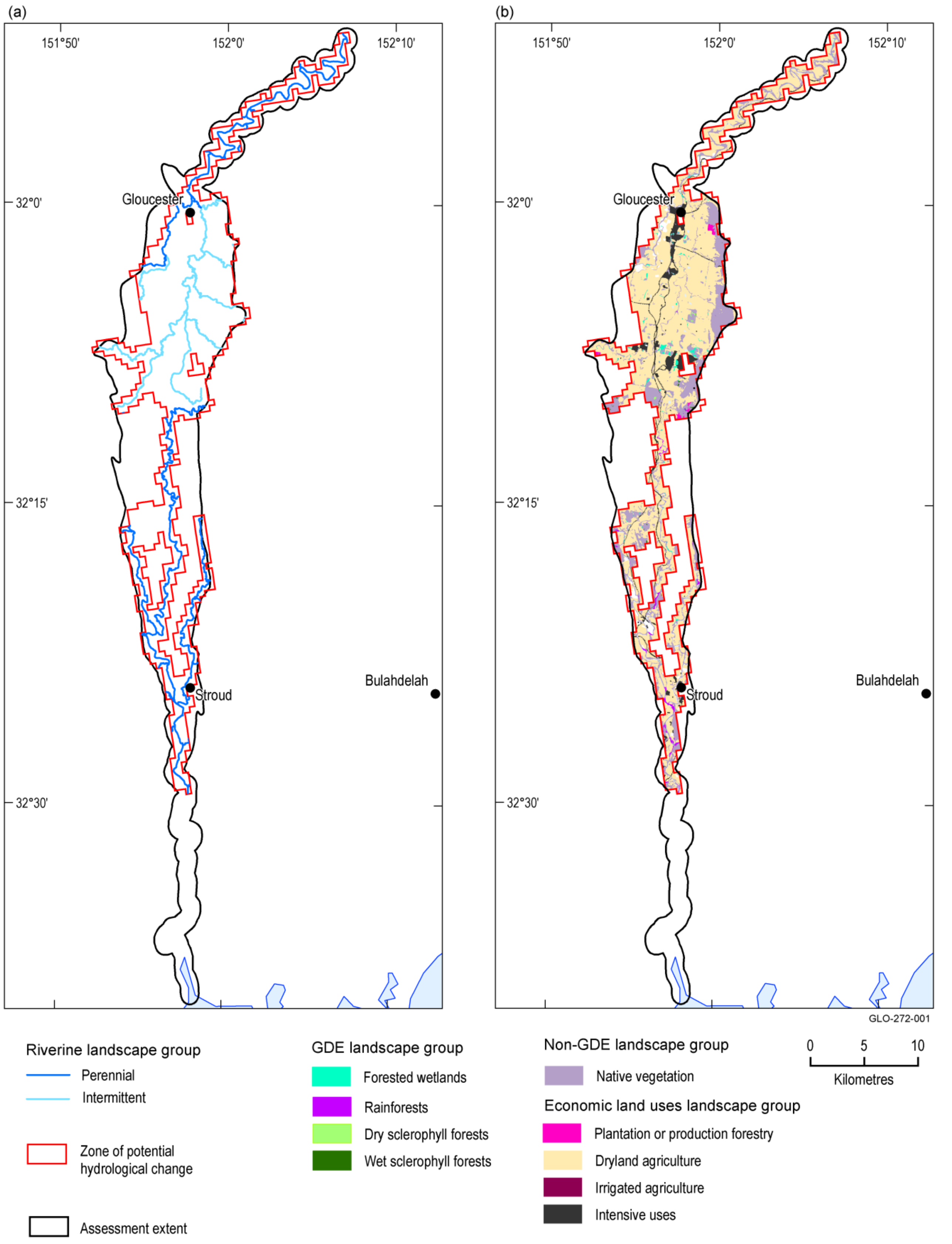

Figure 6 Zone of potential hydrological change for the Gloucester subregion

Distribution of landscape classes is shown for (a) the 'Riverine' landscape group and (b) for the 'Groundwater-dependent ecosystem (GDE)', 'Non-GDE' and 'Economic land use' landscape groups. For clarity, the 'Riverine' landscape group has been simplified to 'Perennial' or 'Intermittent'. The vast majority of stream length has a gravel/cobble substrate (Table 5).
GDE = groundwater-dependent ecosystem
Data: Bioregional Assessment Programme (Dataset 2)

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2.7.3 ‘Riverine’ landscape group

Summary

The two closely related landscape classes, ‘Perennial – gravel/cobble streams’ and ‘Intermittent – gravel/cobble streams’, overwhelmingly dominate potentially impacted stream reaches in the ‘Riverine’ landscape group (see Section 2.7.2). Hence, receptor impact modelling for the ‘Riverine’ landscape group focused on the ‘Perennial – gravel/cobble streams’ and ‘Intermittent – gravel/cobble streams’ landscape classes, and a conceptual model for the two classes is presented here.

Only 3% of the perennial streams and 2% of the intermittent streams within the zone of potential hydrological change were classed as being in good geomorphic condition. Of the intermittent streams within the zone, 51% were in moderate condition and 46% were in poor condition. Of the perennial streams within the zone, 83% were in moderate condition and 15% were in poor condition. The relatively poor geomorphic condition of the intermittent streams was reflected in riparian cover: 59% of the intermittent river reaches within the zone of potential hydrological change had some vegetation cover, while 88% of the perennial river reaches had some vegetation cover.

The qualitative model for the ‘Perennial – gravel/cobble streams’ landscape class identifies three surface water flow regimes, groundwater and precipitation as the main components of the hydrological regime that maintain and shape the ecosystem. The first four components are predicted to change due to coal resource development. Qualitative mathematical modelling of 14 plausible combinations of change in these components indicates a consistently negative effect across all the model’s variables.

The hydrological components were subsequently interpreted into a set of hydrological response variables, and some of the ecological components were chosen as receptor impact variables (with associated sample units), to assess the response of: (i) annual mean percent canopy cover of woody riparian vegetation to changes in 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)), tmaxRef (the year that the maximum difference in drawdown relative to the reference period (1983 to 2012) (dmaxRef) occurs), EventsR0.3 (mean annual number of events with a peak daily flow that is assumed to result in ‘overbench’ flow) and EventsR3.0 (mean annual number of events with a peak daily flow that is assumed to result in ‘overbank’ flow); (ii) mean density of larvae of the Hydropsychidae family (net-spinning caddisflies) to changes in mean annual number of zero-flow days (averaged over 30 years) (ZQD); and (iii) mean density of the eel-tailed catfish (*Tandanus tandanus*) to changes in ZQD and QBFI (baseflow index as described in Table 9).

The first receptor impact model suggests that the amount and rate of groundwater drawdown (dmaxRef and tmaxRef) have the strongest (relative to the other hydrological response variables) effect on annual mean percent canopy cover across the landscape class. If all other hydrological response variables are held at the mid-point of their elicitation range, then a 6-m reduction in groundwater levels (from their average conditions between 1983

and 2012), is predicted to lead to a roughly 20% decrease in mean percent canopy cover in both the short- (2042) and long- (2102) assessment years. The model also indicates that mean percent canopy cover in the future will be influenced by mean percent canopy cover in the reference year (2012).

This model also suggests that an increase in the frequency of overbench flows (EventsR0.3) will have a relatively small positive effect on mean percent canopy cover. However, the large uncertainty reflected in the 80% credible intervals does not preclude the small possibility of EventsR0.3 having a negligible effect on mean percent canopy cover. The summary statistics for the marginal distribution of the other model coefficients indicate that there is insufficient information in the expert-elicited data to determine the effect of overbank flows (EventsR3.0).

The second model strongly supports the hypothesis that an increase in ZQD will have a negative effect on the density of net-spinning caddisfly larvae. The model suggests that larval density can vary substantially across the landscape class (from <100 to 1000 per m^2) under conditions of constant flow (ZQD = 0). As the number of zero-flow days increases, however, the model predicts that density will drop quite dramatically with values less than 1 per m^2 falling within the 80% credible interval under very intermittent flow conditions (ZQD >200 days).

The experts' elicited values in the third model suggest that average density of the eel-tailed catfish will decline as ZQD increases, from about 5 individuals per 600 m^2 transect under continuous flow (ZQD = 0), holding all other covariates at their mid-values, to less than 1 individual in two transects as flow becomes more intermittent (increase in zero-flow days).

The qualitative mathematical model for the 'Intermittent – gravel/cobble streams' landscape class focused primarily on pool habitat and its role in providing refugia for fish and other aquatic organisms during periods of low flow. The model identifies surface water replenishment and groundwater input as the critical hydrological variables that maintain the pools' ecology, and it examined the potential impacts of coal resource development on these hydrological variables, individually and in combination. The three resulting cumulative impact scenarios, reflecting combinations of decrease and no change in the hydrological variables, lead to predictions of a negative or zero (no change) response across most of the model's variables.

The initial receptor impact modelling workshop for the Gloucester subregion was unable to address the 'Intermittent – gravel/cobble streams' landscape class. The Bioregional Assessment Programme addressed this omission by holding a second elicitation with a single expert. This expert, however, elected to address the subsurface fauna (hyporheic invertebrates) in riffle habitats (which are not represented in the qualitative model) and its response to the number of zero-flow days. This relationship was formalised into a receptor impact model that described the response of mean hyporheic invertebrate taxa richness to changes in ZQD.

The model reflects the expert's view that increasing ZQD will have a negative effect on hyporheic taxa richness, despite lack of certainty about its average value. The model suggests that mean taxa richness can vary substantially across the landscape class from 10 to 20 per sampling unit (mean hyporheic invertebrate taxa richness in 6 L water pumped from a depth of 40 cm below the streambed) under conditions of constant flow (ZQD = 0). As the number of zero-flow days increases, however, the expert was of the opinion that density would drop to values from 1 to 8 under extremely intermittent flow conditions (ZQD >300 days).

It is important to recognise that many of the summary statements about the model described in this section simplify the (often more complicated) relationship between receptor impact variables and hydrological response variables captured by the receptor impact models. They are not risk or impact predictions for the Gloucester subregion. These predictions are provided in companion product 3-4 (impact and risk analysis) for the Gloucester subregion (Post et al., 2018).

2.7.3.1 Description

Companion product 2.3 for the Gloucester subregion describes seven landscape classes within the 'Riverine' landscape group in the assessment extent (AE) (Dawes et al., 2018):

- Intermittent – gravel/cobble streams
- Intermittent – high gradient bedrock confined streams
- Intermittent – lowland fine streams
- Perennial – gravel/cobble streams
- Perennial – high gradient bedrock confined streams
- Perennial – lowland fine streams
- Perennial – transitional fine streams.

No moderately intermittent or ephemeral streams were identified as landscape classes in the AE for the Gloucester subregion. The perennial river landscape classes broadly correspond to the 'stable baseflow' classes from Kennard et al. (2010; Classes 1, 2 and 3), while the intermittent river landscape classes correspond broadly to the 'unstable baseflow' and 'rarely intermittent' classes from Kennard et al. (2010; Classes 4 and 5). Perennial streams have flow at least 80% of the year, and an appreciable contribution of groundwater to baseflows. Kennard et al. (2008) reported a baseflow index of 0.15 to 0.4 for perennial streams. Intermittent streams cease flowing more often than perennial streams and have a lesser (0.12 to 0.25) baseflow contribution (Kennard et al., 2008).

The two closely related landscape classes, 'Perennial – gravel/cobble streams' and 'Intermittent – gravel/cobble streams', overwhelmingly dominate potentially impacted stream reaches in the 'Riverine' landscape group (see Section 2.7.2). The 'Perennial – gravel/cobble streams' landscape class represents 52% of the stream network within the non-estuarine region of the AE (refer to companion product 2.3 for the Gloucester subregion (Dawes et al., 2018)). In the northern half of the AE, the landscape class is mainly restricted to the Gloucester River; in the southern half of the AE it also occurs along the Karuah and Mammy Johnsons rivers. The 'Intermittent – gravel/cobble streams' landscape class occupies 20% of the stream network within the non-estuarine region of the AE, with the majority occurring in the northern half of the AE (companion product 2.3 for the

Gloucester subregion (Dawes et al., 2018)). This landscape class is dominated by the Avon River (which itself is a major tributary of the Gloucester River) and its tributaries. The Avon river basin area occupies approximately 73% of the northern-flowing part of the AE, and descends 412 m over its 42 km course (companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)). Hence, receptor impact modelling for the 'Riverine' landscape group focused on the 'Perennial – gravel/cobble streams' and 'Intermittent – gravel/cobble streams' landscape classes, and a conceptual model for the two classes is presented in this section.

Pools and riffles are most common in streams with mixed bed materials ranging from 2 to 256 mm in size (Knighton, 1984); hence, they are a feature of the 'Perennial – gravel/cobble streams' and 'Intermittent – gravel/cobble streams' landscape classes. The mixed substrate favours formation of alternating pool and riffle sequences that increase the geomorphic and habitat complexity along the reach (Boulton et al., 2014). Riparian vegetation lining the banks of the riverine landscape classes provides important instream and terrestrial habitats and contributes to geomorphic condition by maintaining bank stability (Boulton et al., 2014). Within the Gloucester zone of potential hydrological change, this riparian vegetation is dominated by forested wetlands, typically characterised by a eucalypt-dominated overstorey and a grassy or shrubby understorey, although actual species composition is highly variable (Keith, 2004). The Karuah River from Stroud to Karuah is relatively well vegetated but much of the riparian zone is cleared along the Avon and Gloucester rivers (see Section 1.1.7.2 of companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)) and much of the riparian zone outside of the Karuah National Park and reserves is in poor condition (Haine et al., 2012). Patches of rainforest, including the 'Lowland Rainforest of Subtropical Australia' threatened ecological community, are largely restricted to reaches along the Karuah River (see Section 2.3.3.1 of companion product 2.3 for the Gloucester subregion (Dawes et al., 2018)).

Hydrological regimes for the AE for the Gloucester subregion are discussed in more detail in companion product 1.1 (McVicar et al., 2014) and companion product 2.1-2.2 (Frery et al., 2018) and only a brief summary of these is presented here for context. There are no surface water connections between the northern and southern halves of the subregion, and no evidence of substantial groundwater connection between the two. Groundwater monitoring undertaken by Parsons Brinckerhoff (2012a, 2012b, 2013a) within the geological Gloucester Basin provides some evidence for a topographical shallow groundwater flow divide in the middle of the basin north of Wards River, approximately coincident with the surface water divide. This separates the Gloucester Basin into a northern sub-basin (where regional groundwater flow is predominantly from south to north) and a southern sub-basin (where regional groundwater flow is predominantly from north to south) (companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)).

Stream and aquifer salinity indicate that on average, streams within the AE for the Gloucester subregion are gaining; thus, groundwater provides an important source of baseflow in this landscape group (companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)). Groundwater recharge was estimated as zero to 17% (under steady-state conditions) and zero to 28% (under transient conditions) of rainfall, with high values associated with alluvial aquifers (Australasian Groundwater and Environmental, 2013; Heritage Computing, 2009, 2012; Parsons Brinckerhoff, 2013b). Discharge occurs as localised discharge to rivers and streams and as diffuse discharge, via evapotranspiration, from deep-rooted vegetation. Groundwater salinity increases with depth, although typically, groundwater associated with alluvial aquifers varies from fresh to brackish (electrical conductivity (EC) of 387 to 5810 µS/cm; companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)). Companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018) reported that groundwater depths in the alluvium ranged from very near the surface (<0.1 m) to 13.4 m below ground level. Almost no data were available outside the alluvium; however, modelled depths to water (Summerell and Mitchell, 2011) suggest that groundwater is not deeper than 12 to 16 m in any of the lowland areas of the AE (Figure 8).

In the northern half of the AE, approximately 43 km of the middle and lower reaches of the Gloucester River occur within the subregion. In the north of the AE, average annual streamflow and baseflow index (calculated using digital filtering) are 550 GL/year and 0.58 for the gauge at Doon Ayre (208003), respectively (Figure 7). At the Gloucester stream gauge (208020), average annual streamflow and baseflow index are 84 GL/year and 0.56, respectively. There is high interannual variability in high-flow regimes related to rainfall inputs. Baseflows tend to be less variable due to the buffering effects of groundwater inputs (see the surface water hydrology section in companion product 1.1 (McVicar et al., 2014) and companion product 2.1-2.2 for the Gloucester subregion (Frery et al., 2018)). The Barrington River discharges approximately 435 GL/year at the Relf Rd streamflow gauge (208031) located about 1 km upstream from its confluence with the Gloucester River. Stream cross-sections and flow duration curves at the stream gauges for the Gloucester River at Gloucester, Relf Rd and Doon Ayre are shown in Figure 7. At the Gloucester stream gauge, high overbank flows are rare, occurring with an average frequency of 1 in 27 years (overbank threshold ~10 GL/day). Cease-to-flow periods are also extremely rare, occurring at an average frequency of approximately once in 127 years. Streamflow peaks tend to occur in the late summer–autumn period and decline over winter to a minimum in spring (companion product 1.3 for the Gloucester subregion (McVicar et al., 2015)) (Table 6). Only one stream gauge occurs in the ‘Intermittent – gravel/cobble streams’ landscape class, on the Avon River at Waukivory (208028). Maximum monthly flows occur in February and minimum flows occur in January (companion product 1.1 (McVicar et al., 2014)). The overbank threshold for this stream gauge is 3621 GL, occurring at an average frequency of twice per year. Cease-to-flow periods are very frequent, occurring at an average frequency of 26.5 days per year. Mean annual flow at the stream gauge is 96 GL/year and the baseflow index is 0.26. The river cross-section and flow duration curve for Avon River at Waukivory are shown in Figure 7.

In the south of the AE, the ‘Perennial – gravel/cobble streams’ landscape class is largely confined to the Karuah and Mammy Johnsons rivers. There are two stream gauges (209003 Karuah River at Booral; 209002 Mammy Johnson) located within the ‘Perennial – gravel/cobble streams’ landscape class in the southern half of the AE. Annual streamflow and the baseflow index for the Karuah at Booral are 270 GL/year and 0.50, respectively (companion product 1.1 (McVicar et al., 2014)). Mean annual streamflow and baseflow index for the stream gauge at Mammy Johnsons are 56 GL/year and 0.33, respectively. The overbank threshold for this stream gauge is 24 GL, occurring at an average frequency of once every 2.7 years. The cease-to-flow frequency is also higher than in the Gloucester River with a cease-to-flow frequency of once every 1.4 years. Seasonal patterns in the streamflow peaks and minima are similar to that described above, although the maxima and minima vary between stream gauges (Table 6).

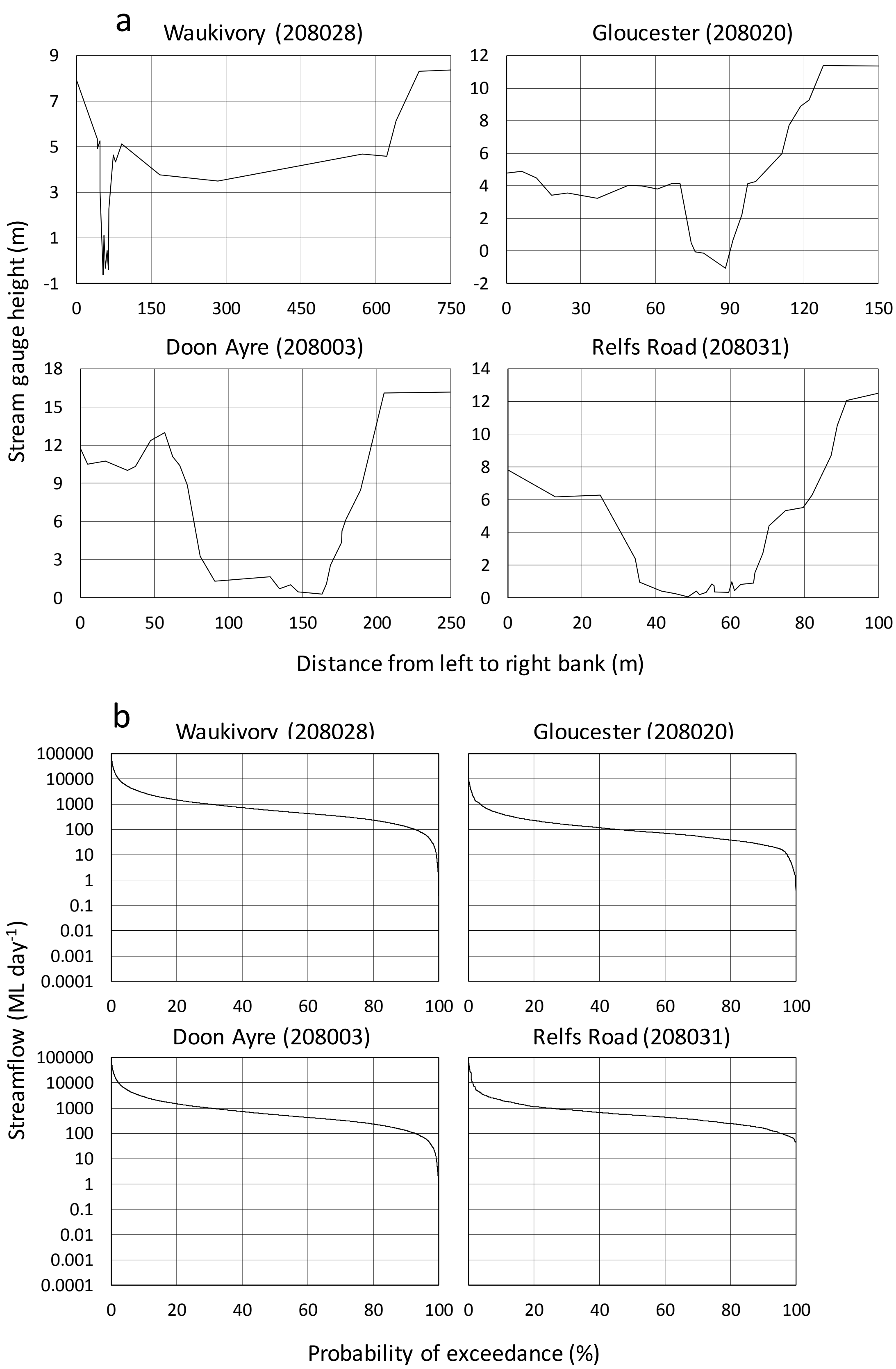

Figure 7 River cross-sections (a) and flow duration curves (b) at stream gauges 208028, 208020, 208003 and 208031 in the Gloucester subregion

The locations of these stream gauge stations are shown on Figure 27 in companion product 1.1 for the Gloucester subregion (McVicar et al., 2014).
Source: NSW Office of Water (2015)

Table 6 Maximum and minimum flow regimes for stream gauges in 'Perennial – gravel/cobble streams' and 'Intermittent – gravel/cobble streams' landscape classes in the Gloucester subregion

Stream gauge	River	Maximum flow (GL/month)	Season	Minimum flow (GL/month)	Season
208020	Gloucester River at Gloucester	16	Late summer/autumn	<4	Early spring
208003	Gloucester River at Doon Ayre	90	Late summer/autumn	25	Early spring
209002	Mammy Johnsons River at crossing	10	Late summer/autumn	<2	Early spring
209003	Karuah River at Booral	>45	Late summer/autumn	<10	Early spring
208028	Avon River at Waukivory	<25	Summer	<5	Late spring/early summer

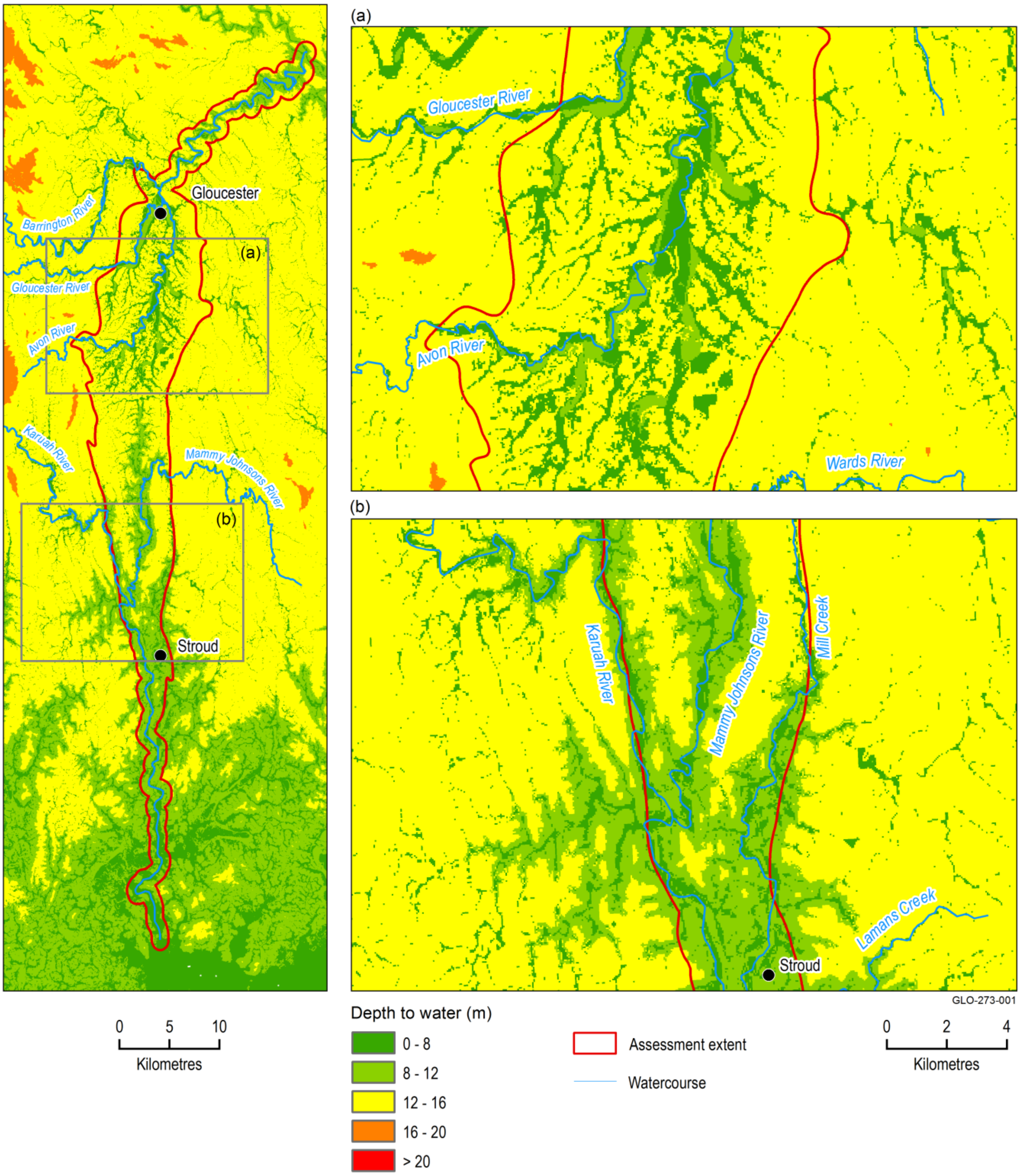

Figure 8 Depth to watertable in the assessment extent for the Gloucester subregion

Data: NSW Department of Primary Industries (Dataset 1)

2.7.3.1.1 Flora and fauna

Only 3% of the perennial stream length and 2% of the intermittent stream length within the zone of potential hydrological change were classed as being in good geomorphic condition (Figure 9; NSW Office of Water, Dataset 2). Chessman et al. (2006) observed that river reaches of the Bega River in good geomorphic condition were important for maintaining native biodiversity and were biologically very different from stream reaches in moderate or poor condition. Deterioration from moderate to poor geomorphic condition resulted in less biological change than the deterioration from good to moderate. Of the intermittent streams within the zone of potential hydrological change, 51% were in moderate condition and 46% were in poor condition. Of the perennial streams within the zone, 83% were in moderate condition and 15% were in poor condition. Of the intermittent river reaches within the zone, 59% had some vegetation cover, while 88% of the perennial river reaches had some vegetation cover (Figure 10).

Riparian vegetation (Figure 10) along both perennial and intermittent streams is dominated by *Waterhousea floribunda*/*Tristaniopsis laurina* riparian warm temperate rainforest and *Casuarina cunninghamiana*/*Melia azedarach* grassy riparian forest (Keith, 2004). Other vegetation associated with these streams includes overstorey trees such as *Angophora costata*, *Corymbia maculata*, *Eucalyptus amplifolia*, *E. canaliculata*, *E. grandis*, *E. punctata*, *E. saligna*, *E. tereticornis* and *Ficus coronata*. *E. tereticornis* is considered to be a primary feed tree for koalas in the central coast region (NSW Office of Environment and Heritage, 2016).

Rainforest patches may provide important habitat for rainforest birds such as the superb fruit-dove (*Ptilinopus superbus*), and include overstorey tree species such as *Lophostemon suaveolens*, *Livistona australis* and *Melaleuca* sp. Understorey shrubs include cheese tree (*Glochidion ferdinandi*), swamp paperback (*Melaleuca ericifolia*) and waterbush (*Myoporum acuminatum*). The grass layer includes a range of forbs, herbs, sedges and grasses (Keith, 2004).

These vegetation associations may form habitat for several threatened plant species included in the asset register for the Gloucester subregion (see companion product 1.3 for the Gloucester subregion (McVicar et al., 2015)), including the Charmhaven apple (*Angophora inopina*), white-flowered wax plant (*Cynanchum elegans*), leafless tongue orchid (*Cryptostylis hunteriana*), slaty redgum (*Eucalyptus glaucina*) and trailing woodruff (*Asperula asthenes*). In addition, riparian vegetation can form habitat for a range of vertebrate and invertebrate fauna. Examples of vertebrate fauna from the asset register listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) that might use riparian vegetation (e.g. forested wetlands), either for habitat or feeding, include the grey-headed flying-fox (*Pteropus poliocephalus*), red goshawk (*Erythrotriorchis radiatus*), regent honeyeater (*Anthochaera phrygia*), swift parrot (*Lathamus discolor*) and giant barred frog (*Mixophyes iteratus*) (CSIRO, Dataset 3). The 'Riverine' landscape group includes platypus habitat (an asset listed in the asset register for the Gloucester subregion). The streams and their associated riparian vegetation provide migration corridors for aquatic and terrestrial fauna and habitat for a range of threatened species, such as the spot-tailed quoll (*Dasyurus maculatus* subsp. *maculatus*).

It is important to note that there is large uncertainty around the mapping of individual plant-community types in the Gloucester subregion; a recent ground-truth study in the Upper Hunter (Hunter, 2015) found that only 7% of plant-community types were reliably mapped. Even at the level of vegetation formation, only dry sclerophyll forests and woodlands were mapped with greater than 50% accuracy. On this basis, the landscape classes were not defined at finer hierarchical levels such as vegetation class or plant-community type.

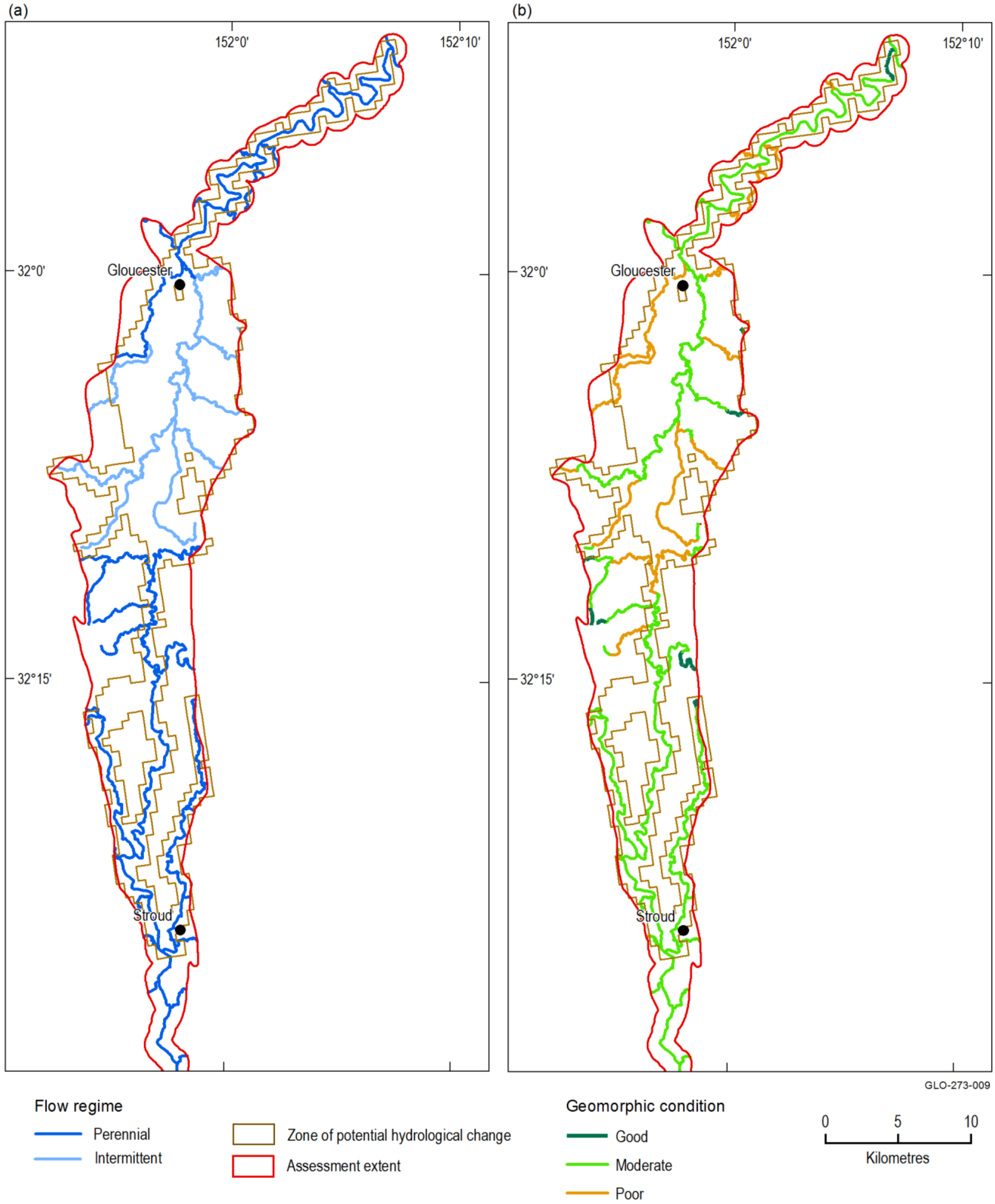

Figure 9 (a) Flow regime and (b) geomorphic condition of streams in the Gloucester subregion

Data: NSW Office of Water (Dataset 2)

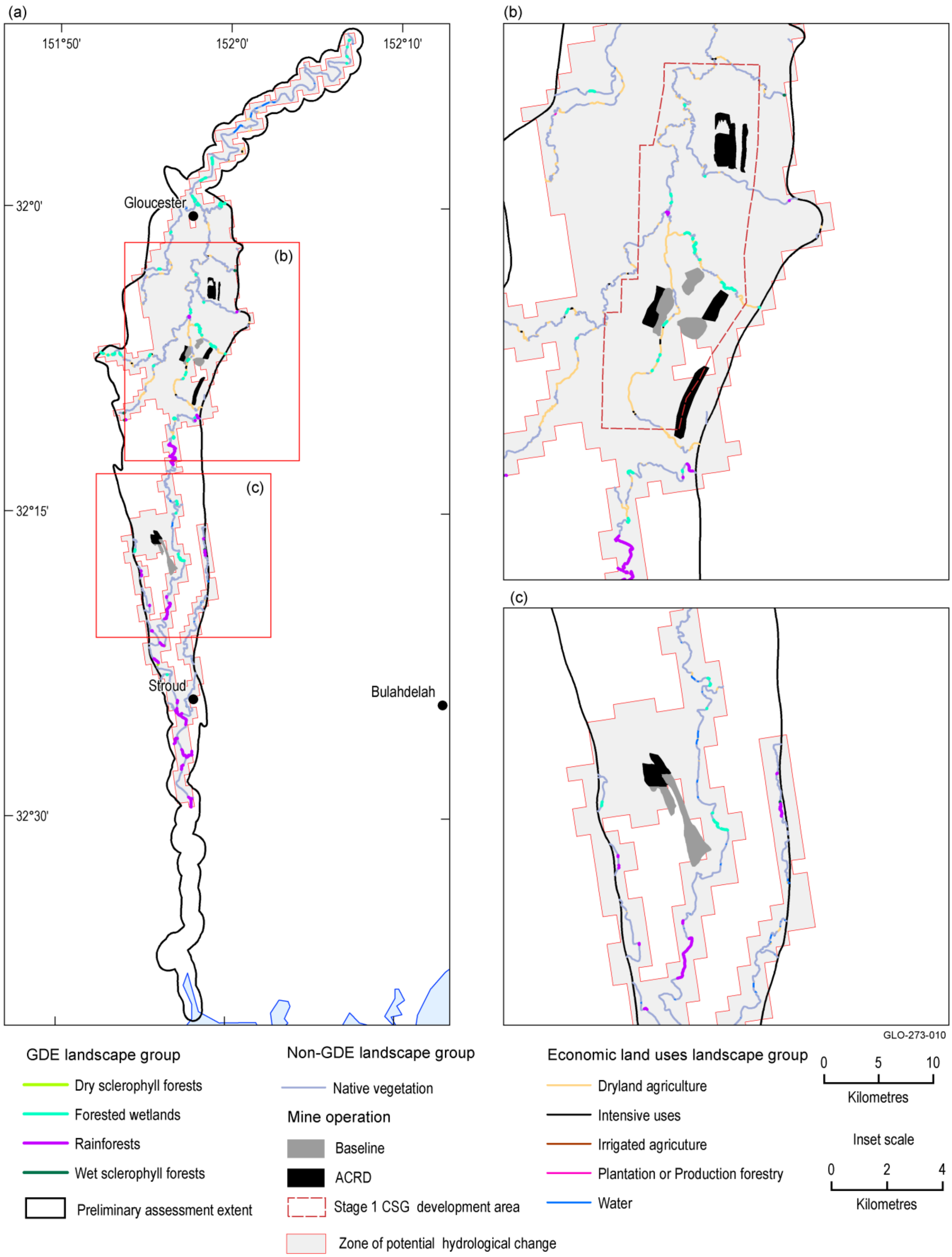

Figure 10 Keith (2004) vegetation classes associated with streams in the zone of potential hydrological change of the Gloucester subregion

ACRD = additional coal resource development, CSG = coal seam gas, GDE = groundwater-dependent ecosystem
Data: NSW Office of Water (Dataset 2)

The ‘Riverine’ landscape group supports a range of native and introduced fish species. Native species that migrate upstream and downstream may be important indicators of longitudinal connectivity (Koehn and Crook, 2013). Examples include the diadromous (migrates between fresh and estuarine waters) Australian bass (*Macquaria novemaculeata*) and striped gudgeon (*Gobiomorphus australis*), and the potamodromous (migrates wholly within fresh waters) Cox’s gudgeon (*Gobiomorphus coxii*). Changes to flow regimes may impact the life cycles of these fish by (NSW Department of Primary Industries, 2006):

- interrupting spawning or seasonal migrations
- restricting access to preferred habitat and available food resources
- reducing genetic flow between populations
- increasing susceptibility to predation and disease through accumulations below barriers
- fragmenting previously continuous communities
- disrupting downstream movement of adults and impeding larval drift through the creation of still water (lentic) environments.

Other native fish species reported from NSW DPI fisheries monitoring (NSW Department of Primary Industries, Dataset 4) of the Gloucester, Karuah, Wards and Mammy Johnsons rivers include Australian smelt (*Retropinna semoni*), bullrout (*Notesthes robusta*), common jollytail (*Galaxias maculatus*), dwarf flathead gudgeon (*Philypnodon macrostomus*), empire gudgeon (*Hypseleotris compressa*), firetail gudgeon (*Hypseleotris galii*), flathead gudgeon (*Philypnodon grandiceps*), eel-tailed catfish (*Tandanus tandanus*), freshwater herring (*Potamalosa richmondia*), freshwater mullet (*Myxus petardi*), long-finned eel (*Anguilla reinhardtii*), sea mullet (*Mugil cephalus*), short-finned eel (*Anguilla australis*), southern blue-eye (*Pseudomugil signifer*) and yellowfin bream (*Acanthopagrus australis*). Exotic fish species have also been observed (e.g. eastern gambusia and goldfish).

2.7.3.1.2 Ecologically important flows

Ecologically important components of the hydrograph can be broadly summarised (Dollar, 2000; Robson et al., 2009) as cease-to-flow periods, periods of low flow, freshes, and periods of high flow (including overbench and overbank flows) as illustrated in Figure 11. Longitudinal, lateral and vertical connectivity is enhanced with increasing flow. Increasing flow increases connectivity between aquatic habitats and enables greater movement of aquatic biota and water-borne nutrients, and fine and coarse particulate organic matter. Flow regimes determine natural patterns of connectivity, which are essential to the persistence of many riverine populations and species (Bunn and Arthington, 2002). High flows are especially important for lateral connectivity and channel maintenance. Low flows are critical to maintaining vertical and longitudinal connectivity, and water quality of inundated habitat including pools. Freshes can trigger fish spawning, maintain water quality in inundated habitats and cleanse and scour the riverbed.

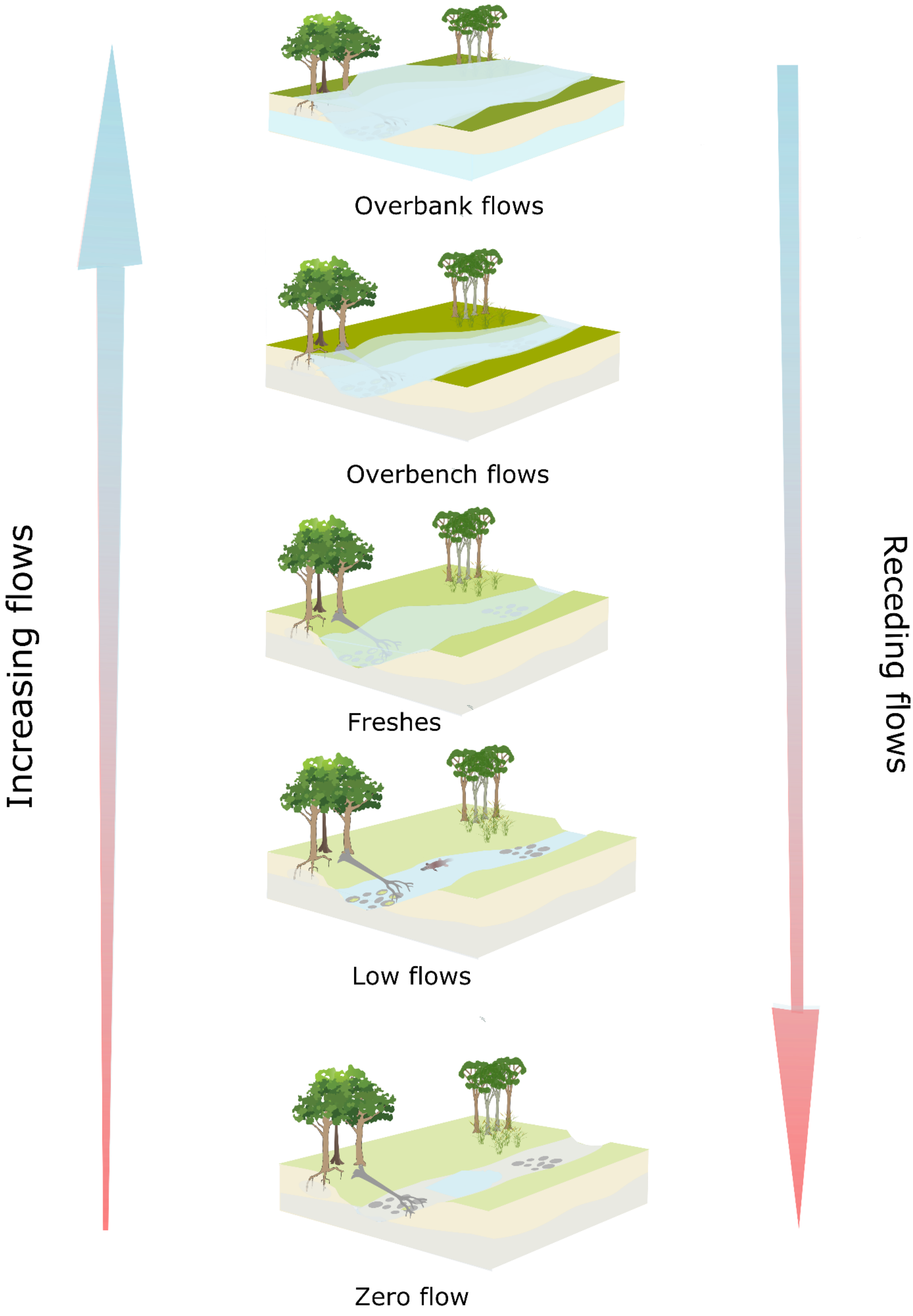

Figure 11 Conceptual representation of components of the hydrograph during wetting and drying cycles in streams

A lack of vertical connection to groundwater can result in zero-flow periods (Figure 12) during periods of little or no rainfall. Cease-to-flow events dry out shallow habitats and can create chains of pools, isolated pools or completely dry riverbeds, depending on riverbed morphology (Robson et al., 2009). Chessman et al. (2012) reported that aquatic macroinvertebrate assemblages that had been exposed to severe flow reduction or zero flow during the period prior to sampling would be dominated by taxa tolerant of low oxygen concentrations, low water velocities and high temperatures, whereas assemblages not exposed to very low flows would be dominated by taxa that favour cool, aerated, fast-flowing conditions. Riffle habitats that are characterised by faster flowing, well oxygenated water tend to be the first habitat type to be impacted by reduced river discharge. Marsh et al. (2012) also concluded that communities in streams that are usually perennial but cease to flow for short periods (weeks) will mostly recover the following season but that the community composition will decline if cease-to-flow periods recur over consecutive years.

During periods of zero flow and low flow (Figure 12 and Figure 13), lateral connectivity is likely to be limited; however, low flows are important for maintaining vertical connectivity to the hyporheic zones of the streambeds (Ward, 1989; Kondolf et al., 2006), and for maintaining longitudinal connectivity within the landscape by linking instream habitats and allowing dispersal of instream biota (Dollar, 2000; Robson et al., 2009; Marsh et al., 2012; Boulton et al., 2014). Low flows (Figure 13) provide seasonal habitat for many species and can maintain refugia for other species during droughts (Dollar, 2000). In regions with seasonal rainfall, low flows are maintained by baseflow, which is generally considered to be a groundwater contribution to the hydrograph, hence the importance of the vertical connection of the riverbed to groundwater. In a synthesis of case studies, Marsh et al. (2012) concluded that increasing durations of low flow are correlated with declining water quality (increased temperature and salinity and reduced dissolved oxygen), and that this a primary driver of ecological responses of most aquatic biota, especially in pools. Riffle habitats are not only affected by changes in water quality but also by reduced habitat area, as riffles dry out and contract.

Although lateral connectivity is limited under zero-flow and low-flow conditions, riparian vegetation may directly access alluvial groundwater, in addition to accessing perched watertables within the stream bank and directly accessing riverine water. The contribution of groundwater to evapotranspiration is likely important for maintaining function of the riparian vegetation (Dawson and Ehleringer, 1991) and may be higher during periods of low flow (Lamontagne et al., 2005).

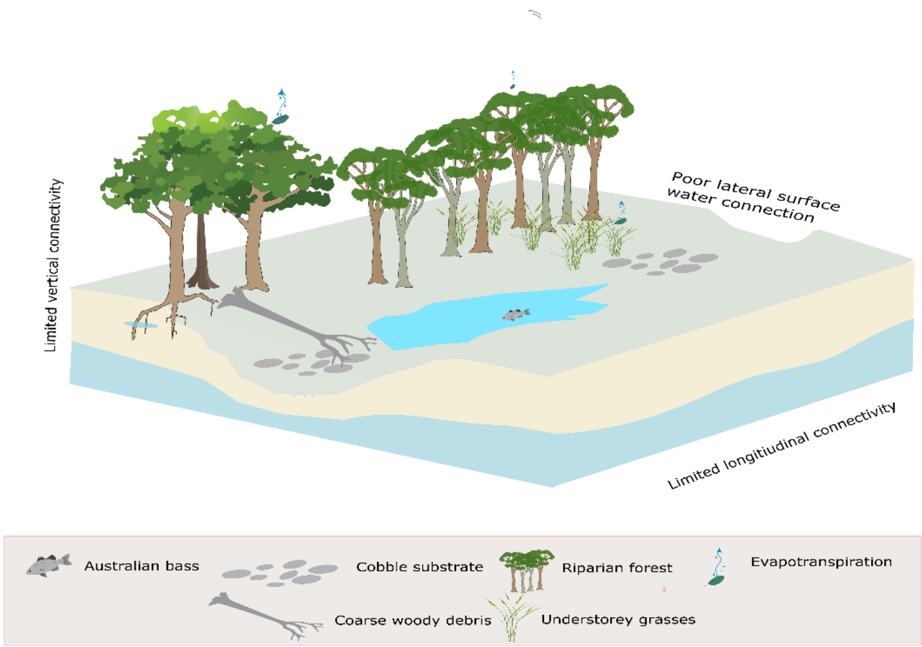

Figure 12 Conceptual model of streams during periods of zero flow when there is no connection to groundwater

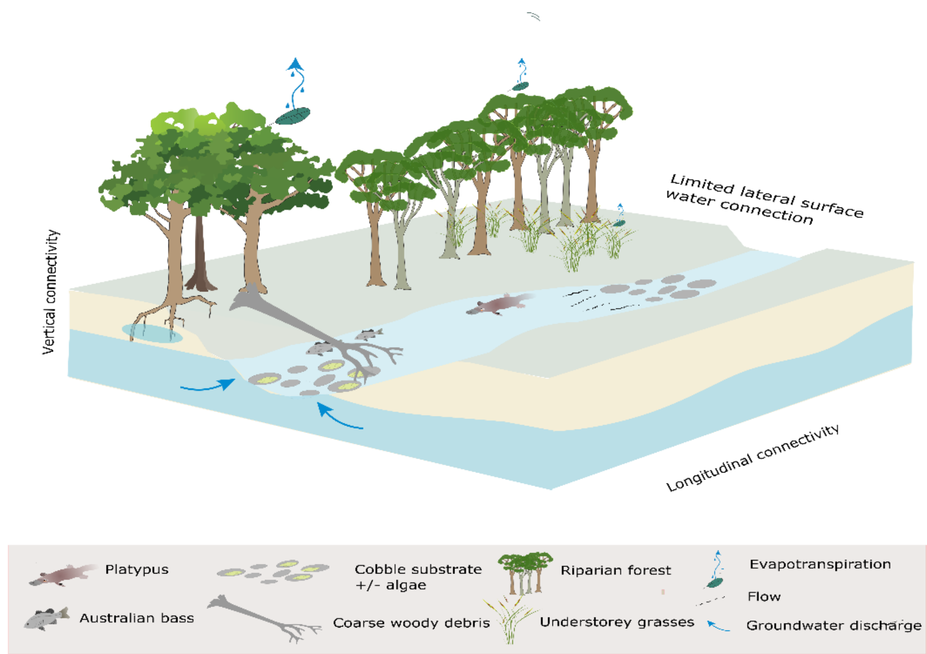

Figure 13 Conceptual model of streams during periods of low flow when baseflows predominate

Freshes (Figure 14) are defined as flows greater than the median for that time of the year (Robson et al., 2009). They can last for several days and typically increase the flow variability within the stream as well as playing an important role in the regulation of water quality through inputs of fresh water. Freshes can mobilise sediment, inundate larger areas of potential habitat, and connect in-channel habitats – thereby permitting migration of aquatic fauna (Robson et al., 2009). Freshes can increase vertical connectivity between the streambed and the hyporheic zone by scouring and cleansing the riverbed (Hancock and Boulton, 2005), and can trigger spawning in some fish (King et al., 2009).

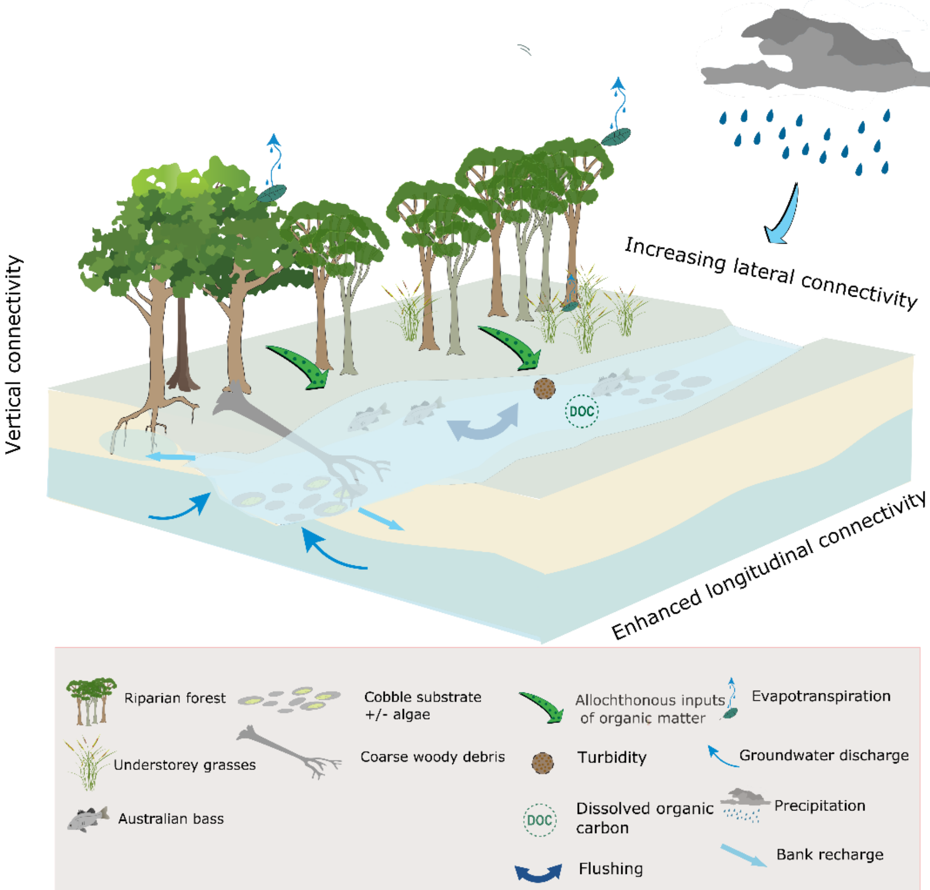

Figure 14 Conceptual model of streams during freshes

The longitudinal connectivity is enhanced when compared to the low-flow conceptual model (Figure 13).

High flows (Figure 15 and Figure 16) inundate specific habitats and can alter riverbed morphology (Robson et al., 2009). In the event of flooding, they can also reconnect floodplains to the rivers and streams, fill wetlands, improve the health of floodplain trees and trigger waterbird breeding (Robson et al., 2009). High flows are often categorised as 'wet season baseflows', 'bank-full flows' and 'overbank flows' (e.g. Robson et al., 2009). For consistency with terminology used by experts during elicitation workshops (see Section 2.7.3.2), the term 'overbench flow' is used here to represent both wet season baseflows and bank-full flows. A bench is a bank-attached, narrow, planar sediment deposit that develops between the riverbed and the floodplain.

Overbench flows partially or completely fill the channel for longer periods than freshes – typically weeks to months. Practically all habitats within the river channel will be wetted including boulders, logs, and lateral benches (if present), and the entire length of the channel is connected with relatively deep water, allowing movement of biota along the river (Department of Sustainability and Environment, 2003). As for freshes, some native fish species rely on seasonal high flows during winter and spring as cues to start migration and prepare for spawning (Department of Sustainability and Environment, 2003), such as the diadromous and potamodromous species listed in Section 2.7.3.1.1.

Increased flow rates, such as during bank-full flows, scour banks and river substrate, and increase erosion of banks. Bank erosion is accentuated under high discharge (bank-full condition), with the effectiveness of these erosional forces being a function of bank condition and the health of the riparian vegetation (Brierley and Fryirs, 2005), in addition to factors such as particle shape, density, packing and biological activity such as algal growth (Boulton et al., 2014). Bank slumping or undercutting can create new habitats and contribute additional coarse woody debris to streams. Logs, sticks and root masses in the channel create depositional areas for sediment and for particulate organic matter. Localised increases in velocity profiles around snags scour out pools or undercut banks that provide habitat for large fish and other organisms such as platypus (Boulton et al., 2014). Scouring of the benthic algal communities, often considered to be an important source of energy for higher trophic levels, can temporarily reduce stream primary production (Davie et al., 2012); however, benthic algal communities typically recover rapidly and many grazing macroinvertebrates feed preferentially on early-succession benthic algal taxa, whereas late-succession algae are less palatable or physically difficult to consume. High flow rates may also dislodge macrophytes and macroinvertebrates, resulting in population drift downstream (Downes and Lancaster, 2010).

Overbank flows (Figure 16) inundate the surrounding floodplains, providing lateral connectivity, fresh water, nutrients and particulate matter to floodplain wetlands. In the Gloucester subregion, the surrounding floodplains are extensively cleared for agriculture (companion product 1.1 for the Gloucester subregion (McVicar et al., 2014)). These high-flow events also tend to enhance vertical connectivity, providing a source of recharge for alluvial aquifers below the inundated floodplains (Doble et al., 2012) and recharge soil water reserves, which may promote seedling recruitment and maintain the health of the forested wetlands. However, Chalmers et al. (2009) also note that scouring of benches and bars can substantially increase seedling mortality. Connectivity to offstream wetlands, via overbank flows, enables replenishment of fresh water in these systems, and migration of riparian floodplain biota to and from the main channel. In some agricultural environments, these processes may lead to high loads of nutrients being imported to the stream environment, which may have deleterious effects on instream habitats through algal blooms (Boulton et al., 2014).

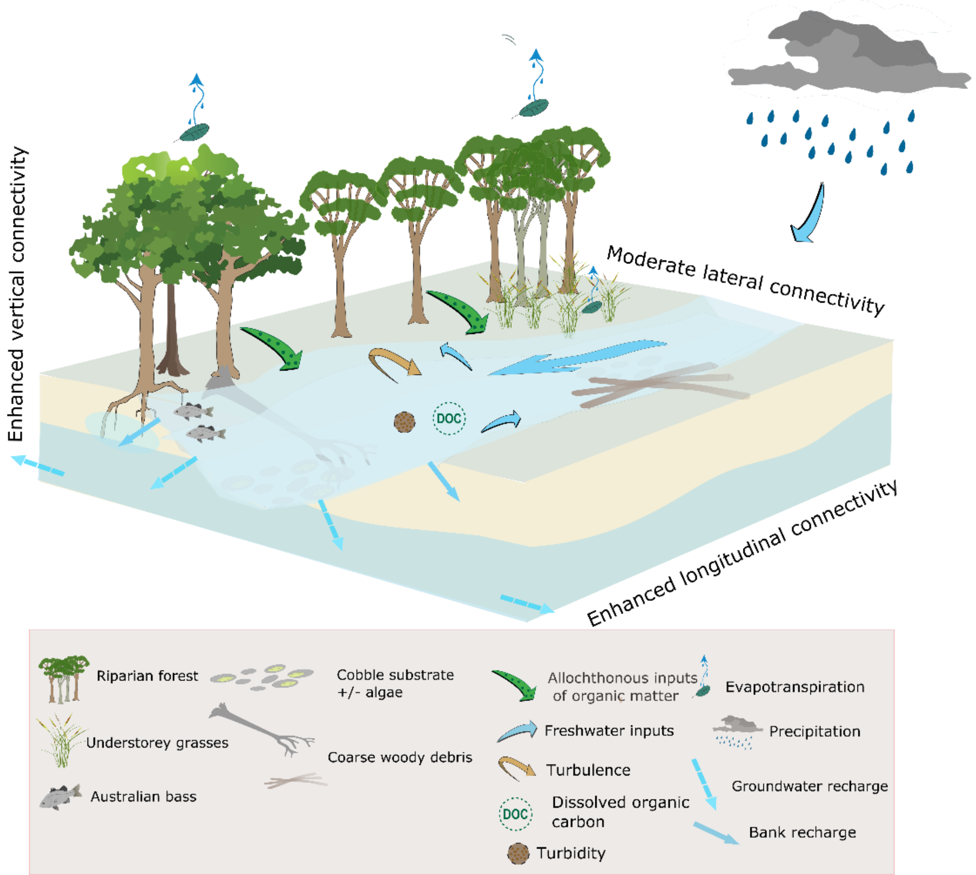

Figure 15 Conceptual model of streams during periods of overbench flow

Dashed arrow represents high uncertainty in relation to the flux. The enhanced connectivity is when compared to the freshes flow conceptual model (Figure 14).

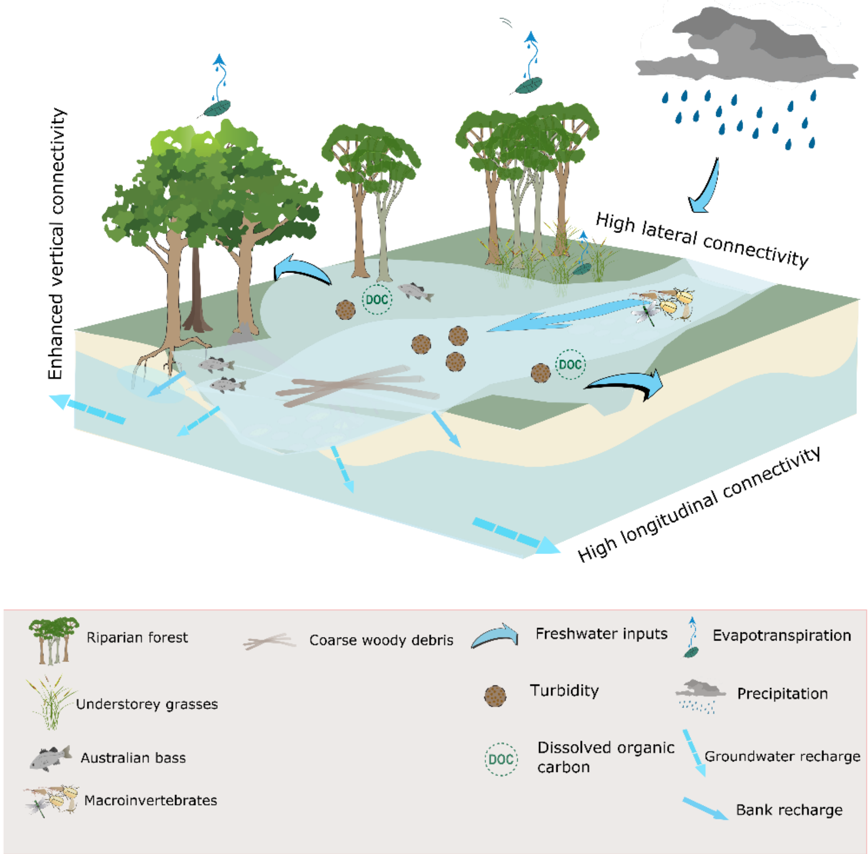

Figure 16 Conceptual model of streams during periods of overbank flow

The ‘high’ and ‘enhanced’ connectivity states are relative to the overbench flow conceptual model (Figure 15).

2.7.3.2 ‘Perennial – gravel/cobble streams’ landscape class

2.7.3.2.1 Qualitative mathematical model

The qualitative model for the reaches of the ‘Perennial – gravel/cobble streams’ landscape class (Figure 17) focuses on the riparian-dependent community, the dynamics of which are strongly influenced by stream hydrology. The model recognises that woody riparian vegetation provides a critical role in stabilising stream banks, and in supplying large woody debris to the stream channel. This debris forms key habitat elements for multiple species, as well as providing allochthonous inputs of organic matter that in turn drives production of various macroinvertebrate populations (Boulton et al., 2014). Seedlings of woody vegetation species have greater survival in the presence of stable stream banks, which is facilitated by the binding of stream bank sediments by roots of trees. Herbaceous vegetation, which includes both terrestrial and aquatic plants, also provides inputs of organic matter.

The model identifies stuttering frogs (*Mixophyes balbus*) as a riparian species of particular interest. The egg laying and egg maturation of these frogs depends on spring baseflows, and the tadpole life stage depends on habitat elements provided by large woody debris (NSW Scientific Committee, 2002). The nationally endangered regent honeyeater is also included in the model due to its dependency on woody riparian vegetation (i.e. river sheoaks) for nesting habitat (Catterall et al., 2007; TSSC, 2015).

Stream macroinvertebrates in the model are classified into three groups based on their affinity for different aspects of stream velocity and flow, namely still-water macroinvertebrates, which occupy pool habitats, and slow- and high-flow macroinvertebrates, which are both associated with fast-water habitats. The model includes two general groups of macroinvertebrate predators, differentiated by their mode of feeding. The benthic-feeding platypus consumes slow- and high-flow benthic macroinvertebrates (NSW Office of Environment and Heritage, 2014), while still-water macroinvertebrates are targeted by wading and diving birds (e.g. black bittern and kingfisher). The model also depicts fine sediment deposition as suppressing primary production and populations of the slow- and high-flow benthic macroinvertebrates. Recruitment of macroinvertebrate populations and woody riparian vegetation are both aided by delivery of propagules in flow from upstream reaches of the stream channel.

The model identifies three surface water flow regimes that regulate key physical and ecological processes in the riparian system (Figure 11). Overbench (and bank-full) flows, with return intervals of two to five times per year (flow regime 1), were described by the participants of the qualitative modelling workshop as being a key factor in primary production: the scouring flows they produce rejuvenate production of benthic algae and remove fine sediments from stream substrates (Brierley and Fryirs, 2005). These flows also provide a source of organic matter by transporting leaf-fall from riparian trees into the stream channel (Boulton et al., 2014). Overbench flows also increase survivorship of both adult and seedlings of woody riparian vegetation (Robson et al., 2009). The model identifies a second flow regime (flow regime 2) associated with overbank flows with a 2- to 5-year return interval. This regime is considered to be key in lateral transport of organic matter from the floodplain into the stream channel. Overbank flows also increase soil moisture of floodplain soils, which contributes to survivorship of woody riparian vegetation. Flow regimes 1 and 2 are depicted as having a positive influence on upstream recruitment.

The third flow regime (flow regime 3) describes the role of baseflow conditions being above very low or minimum levels, which is important for a variety of species, including stream macrophytes (herbaceous vegetation), high-flow macroinvertebrates, and the stuttering frog (for egg laying in spring), and for the survival of seedlings of woody riparian vegetation. As previously stated, cease-to-flow events can create chains of pools, isolated pools or completely dry riverbeds, depending on riverbed morphology (Robson et al., 2009). The flow regime also influences riffle habitats through changes in water quality and reduced habitat area, as riffles dry out and contract.

Accessible groundwater levels are identified in the model as being critical for survival of adult woody riparian vegetation. Finally, rainfall (precipitation) is identified as important for the survival of seedlings of woody riparian vegetation, particularly during periods of summer low flows.

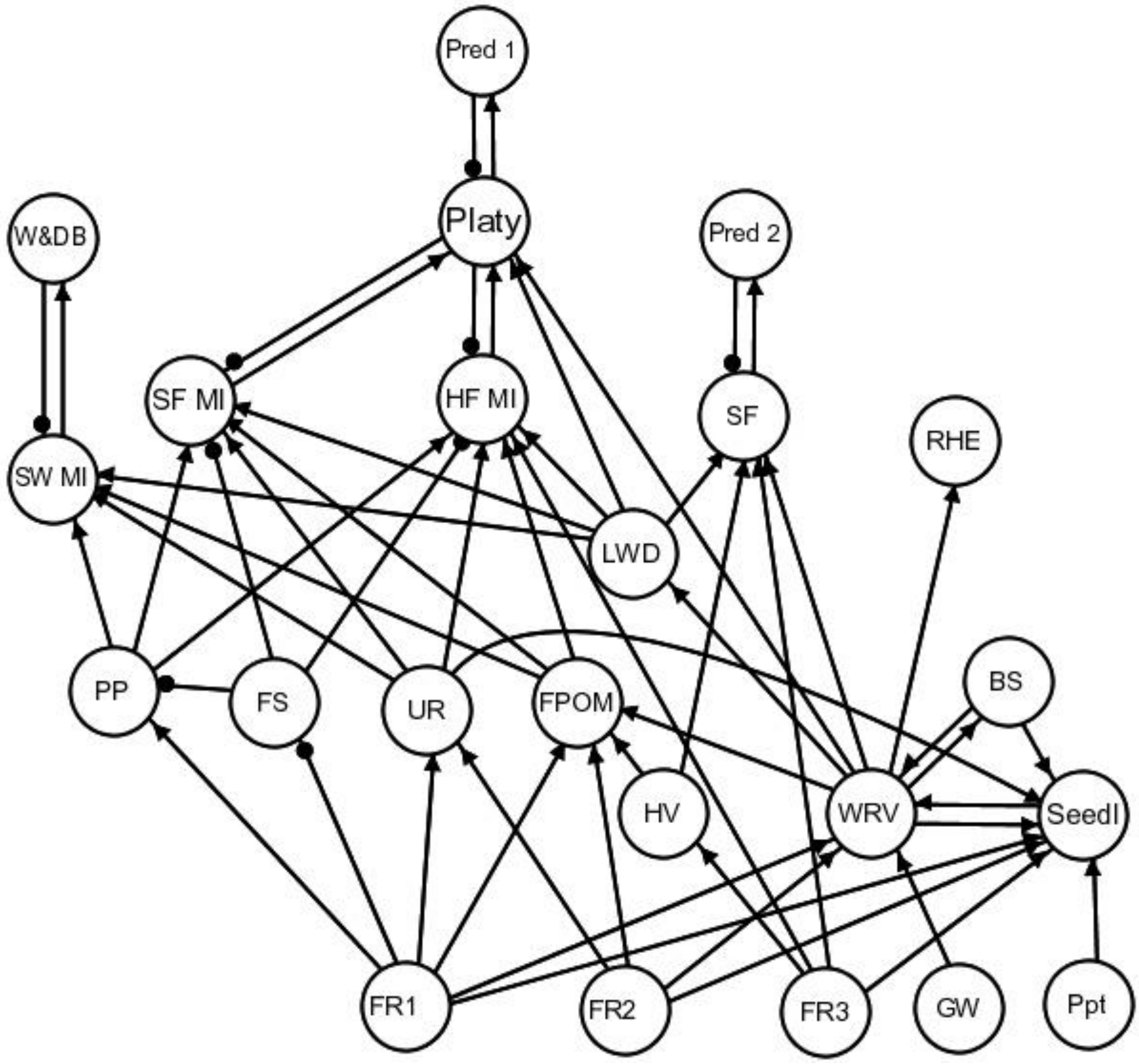

Figure 17 Signed digraph of riparian-dependent community in reaches in the 'Perennial – gravel/cobble streams' landscape class for the Gloucester subregion

Variables are: bank stability (BS), fine particulate organic matter (FPOM), fine sediments (FS), flow regimes (FR1, FR2 and FR3), groundwater (GW), high-flow macroinvertebrates (HF MI), herbaceous vegetation (includes aquatic macrophytes) (HV), large woody debris (LWD), platypus (Platy), primary production (PP), precipitation (Ppt), predators (Pred 1 and Pred 2), regent honeyeater (RHE), seedlings (Seedl), slow-flow macroinvertebrates (SF MI), stuttering frogs (SF), still-water macroinvertebrates (SW MI), upstream recruitment (Ur), wading and diving birds (W&DB), woody riparian vegetation (WRV).
Data: Bioregional Assessment Programme (Dataset 5)

Qualitative mathematical modelling enables bioregional assessments (BAs) to consider the potential for coal resource development to impact hydrological variables either individually or in a cumulative (combined) fashion (companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018)). Surface water and groundwater modelling predict significant potential impacts of coal mining to the three flow regimes and groundwater. Considering all combinations of plausible impacts suggests that there are 15 types of potential (some cumulative) impact scenarios that may occur in this landscape class due to individual or combined changes in the hydrological regimes identified in the model (Table 7).

Table 7 Summary of the cumulative impact scenarios for the riparian-dependent community in the 'Perennial – gravel/cobble streams' landscape class for the Gloucester subregion

Cumulative impact scenario	Flow regime 1	Flow regime 2	Flow regime 3	Groundwater
C1	0	–	0	–
C2	–	0	0	–
C3	–	–	0	–
C4	0	–	0	0
C5	–	0	0	0
C6	–	–	0	0
C7	0	0	0	–
C8	0	–	–	–
C9	–	0	–	–
C10	–	–	–	–
C11	0	–	–	0
C12	–	0	–	0
C13	–	–	–	0
C14	0	0	–	–
C15	0	0	–	0

Cumulative impact scenarios are determined by combinations of no change (0) or a decrease (–) in the following signed digraph variables: flow regime 1 (FR1), flow regime 2 (FR2), flow regime 3 (FR3) and depth to groundwater (GW). Scenario C10 shows the changes to these variables under the coal resource development pathway (CRDP).
Data: Bioregional Assessment Programme (Dataset 5)

Qualitative analysis of the signed digraph model (Figure 17) under each of the impact scenarios predicts a consistently negative response across virtually all the variables within the riparian-dependent community (Table 8). While some variables have a response prediction of zero for many or all of the scenarios (i.e. herbaceous vegetation), and fine sediments has a positive response prediction, all other variables are predicted to decline in their abundance, level or intensity with a relatively high level of sign determinacy.

Table 8 Predicted response of the signed digraph variables of the riparian-dependent community in the 'Perennial – gravel/cobble streams' landscape class to changes (some cumulative) in hydrological response variables for the Gloucester subregion

Signed digraph variable		Cumulative impact scenario														
Full name	Shortened form	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Platypus	Platy	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Predator	Pred	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Primary production	PP	0	–	–	0	–	–	0	0	–	–	0	–	–	0	0
Fine sediments	FS	0	+	+	0	+	+	0	0	+	+	0	+	+	0	0
Upstream recruitment	UR	–	–	–	–	–	–	0	–	–	–	–	–	–	0	0
Fine particulate organic matter	FPOM	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Large woody debris	LWD	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Woody riparian vegetation	WRV	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Herbaceous vegetation (includes aquatic macrophytes)	HV	0	0	0	0	0	0	0	–	–	–	–	–	–	–	–
Stuttering frogs	SF	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Predator 2	Pred 2	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Regent honeyeater	RHE	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
High-flow macroinvertebrates	HF MI	(–)	(–)	(–)	(–)	(–)	(–)	?	(–)	(–)	–	(–)	(–)	–	(–)	–
Slow-flow macroinvertebrates	SF MI	(–)	(–)	(–)	(–)	(–)	(–)	?	(–)	(–)	–	(–)	(–)	(–)	(–)	?
Still-water macroinvertebrates	SW MI	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Seedlings	Seedl	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Bank stability	BS	–	–	–	–	–	–	–	–	–	–	–	–	–	–	0
Wading and diving birds	W&DB	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–

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 a completely determined prediction of no change.
Data: Bioregional Assessment Programme (Dataset 5)

2.7.3.2.2 Temporal scope, hydrological response variables and receptor impact variables

In BAs, the potential ecological impacts of coal resource development are assessed in two future years – 2042 and 2102. These are labelled as the short- and long-assessment years, 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 that landscape class 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 (companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)).

For surface water and groundwater variables in the Gloucester subregion, the reference assessment interval is defined as the 30 years preceding and including 2012 (i.e. 1983 to 2012). For surface water variables in the Gloucester subregion, the short-assessment interval is defined as the 30 years preceding the short-assessment year (i.e. 2013 to 2042), and the long-assessment interval is defined as the 30 years that precede the long-assessment year (i.e. 2073 to 2102). For groundwater, maximum drawdown (metres) and time to maximum drawdown are considered across the full 90-year window: 2013 to 2102.

In BAs, choices about receptor impact variables must balance the project's time and resource 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 perennial gravel/cobble streams, the qualitative modelling workshop identified five variables – three flow regimes, groundwater and precipitation – as the hydrological factors that were thought to: (i) be instrumental in maintaining and shaping the ecosystem and/or, (ii) have the potential to change due to coal resource development (Figure 17). All of the ecological components and processes represented in the qualitative model are potential receptor impact variables and all of these, with the exception of upstream recruitment, are predicted to vary as the hydrological factors vary either individually or in combination (Table 8).

Following advice received from participants during (and after) the qualitative modelling workshop, and guided by the availability of experts for the receptor impact modelling workshop, the scope of the BA numerical modelling and the receptor impact variable selection criteria (see Section 2.7.1.2.3), the receptor impact models focused on the following relationships:

1. The response of the woody riparian vegetation (WRV) to changes in flow regime 1 (FR1), flow regime 2 (FR2) and depth to groundwater (GW).
2. The response of high-flow macroinvertebrates (HF MI) to changes in flow regime 3 (FR3).
3. The response of predators (Pred 2) to changes in flow regime 3 (FR3).

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 'Perennial – gravel/cobble streams' landscape class are summarised in Table 9. The precise definition of each receptor impact variable, typically a species or group of species represented by a qualitative model node, was determined during the receptor impact modelling workshop and satisfy the generic criteria set out in 2.7.1.2.3.

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 three receptor impact models (Table 10).

Table 9 Summary of the hydrological response variables used in the receptor impact models, together with the signed digraph variables that they correspond to, for the 'Perennial – gravel/cobble streams' landscape class in the Gloucester subregion

Hydrological response variable	Definition of hydrological response variable	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)	GW
tmaxRef	The year that the maximum difference in drawdown relative to the reference period (1983 to 2012) (dmaxRef) occurs.	GW
EventsR0.3	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 0.3 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 overbench flow events in future 30-year periods. This is typically reported as the maxmum change due to additional coal resource development.	FR1
EventsR3.0	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 3.0 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 maxmum change due to additional coal resource development.	FR2
ZQD	The number of zero-flow days per year, averaged over a 30-year period. This is typically reported as the maxmum change due to additional coal resource development.	FR3
QBFI	Ratio of total baseflow generation to total streamflow generation, averaged over a 30-year period. This is typically reported as the maxmum change due to additional coal resource development.	FR3

FR1 = flow regime 1, FR2 = flow regime 2, FR3 = flow regime 3, GW = groundwater, ZQD = zero-flow days (averaged over 30 years)

Table 10 Summary of the three receptor impact models developed for the 'Perennial – gravel/cobble streams' landscape class in the Gloucester subregion

Relationship being modelled	Receptor impact variable (with associated sample units)	Hydrological response variables
Response of the woody riparian vegetation to changes in flow regime 1, flow regime 2 and groundwater	Annual mean percent canopy cover of woody riparian vegetation (predominately *Casuarina cunninghamiana, Melia azedarach, Eucalyptus amplifolia, E. tereticornis* and *Angophora subvelutina*) in a transect 20 m wide and 100 m long covering the bottom of the stream bench to the high bank	dmaxRef tmaxRef EventsR0.3 EventsR3.0
Response of high-flow macroinvertebrates to changes in flow regime 3	Mean density of larvae of the family Hydropsychidae (net-spinning caddisflies) in a 1 m^2 sample of riffle habitat	ZQD
Response of predators to changes in flow regime 3	Mean density of the eel-tailed catfish (*Tandanus tandanus*) in a 600 m^2 transect (100 m by 6 m) whose long axis lies along the mid-point of the stream	ZQD QBFI

Hydrological response variables are defined in Table 9. ZQD = zero-flow days (averaged over 30 years), QBFI = baseflow index, as defined in Table 9

2.7.3.2.3 Receptor impact models

2.7.3.2.3.1 Canopy cover of woody riparian vegetation

Table 11 summarises the elicitation design matrix for the mean percent canopy cover of woody riparian vegetation in the 'Perennial – gravel/cobble streams' landscape class. Each row of the design matrix is a separate elicitation scenario defined by a unique combination of hydrological response variable values. Experts are asked to predict the values of the receptor impact variable in the landscape class under each of these scenarios (companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)). The first six design points – design point identifiers 8, 1, 3, 6, 9 and 7 – address the predicted variability (across the perennial streams in the landscape class during the reference interval) in the overbench (R0.3) and overbank (R3.0) flows that define floods with a return interval of 3.3 events and 0.33 events per year, respectively. The design points 9, 7, 3, and 1 capture the combination of the extremes of each hydrological response variable, whilst design points 6 and 8 capture intermediate points in each hydrological response variable axis. 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.

The first six design points provide for an estimate of the uncertainty in mean percent canopy cover across the landscape class in the reference year 2012 (Yref). 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- (2042) and long- (2102) assessment years.

Table 11 Elicitation design matrix for the receptor impact model of mean percent canopy cover in the riparian-dependent community in the 'Perennial – gravel/cobble streams' landscape class in the Gloucester subregion

Design point identifier	Hydrological response variable						Yref	Year
	R0.3 (ML/d)	R3.0 (ML/d)	dmaxRef (m)	tmaxRef (year)	EventsR0.3 (events/yr)	EventsR3.0 (events/yr)		
8	5500	35,000	0.0	0	3.3	0.33	na	2012
1	2000	10,000	0.0	0	3.3	0.33	na	2012
3	9000	10,000	0.0	0	3.3	0.33	na	2012
6	9000	22,500	0.0	0	3.3	0.33	na	2012
9	9000	35,000	0.0	0	3.3	0.33	na	2012
7	2000	35,000	0.0	0	3.3	0.33	na	2012
72	na	na	6.0	2102	4.0	0.34	0.3	2042
93	na	na	6.0	2019	4.0	0.23	0.6	2042
134	na	na	1.7	2102	4.6	0.29	0.6	2042
100	na	na	0.0	2019	4.6	0.23	0.6	2042
159	na	na	6.0	2060	4.6	0.34	0.6	2042
58	na	na	0.0	2060	3.3	0.34	0.3	2042
57	na	na	6.0	2019	3.3	0.34	0.3	2042
9	na	na	6.0	2102	3.3	0.23	0.3	2042
210	na	na	6.0	2019	4.6	0.29	0.3	2102
276	na	na	6.0	2060	3.3	0.29	0.6	2102
305	na	na	1.7	2102	3.3	0.34	0.6	2102
250	na	na	0.0	2102	3.3	0.23	0.6	2102
163	na	na	0.0	2019	3.3	0.23	0.3	2102
307	na	na	0.0	2019	4.0	0.34	0.6	2102
241	na	na	0.0	2102	4.6	0.34	0.3	2102
270	na	na	6.0	2102	4.6	0.23	0.6	2102
176	na	na	1.7	2060	4.0	0.23	0.3	2102

The elicitation scenarios allow for the possibility that the response of Y(short) or Y(long) may be conditional on Y(ref). To do this the elicitation scenarios for the short- and long-assessment years take a representative set of values of Y(ref) – calculated from the elicitations conducted for scenarios in the reference year – and use these in the elicitation scenarios for the short- and long-assessment years. All other design points are either default values or values determined by groundwater and surface water modelling. See Table 9 for definitions of hydrological response variables. na = not applicable
Data: Bioregional Assessment Programme (Dataset 5)

Design point identifiers 72 through to 176 (as listed in Table 11) represent combinations of the four hydrological response variables (dmaxRef, tmaxRef, EventsR0.3 and EventsR3.0), together with high and low values of Yref, that respect certain logical constraints; for example, the number of overbank flood events (EventsR3.0) cannot be greater than the number of overbench flood events (EventsR0.3) (companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et. al., 2018)). The high and low values for Yref were calculated during the receptor impact modelling workshop following the experts' response to the first six design points, and then automatically included within the design for the elicitations at the subsequent design points.

The receptor impact modelling methodology allows for a very flexible class of statistical models to be fitted to the values of the receptor impact variables elicited from the experts at each of the design points (companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)). The model fitted to the elicited values of mean percent canopy cover for the 'Perennial – gravel/cobble streams' landscape class is summarised in Figure 18 and Table 12. The fitted model takes the form:

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

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 represent 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 $x_{h_j}, j = 1 \dots 4$ are the (continuous or integer) values of the four hydrological response variables (dmaxRef, tmaxRef, EventsR0.3 and EventsR3.0). Note that the modelling framework provides for more complex models, including quadratic value of, and in 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 finds the parameters of this distribution conditional on the data (the elicited expert opinion) for a number of different models, and then selects the most parsimonious model using a common information criterion (companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018) – in this case a simple linear model. Table 12 summarises the estimated mean and 80% credible interval of the eight model coefficients. Figure 18 shows the resulting model predictions for the (marginal) mean and 80% central credible intervals[1] of the four hydrological response variable.

The model indicates that the experts' opinion provides strong evidence for Yref having a positive effect on mean percent canopy cover. This suggests that given a set of hydrological response variable values in the future, a site with a higher mean percent canopy cover at the 2012 reference point is more likely to have a higher mean percent canopy cover in the future than a site with a

[1] A central credible interval is the region in the centre of a posterior or prior distribution that contains a specified amount of the probability of the distribution, such that there is equal probability above and below the interval. Hence, an 80% central credible interval is defined as the range of values with posterior (or prior) probability (1 – 0.8)/2 above and below the interval.

lower mean percent canopy cover value at this time point. This reflects the lag in the response of mean percent canopy cover to changes in hydrological response variables that would be expected of mature trees with long life spans and is relevant to both the short- and long-assessment periods.

The model also indicates that the experts’ opinion provides strong evidence for dmaxRef having a negative effect on mean percent canopy cover. This suggests that mean percent canopy cover will 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 mean percent canopy cover will drop from just under 50% without any change in groundwater level, to about 35% if the levels decease by 6 m relative to the reference level in 2012. There is, however, considerable uncertainty in these predictions, with an 80% chance that the mean percent canopy cover will lie somewhere between approximately 60% and 20% in the short-assessment period, and somewhere between roughly 62% and 17% in the long-assessment period, with a 6 m drop in groundwater level.

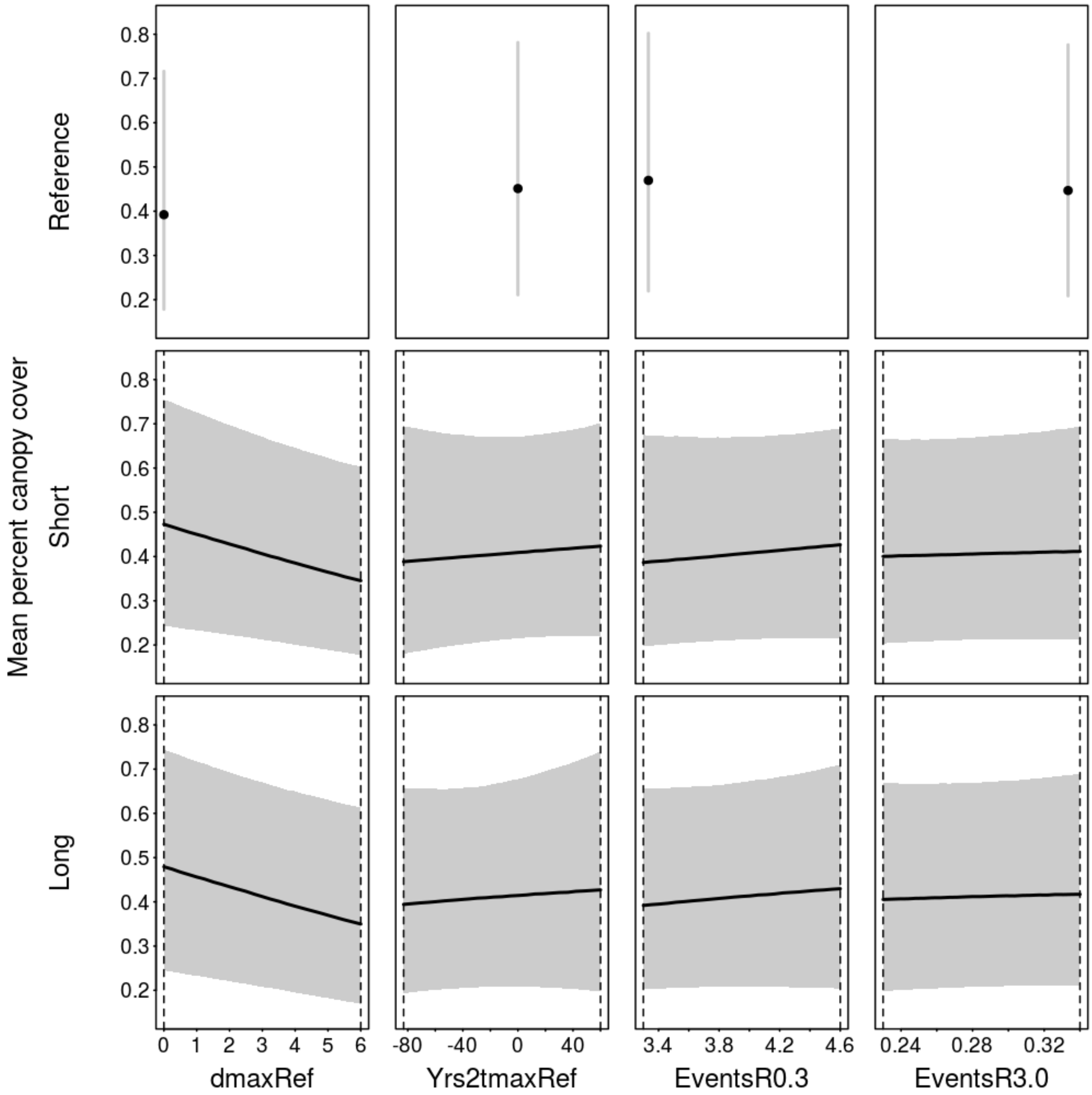

Figure 18 (Top row) Predicted mean (black dot) and 80% central credible interval (grey line) of mean percent canopy cover under reference hydrological conditions; (middle and bottom rows) predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on mean percent canopy cover for the Gloucester subregion

In middle and bottom rows, the uncertainty in mean percent canopy cover in the reference year was integrated out, holding all other hydrological response variables constant at the mid-point of their elicitation range (during risk estimation all hydrological response variables vary simultaneously). Dashed vertical lines show the range of hydrological response variables used in the elicitation. Yrs2tmaxRef is the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102). See Table 9 for definitions of hydrological response variables. 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 5)

Table 12 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for mean percent canopy cover in the riparian-dependent community in the 'Perennial – gravel/cobble streams' landscape class for the Gloucester subregion

	Mean	10th percentile	90th percentile
(Intercept)	–0.908	–2.72	0.905
future1	0.421	–0.64	1.48
long1	0.00204	–0.452	0.456
Yref	0.783	0.363	1.2
dmaxRef	–0.0666	–0.132	–0.00099
Yrs2tmaxRef	0.000818	–0.00397	0.0056
EventsR0.3	0.0747	–0.266	0.415
EventsR3.0	0.473	–3	3.95

Yref is value of receptor impact variable in the reference year; set to zero if the design point is in the reference assessment year. Future is a binary variable scored 1 if the design point is in a short- or long-assessment year. Long is a binary variable scored 1 if the design point is in the long-assessment year. dmaxRef, EventsR0.3 and EventsR3.0 are as defined in Table 9. Yrs2tmaxRef is the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102). These coefficients show, on the transformed scale, the change in the expected value of the receptor impact variable for a unit change in their associated hydrological response variable, ignoring the effect of all other hydrological response variables. This effect cannot be directly interpreted, however, without first fixing all other hydrological response variables to a specific value and second applying the inverse of the model link function.
Data: Bioregional Assessment Programme (Dataset 5)

The fitted model suggests that the evidence for the effect of EventsR0.3 in the experts' responses is weaker than for the other hydrological response variables discussed above. The 80% credible interval for this hydrological response variable's coefficient spans zero, whereas the 80% central credible interval of Yref and dmaxRef lie wholly within the positive or negative parts of the real line (Table 12). Nonetheless, if all other hydrological response variables are held at the mid-point of their elicitation range, the model suggests that an increase in the frequency of overbench flows will have a relatively small positive effect on mean percent canopy cover – the predicted slight increase in the average frequency of overbench flood events, from 3.3 (by definition) in the 30 years preceding the reference year, to a maximum average value of 4.6 over the future period, causes the mean percent canopy cover to increase by about 5%. However, the large uncertainty reflected in the 80% credible intervals in Figure 18 does not preclude the small possibility of EventsR0.3 having a negligible effect on mean percent canopy cover.

The summary statistics for the marginal distribution of the model coefficients (Table 12) and the partial regression plots (Figure 18) for all of the other model coefficients indicate that there is insufficient information in the expert-elicited data to determine the effects of the future coefficient, the long coefficient and the coefficients for Yrs2tmaxRef and EventsR3.0. This situation is indicated by relatively large positive (negative) 10th and negative (positive) 90th percentiles in Table 12, parallel slopes in the short and long partial regression plots in Figure 18, and the almost-zero mean (flat slope) of the coefficients for Yrs2tmaxRef and EventsR3.0 in Table 12. With the exception of the last two variables, these results are not surprising as they suggest that the variation in the elicited values of the receptor impact variable can be adequately described by the other hydrological response variables. For Yrs2tmaxRef and EventsR3.0, however, this indicates that either the experts believe that the effect of the rate of groundwater drawdown and overbank floods is very weak compared to that of the other hydrological response variables or that there was insufficient information in the elicited values to adequately quantify the effect of these variables.

2.7.3.2.3.2 Density of Hydropsychidae larvae

Table 13 summarises the elicitation matrix for the density of Hydropsychidae larvae. The first four design points – design point identifiers 8, 1, 6 and 999 – address the predicted variability (across the landscape class in the reference interval) in ZQD, capturing the lowest and highest predicted values together with two intermediate values. These design points provide for an estimate of the uncertainty in Hydropsychidae larval density across the landscape class in the reference year 2012 (Yref).

Design points 16 to 21 inclusive (as listed in Table 13) represent scenarios that span the uncertainty in the predicted values of ZQD in the relevant time period of hydrological history associated with the short- (2042) and long- (2102) assessment years, combined with high and low values of Yref. Again, the high and low values for Yref were calculated during the receptor impact modelling workshop.

The fitted model for Hydropsychidae larval density takes the form:

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \beta_{h_1} x_{h_1} \quad (2)$$

where the terms x_0, x_f, x_l and x_r are as before and x_{h_1} is the integer value of ZQD. The (marginal) mean and 80% central credible interval of the coefficient for this hydrological response variable are summarised in the partial regression plots in Figure 19, whilst Table 14 summarises the same information for all five model coefficients.

Unlike the previous model, the hydrological response variable in the Hydropsychidae model varies during the reference interval and the future interval. The model indicates that the experts’ elicited information strongly supports the hypothesis that an increase in ZQD will have a negative effect on the density of Hydropsychidae larvae despite the experts being quite uncertain about its average value. The model suggests that larval density can vary substantially across the landscape class from less than 100 per m^2 to almost 1000 per m^2 under conditions of constant flow (ZQD = 0), holding all other covariates at their mid-values. As the number of zero-flow days (averaged over 30 years) (ZQD, subsequently referred to in this Section as ‘zero-flow days’) increases, however, experts were of the opinion that larval density would drop quite dramatically with values of less than 1 per m^2 falling within the 80% credible interval under very intermittent flow conditions (ZQD >200 days) (Figure 19).

There was very little evidence in the elicited data to suggest that this effect would be substantially different in the future assessment years. Again, this is indicated by the almost identical partial regression plots in the reference, short- and long-assessment years (Figure 19), and the relatively large negative 10th and positive 90th percentiles for the long and future coefficients in Table 14.

The model does, however, suggest that the experts' uncertainty increased for predictions in the future assessment years relative to the reference year.

Table 13 Elicitation design matrix for the receptor impact model of the mean density of Hydropsychidae larvae in the 'Perennial – gravel/cobble streams' landscape class for the Gloucester subregion

Design point identifier	Hydrological response variable	Yref	Year
	ZQD (days/year)		
8	90.00	na	2012
1	0.00	na	2012
6	45.00	na	2012
999	232.57	na	2012
16	40.00	240	2042
15	20.00	240	2042
8	40.00	36	2042
1	0.00	36	2042
22	20.00	36	2102
36	40.00	240	2102
29	0.00	240	2102
21	0.00	36	2102

The elicitation scenarios allow for the possibility that the response of Y(short) or Y(long) may be conditional on Y(ref). To do this the elicitation scenarios for the short- and long-assessment years take a representative set of values of Y(ref) – calculated from the elicitations conducted for scenarios in the reference year – and use these in the elicitation scenarios for the short- and long-assessment yearsAll other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling.
na = not applicable, ZQD = zero-flow days (averaged over 30 years)
Data: Bioregional Assessment Programme (Dataset 5)

Another notable difference between this model and the previous model is the estimated values for the Yref coefficient. In the canopy cover model there was strong evidence within the experts' elicited values that mean percent canopy cover in the reference year had a positive influence on the values in the future assessment years ($\beta_r > 0$). The best-fitting model in this case, however, is unable to eliminate the possibility that the average density of Hydropsychidae larvae in the reference years has no influence on its density in the future years. This is indicated by the fact that $\beta_r = 0$ is close to the 50th percentile of its induced prior (Table 14). This suggestion is consistent with the hypothesis that there is likely to be very little lag in the response of this short-lived species to changes in the hydrological response variables.

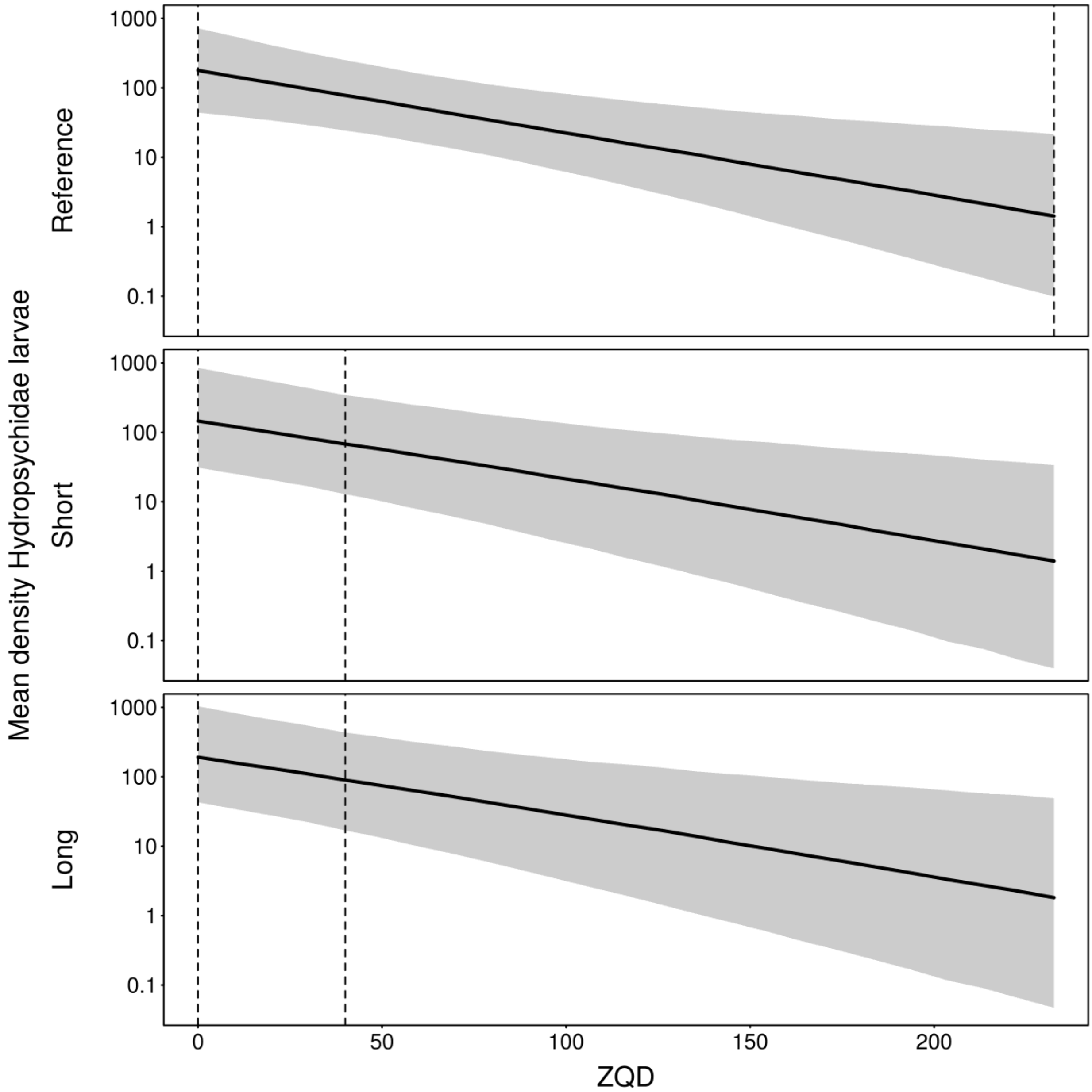

Figure 19 (Top row) Predicted mean (black line) and 80% central credible interval (grey polygon) of mean density of Hydropsychidae larvae in the 'Perennial – gravel/cobble streams' landscape class under reference hydrological conditions; (middle and bottom rows) predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on mean density of Hydropsychidae larvae for the Gloucester subregion

In middle and bottom rows, all other hydrological response variables are held constant at the mid-point of their elicitation range (during risk estimation all hydrological response variables vary simultaneously). Dashed vertical lines show range of hydrological response variables used in the elicitation. ZQD = zero-flow days (averaged over 30 years). Note that the apparent extrapolation of the relationship beyond the elicitation range reflects the preliminary hydrological model output for the reference period where there was a high maximum number of zero-flow days. In future periods the [preliminary] hydrological modelling indicated that the maximum number of zero-flow days is around 40. Extrapolation beyond 40 zero-flow days in the future periods is visualised here for comparison with the reference period prediction. (Note that the apparent extrapolation of the relationship beyond the elicitation range reflects the preliminary hydrological model output for the reference period which showed a high maximum number of zero-flow days.)
Data: Bioregional Assessment Programme (Dataset 5)

Table 14 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for the mean density of Hydropsychidae larvae in the riparian-dependent community in the ‘Perennial – gravel/cobble streams’ landscape class for the Gloucester subregion

	Mean	10th percentile	90th percentile
(Intercept)	5.18	3.79	6.58
future1	0.279	–3.32	3.88
long1	0.263	–1.08	1.61
Yref	–0.139	–0.849	0.571
ZQD	–0.0207	–0.0347	–0.00671

Yref is value of receptor impact variable in the reference assessment year; set to zero if case is in the reference assessment year. Long is a binary variable scored 1 if the design point is in the long-assessment year. Future is a binary variable scored 1 if the design point is in a short- or long-assessment year. ZQD = zero-flow days (averaged over 30 years)
Data: Bioregional Assessment Programme (Dataset 5)

*2.7.3.2.3.3 Density of eel-tailed catfish (*Tandanus tandanus*)*

The elicitation scenarios for the average density of the eel-tailed catfish (*Tandanus tandanus*) are summarised in Table 15. This elicitation proved to be similar to that for the Hydropsychidae larvae. Although Yref, QBFI and ZQD were considered in the elicitation design, only ZQD was subsequently determined to be predictive of the density of eel-tailed catfish in the future assessment years (see below).

The elicitation scenarios were again chosen to enable the model to estimate the uncertainty in the average density of the eel-tailed catfish in the reference year 2012 (design point identifiers 8 to 7 inclusive as shown in Table 15). Thereafter into the future assessment years, the design points reflect high, medium and low values of the two hydrological response variables (ZQD and QBFI), in combination with high and low values of average density in 2012.

The best-fitting model for the average density of the eel-tailed catfish takes the form:

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

where the terms x_0, x_f, x_l and x_r are as before, x_{h_1} is the integer value of ZQD, and x_{h_2} is the continuous value of QBFI. The (marginal) mean and 80% central credible interval of the coefficient for the two hydrological response variables are summarised in the partial regression plots in Figure 20, whilst Table 16 summarises the same information for all six model coefficients.

Table 15 Elicitation design matrix for the receptor impact model of the density of eel-tailed catfish (*Tandanus tandanus*) in the 'Perennial – gravel/cobble streams' landscape class for the Gloucester subregion

Design point identifier	Hydrological response variable		Yref	Year
	QBFI (ratio)	ZQD (days/year)		
8	0.33	90	na	2012
1	0.14	0	na	2012
3	0.52	0	na	2012
6	0.52	45	na	2012
9	0.52	90	na	2012
7	0.14	90	na	2012
16	0.16	40	8.50	2042
15	0.57	20	8.50	2042
8	0.36	40	0.35	2042
1	0.16	0	0.35	2042
22	0.16	20	0.35	2102
36	0.57	40	8.50	2102
29	0.36	0	8.50	2102
21	0.57	0	0.35	2102

The elicitation scenarios allow for the possibility that the response of Y(short) or Y(long) may be conditional on Y(ref). To do this the elicitation scenarios for the short- and long-assessment years take a representative set of values of Y(ref) – calculated from the elicitations conducted for scenarios in the reference year – and use these in the elicitation scenarios for the short- and long-assessment years. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling.
na = not applicable, QBFI = baseflow index as described in Table 9, ZQD = zero-flow days (averaged over 30 years)
Data: Bioregional Assessment Programme (Dataset 5)

In this model ZQD again varies in the reference year, and the experts' elicited values for this assessment year provide some evidence that average density of the catfish will decline as ZQD increases, from about 5 individuals per 600 m^2 transect under continuous flow (ZQD = zero), holding all other covariates at their mid-values, decreasing to less than 1 individual in two transects as flow becomes more intermittent (ZQD >80 days). Again, however, there is considerable uncertainty in these predictions, and the 80% credible interval does not preclude the possibility of this variable having no further effect on the average denstity of catfish once ZQD increases beyond days.

There was insufficient information in the experts' elicited response to exclude the possibility that QBFI has no effect on the average density of eel-tailed catfish. This is indicated by the horizontal partial regression plots for QBFI in Figure 20, and the large negative 10th percentile and large positive 90th percentile, with a mean very close to zero, in Table 16. The best-fitting model also does not exclude the possibility that all other covariates, including Yref, have no effect on the average density of the catfish. This again suggests that the experts' response indicates that the catfish is sufficiently short-lived (generally less than 8 years) such that the experts did not anticipate any significant lag (>30 years) in its response to declines in ZQD.

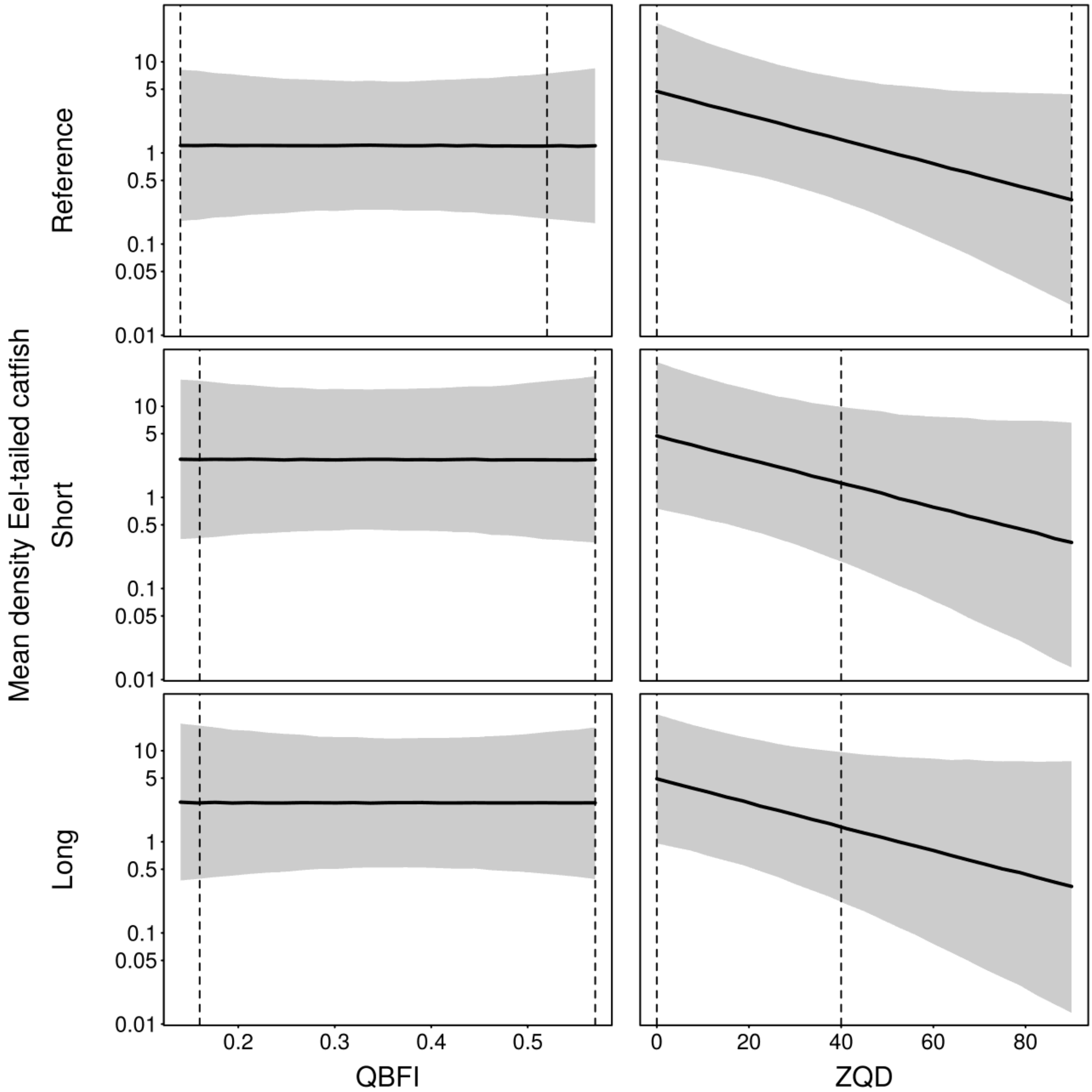

Figure 20 (Top row) Predicted mean (black line) and 80% central credible interval (grey polygon) of density of eel-tailed catfish (*Tandanus tandanus*) under reference hydrological conditions; (middle and bottom rows) predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on the mean density of eel-tailed catfish (*Tandanus tandanus*) for the Gloucester subregion

In middle and bottom rows, all other hydrological response variables are held constant at the mid-point of their elicitation range (during risk estimation all hydrological response variables vary simultaneously). Dashed vertical lines show range of hydrological response variables used in the elicitation. QBFI = index of baseflow as described in Table 9, ZQD = zero-flow days (averaged over 30 years)

Data: Bioregional Assessment Programme (Dataset 5)

Table 16 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for the mean density of eel-tailed catfish (*Tandanus tandanus*) in the 'Perennial – gravel/cobble streams' landscape class for the Gloucester subregion

	Mean	10th percentile	90th percentile
(Intercept)	1.57	–0.87	4.01
future1	l0.0203	–2.19	2.23
long1	0.0333	–2.07	2.14
Yref	–0.00764	–0.714	0.699
QBFI	–0.044	–5	4.91
ZQD	–0.0305	–0.065	0.00409

Yref is value of receptor impact variable in the reference assessment year; set to zero if case is in the reference assessment year. Long is a binary variable scored 1 if the design point is in the long-assessment year. Future is a binary variable scored 1 if the design point is in a short- or long-assessment year. QBFI is the ratio of total baseflow generation to total streamflow generation, averaged over a 30-year period. ZQD = zero-flow days (averaged over 30 years)
Data: Bioregional Assessment Programme (Dataset 5)

2.7.3.3 'Intermittent – gravel/cobble streams' landscape class

2.7.3.3.1 Qualitative mathematical model

The signed digraph for the qualitative mathematical model of intermittent gravel/cobble streams (Figure 21) combines a subset of the components and processes identified in the model for perennial gravel/cobble stream reaches and pools with ecological and environmental features expected to characterise refugia in intermittent streams. The model is based primarily on no-flow conditions, when the isolated pools are separated by dry reaches of stream channel. This essentially eliminates the fast-water habitat units from the system at this time, along with slow- and high-flow macroinvertebrates, which are both associated with this habitat type (Chessman et al., 2012). The model also removes groups that depend on these macroinvertebrate communities (i.e. their predators and platypus).

Pool habitat is included in the model because of its importance in providing pool refugia for fishes. These pools are maintained by groundwater and periodically replenished with surface flow. The model identifies two fish groups that are especially dependent on these pools, namely gudgeon and other small native fishes, and catfish. The eel-tailed catfish (*Tandanus tandanus*) is non-migratory and, although it lives in a wide range of habitats, it prefers sluggish or still waters (Fisheries Scientific Committee, 2008). Amphibians and reptiles also depend on pool habitats and components associated with riparian vegetation, such as large woody debris, woody riparian vegetation and herbaceous vegetation (Catterall et al., 2007). The model notes that the biomass of amphibians, gudgeon and other native fishes can be impacted by predators including the introduced mosquito fish *Gambusia holbrooki* (Pyke, 2008). Similarly, carp (*Cyprinus carpio*) are depicted as having a negative effect on catfish recruitment through egg predation (Koehn et al., 2000). Submerged macrophytes act in the model as an important flowing-water habitat feature that supports recruitment of native fishes, and also predators that migrate into wetted stream reaches (e.g. eels, bass and avian predators), and then regulate populations of native fishes (Robson et al., 2009). This variable, however, and others marked with an asterisk in Figure 21 are only present or activated during flowing-water conditions (Figure 11).

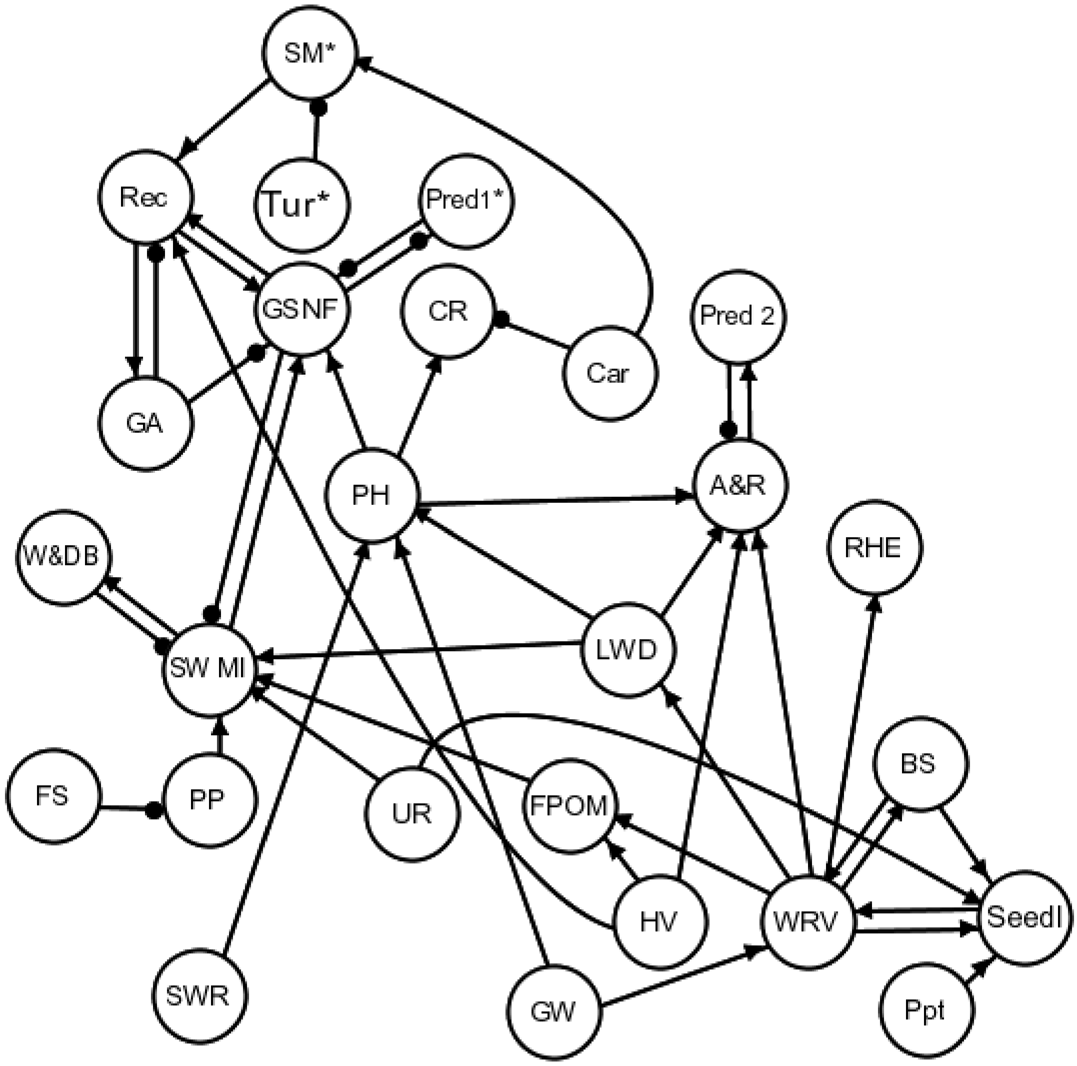

Figure 21 Signed digraph of the riparian-dependent community in the 'Intermittent – gravel/cobble streams' landscape class for the Gloucester subregion

Variables are: amphibians & reptiles (A&R), bank stability (BS), carp (car), catfish recruitment (CR), fine particulate organic matter (FPOM), fine sediments (FS), *Gambusia holbrooki* (GA), gudgeon and small native fishes (GSNF), groundwater (GW), herbaceous vegetation (includes emergent aquatic macrophytes) (HV), large woody debris (LWD), pool habitat (PH), primary production (PP), precipitation (Ppt), predators (Pred 1 and Pred 2), recruitment (Rec), regent honeyeater (RHE), seedlings (Seedl), submerged macrophytes (SM), still-water macroinvertebrates (SW MI), surface water replenishment (SWR), turbidity (Tur), upstream recruitment (UR), wading and diving birds (W&DB), and woody riparian vegetation (WRV). Asterisks denote variables present during flowing-water conditions.
Data: Bioregional Assessment Programme (Dataset 5)

An analysis of plausible impacts due to coal resource development, suggests that there are three potential impact scenarios that may occur in this landscape class due to individual or combined changes in the hydrological regimes identified in the model (Table 17).

Table 17 Summary of the cumulative impact scenarios for the riparian-dependent community in the 'Intermittent – gravel/cobble streams' landscape class for the Gloucester subregion

Cumulative impact scenario	Surface water replenishment	Groundwater
C1	–	–
C2	0	–
C3	–	0

Cumulative impact scenarios are determined by combinations of no change (0) or a decrease (–) in the following signed digraph variables: surface water replenishment (SWR) and depth to groundwater (GW). Scenario C3 shows the changes to these variables under the coal resource development pathway (CRDP).
Data: Bioregional Assessment Programme (Dataset 5)

Qualitative analysis of the signed digraph (Figure 21) generally gives predictions for a negative or zero (no change) response for many of the variables across the three cumulative impact scenarios (Table 18). Scenarios involving a decrease in groundwater (C1 and C2), lead to a predicted decrease in the woody riparian vegetation, large woody debris, bank stability and fine particulate organic matter, which accordingly results in a predicted decrease in quality of pool habitat, and densities of amphibians and reptiles. Flow-on effects also include a predicted decrease in native fish recruitment and population density and also a decrease in catfish recruitment. The predicted response to still-water macroinvertebrates, however, is ambiguous in these two scenarios due to both a diminishment of benefits provided by woody riparian vegetation (via large woody debris and fine particulate organic matter) and a release from native fish predation. In the scenario involving only impacts to surface water replenishment (C3), there are no predicted impacts to woody riparian vegetation, and the release from predation is predicted to cause an increase in still-water macroinvertebrates as well as their wading-bird predators.

Table 18 Predicted response of the signed digraph variables of the riparian-dependent community in the ‘Intermittent – gravel/cobble streams’ landscape class to cumulative changes in hydrological response variables for the Gloucester subregion

Signed digraph variable		Cumulative impact scenario		
Full name	**Shortened form**	**C1**	**C2**	**C3**
Primary production	PP	0	0	0
Fine sediments	FS	0	0	0
Upstream recruitment	UR	0	0	0
Fine particulate organic matter	FPOM	–	–	0
Large woody debris	LWD	–	–	0
Woody riparian vegetation	WRV	–	–	0
Herbaceous vegetation (includes emergent aquatic macrophytes)	HV	0	0	0
Amphibians and reptiles	A&R	–	–	–
Predator 2	Pred2	–	–	–
Regent honeyeater	RHE	–	–	0
Still-water macroinvertebrates	SW MI	?	?	+
Seedlings	Seedl	–	–	0
Bank stability	BS	–	–	0
Precipitation	Ppt	0	0	0
Wading and diving birds	W&DB	?	?	+
Pool habitat	PH	–	–	–
Gudgeon and small native fishes	GSNF	–	–	–
Catfish recruitment	CR	–	–	–
Carp (*Cyprinus carpio*)	Car	0	0	0
Gambusia holbrooki	GA	–	–	–
Predator 1	Pred1*	+	+	+
Submerged macrophytes	SM*	0	0	0
Recruitment	Rec	–	–	–
Turbidity	Tur*	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 determinancy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinancy are denoted by a question mark. Zero denotes completely determined predictions of no change. Asterisks denote variables present during flowing-water conditions.
Data: Bioregional Assessment Programme (Dataset 5)

2.7.3.3.2 Temporal scope, hydrological response variables and receptor impact variables

The temporal scope for the intermittent gravel/cobble streams landscape class is the same as that described for the perennial gravel/cobble streams. For surface water and groundwater variables the reference assessment interval is defined as the 30 years preceding and including 2012 (i.e. 1983 to 2012). For surface water variables, 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). For groundwater, maximum drawdown (metres) and time to maximum drawdown are considered across the full 90-year window: 2013 to 2102

The initial receptor impact modelling workshop for the Gloucester subregion was unable to address the 'Intermittent – gravel/cobble streams' landscape class. The Bioregional Assessment Programme addressed this omission by holding a second elicitation with a single expert. This expert, however, elected to address the subsurface fauna in riffle habitats (which was not represented in the qualitative model) and its response to the number of zero-flow days (averaged over 30 years) (ZQD, subsequently referred to in this Section as 'zero-flow days'). During periods of zero flow and low flow (Figure 12 and Figure 13), low flows are important for maintaining vertical connectivity to the hyporheic zones of the streambeds (Ward, 1989; Kondolf et al., 2006), and for maintaining longitudinal connectivity within the landscape by linking instream habitats and allowing dispersal of instream biota (Dollar, 2000; Robson et al., 2009; Marsh et al., 2012; Boulton et al., 2014). The hyporheic zone is functionally very important to river ecosystems. Interactions among hydrological, ecological, and biogeochemical processes in the hyporheic zone influence key stream ecosystem processes, such as primary productivity and nutrient cycling (Boulton et al., 2010) and the hyporheic zone provides refuge to microbes and nearly all groups of invertebrates (Mugani et al., 2015) and are used by some fish for spawning (see Boulton et al., 2010 and references therein). The ecology of the taxa of the hyporheic zone is increasingly well known (see reviews by Boulton et al., 2010; Mugnai et al., 2015). The hyporheic zone relies on subsurface flow to persist when surface flow ceases; hence, it can persist in intermittent rivers and streams but is sensitive to the length and frequency of zero-flow spells.

The receptor impact model for intermittent gravel/cobble streams therefore focused on the following relationship: the mean richness of hyporheic invertebrate taxa in 6 L of water pumped from a depth of 40 cm below the streambed (riffle and gravel bars), to changes in ZQD (Table 19).

Table 19 Summary of the hydrological response variables used in the receptor impact models for the 'Intermittent – gravel/cobble streams' landscape class, together with the signed digraph variables that they correspond to for the Gloucester subregion

Hydrological response variable	Definition of hydrological response variable	Signed digraph variable
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.	SWR

SWR = surface water replenishment, ZQD = zero-flow days (averaged over 30 years)

2.7.3.3.3 Receptor impact models

2.7.3.3.3.1 Hyporheic taxa richness

Table 20 summarises the elicitation matrix for the richness of hyporheic taxa. The first three design points – design point identifiers 1, 2 and 3 – address the predicted variability (across the landscape class in the reference interval) in ZQD, capturing the lowest and highest predicted values together with one intermediate value. These design points provide for an estimate of the uncertainty in hyporheic invertebrate taxa richness across the landscape class in the reference year 2012 (Yref).

Design points 1, 3, 5, 8 and 12 represent scenarios that span the uncertainty in the predicted values of ZQD in the relevant time period of hydrological history associated with the short (2042) and long (2102) assessment years, combined with high and low values of Yref. The high and low values for Yref were again calculated during the receptor impact modelling workshop.

Table 20 Elicitation design matrix for the receptor impact model of mean hyporheic taxa richness in the ‘Intermittent – gravel/cobble streams’ landscape class for the Gloucester subregion

Design point identifier	ZQD (days/year)	Yref	Year
1	330	na	2012
2	165	na	2012
3	0	na	2012
1	0	6	2042
5	165	12	2042
3	330	6	2042
12	330	12	2102
8	165	6	2102

Design points for the reference value (Yref) that are used to evaluate ts effect on impacts that occur 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. ZQD = zero-flow days (averaged over 30 years), na = not applicable
Data: Bioregional Assessment Programme (Dataset 5)

The fitted model for hyporheic taxa richness takes the form:

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \beta_{h_1} x_{h_1} \quad (4)$$

where the terms x_0, x_f, x_l and x_r are as before and x_{h_1} is the value of ZQD. The (marginal) mean and 80% central credible interval of the coefficient for this hydrological response variable are summarised in the partial regression plots in Figure 22, whilst Table 21 summarises the same information for all five model coefficients.

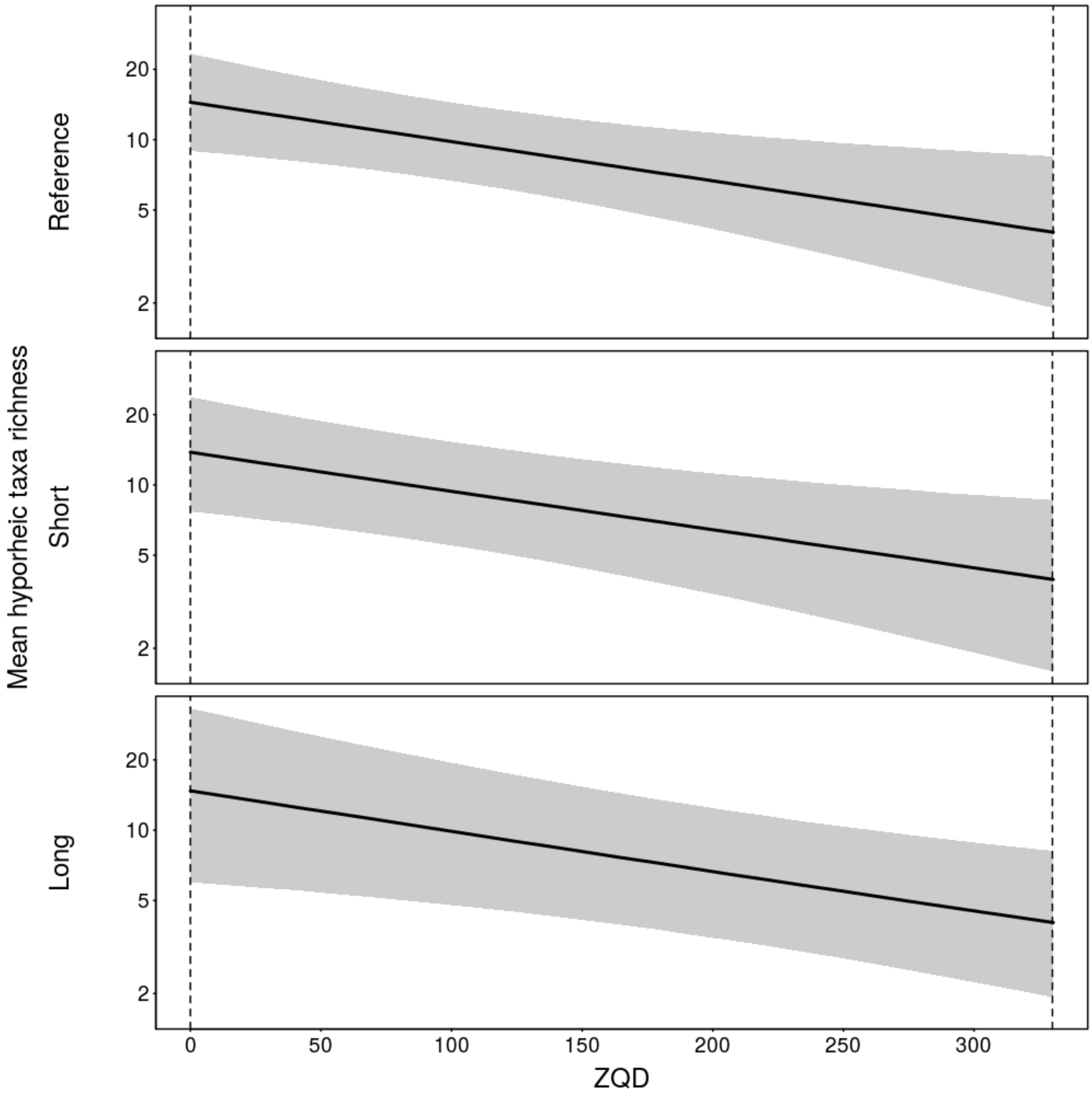

Figure 22 (Top row) Predicted mean (black line) and 80% central credible interval (grey polygon) of mean hyporheic taxa richness under reference hydrological conditions; (middle and bottom rows) predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on mean hyporheic taxa richness for the Gloucester subregion

In middle and bottom rows, all other hydrological response variables are held constant at the mid-point of their elicitation range (during risk estimation all hydrological response variables vary simultaneously). Dashed vertical lines show range of hydrological response variables used in the elicitation.
Data: Bioregional Assessment Programme (Dataset 5)

Table 21 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for mean hyporheic taxa richness in the 'Intermittent – gravel/cobble streams' landscape class for the Gloucester subregion

	Mean	10th percentile	90th percentile
(Intercept)	2.67	2.19	3.15
future1	−0.153	−2.55	2.24
long1	0.0503	−0.719	0.82
Yref	0.0726	−1.04	1.18
ZQD	−0.00388	−0.00668	−0.00107

Yref is value of receptor impact variable in the reference assessment year; set to zero if case is in the reference assessment year. Long is a binary variable scored 1 if the design point is in the long-assessment year. Future is a binary variable scored 1 if the design point is in a short- or long-assessment year. ZQD = zero-flow days (averaged over 30 years)
Data: Bioregional Assessment Programme (Dataset 5)

The model indicates that the expert's elicited information strongly supports the hypothesis that an increase in ZQD will have a negative effect on the mean richness of hyporheic invertebrate taxa despite the expert being quite uncertain about its average value. The model suggests that it can vary substantially across the landscape class from 10 to 20 per sampling unit under conditions of constant flow (ZQD = zero), holding all other covariates at their mid-values. As the number of zero-flow days (averaged over 30 years) (ZQD, subsequently referred to in this Section as 'zero-flow days') increases, however, experts were of the opinion that density would drop to values from 1 to 8 under extremely intermittent flow conditions (ZQD >300 days) (Figure 22).

There was very little evidence in the elicited data to suggest that this effect would be substantially different in the future assessment years. Again this is indicated by the almost-identical partial regression plots in the reference, short- and long-assessment years (Figure 22), and the relatively symmetric negative 10th and positive 90th percentiles for the long and future coefficients in Table 21. The model does, however, suggest that the experts' uncertainty increased slightly for predictions in the future assessment years relative to the reference year.

The best-fitting model in this case, again, is unable to eliminate the possibility that the average richness of hyporheic invertebrate taxa in the reference years has no influence on its density in the future years. This is indicated by the fact that $\beta_r = 0$ is close to the 50th percentile of its induced prior (Table 21). This suggestion is consistent with the hypothesis that there is likely to be very little lag in the response of short-lived (most taxa live less than 5 to 10 years) species to changes in the hydrological response variables.

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2.7.3 ‘Riverine’ landscape group

2.7.4 'Groundwater-dependent ecosystem (GDE)' landscape group

Summary

The subregion has three main hydrogeological units relevant to sustaining groundwater-dependent ecosystem (GDE) structure and function, which provide a useful conceptual framework for examining landscape classes that are dependent on groundwater: (i) alluvial aquifers along major creek lines; (ii) relatively shallow weathered/fractured rock aquifers; and (iii) impermeable Alum Mountain Volcanics that underlie these hydrogeological units.

The Quaternary alluvial aquifers are developed close to the rivers. The Permian fractured rock and weathered zone is up to 150 m thick. It underlies the alluvial system and extends to the edges of the subregion. The outcropping Alum Mountain Volcanics are generally considered to be impermeable but localised fractures may provide pathways for localised groundwater flow paths.

GDEs occur within each of the three hydrogeological units described above but they are predominantly associated with the weathered/fractured rock zone and alluvial aquifers. Few GDEs are present above the Alum Mountain Volcanics. Of the five GDE landscape classes that were identified as likely to be groundwater dependent in the Gloucester subregion, qualitative models were developed for three landscape classes: 'Forested wetlands', 'Wet sclerophyll forests' and 'Dry sclerophyll forests'. A qualitative model for rainforests was not developed owing to its small area within the subregion and lack of proximity to coal resource development.

The qualitative mathematical model for the 'Forested wetlands' landscape class focused on the role that forest canopies play in providing flower nectar (a food resource for insect, bird and mammal consumers), habitat structure for nesting and general habitat for various predators. The model recognises the possibility for coal resource development to impact the supply of both deep and shallow groundwater to these forest communities, and in some instances, new coal mines could lead to further fragmentation of the remaining forested wetlands in the Gloucester subregion.

A single impact scenario focusing on simultaneous reduction in deep and shallow groundwater generally indicates an ambiguous or negative response prediction for biological variables within the forested wetlands community as a consequence of decreases in available nectar production and quality of forest habitats. Ambiguous responses arise from positive effects associated with the potential release from predation or competitive dominance, matched by negative effects resulting from reduced nectar production.

The qualitative mathematical model for the 'Wet sclerophyll forests' landscape class is based on the model structure for forested wetlands, with the overstorey providing the same ecosystem functions as forested wetlands. An added feature of this model is the effect of the overstorey in creating a microclimate that supports ground-layer and mid-storey vegetation. The model identifies deep groundwater as being important to the survival of the trees but it is recognised that this is likely only happening in the alluvial deposits of river floodplains or on lower slopes. The qualitative mathematical predictions for a single impact scenario

(simultaneous decrease in shallow and deep groundwater) are the same as for the ‘Forested wetlands’ landscape class.

The qualitative mathematical model for the ‘Dry sclerophyll forests’ landscape class is based on the model structure of the ‘Wet sclerophyll forests’ landscape class. All features of this model are the same as for the ‘Wet sclerophyll forests’ landscape class, but with added uncertainty in the role of microclimate in supporting understorey vegetation components. The model also captures (via alternative model structures) additional uncertainty as to whether or not dry sclerophyll trees can effectively access stores of deep groundwater outside of alluvial deposits, and also whether the microclimate created by the overstorey is beneficial to mid-storey and ground-layer vegetation. The model predictions for a single impact scenario (simultaneous decrease in shallow and deep groundwater) match those for the ‘Forested wetlands’ and ‘Wet sclerophyll forests’ landscape classes, except for the predicted zero (no change) response of ground-layer and mid-storey vegetation in the second model.

No receptor impact models were developed for the ‘Groundwater-dependent ecosystem (GDE)’ landscape group due to time restrictions and the limited availability of suitable experts.

2.7.4.1 Description

Groundwater-dependent ecosystems (GDEs) are those that rely on the surface or subsurface expression of groundwater to meet all or some of their life cycle requirements (Eamus et al., 2006). The dependence of GDEs on groundwater varies both spatially and temporally (Eamus et al., 2006). Ecosystems may be obligate GDEs, with a continuous or entire dependence on groundwater, or facultative GDEs, with an infrequent or partial dependence on groundwater (Zencich et. al., 2002). Plants that depend solely on moisture held within the soil profile are known as vadophytes and are not groundwater dependent (Sommer and Froend, 2010). In the Gloucester subregion, as in much of Australia, there is considerable uncertainty as to the nature of groundwater dependency for much terrestrial vegetation. The hydroclimatic environment of the Gloucester subregion is subtropical. Average annual rainfall is reasonably high (960 to 1400 mm/year) and is summer dominated, when potential evaporation is also highest (McVicar et al., 2014). Nonetheless, the region is still classified as being water limited inasmuch as potential evaporation (1400 to 1700 mm/year) exceeds rainfall in most months of the year. Rainfall is also highest along the margins of the subregion because this area is associated with higher elevation, whereas the deficit of rainfall, relative to potential evaporation, is greater throughout much of the lowland areas of the subregion. The Gloucester Basin underlies the Gloucester subregion and is characterised as a closed hydrogeological system. Thus, water entering the system must leave as either surface water or groundwater discharge (Dawes et al., 2018). Groundwater recharge is estimated to be up to 17% of rainfall under steady-state conditions and up to 28% of rainfall under transient conditions, with high values associated with alluvial aquifers (McVicar et al., 2014). This combination of rainfall deficit and surface water and groundwater recharge create the potential for GDEs to exist within the Gloucester subregion.

The subregion has three main hydrogeological units (McVicar et al., 2014) relevant to sustaining GDE structure and function, which provide a useful conceptual framework for examining landscape classes dependent on groundwater:

- alluvial aquifers along major creek lines
- relatively shallow weathered/fractured rock aquifers
- impermeable Alum Mountain Volcanics that underlie these hydrogeological units.

The geomorphology of the Gloucester subregion has been described in detail elsewhere (McVicar et al., 2014; Dawes et al., 2018), and only a brief summary is presented here as context (Figure 23). The Quaternary alluvial aquifers are developed close to the rivers. Soils in these alluvial deposits are dominated by Tenosols and are composed of clay layers and highly permeable sediments with high hydraulic conductivities (up to 500 m/day). The thickness of the alluvia varies from 9 to 15 m and the watertable is shallow and responsive to rainfall and flood events close to the river.

The Permian fractured rock and weathered zone is up to 150 m thick. It underlies the alluvial system and extends to the edges of the subregion. These shallow rock hydrogeological units are composed of interbedded sandstone, silt and claystone. Soils of the fractured rock and weathered zone tend to be dominated by Kurosols. Typically, these soils have a sharp, abrupt boundary between the upper coarser-textured A horizon and the finer-textured B horizon. This boundary may provide a pathway for subsurface lateral flows of water. Generally, hydraulic conductivities of these aquifers are low with a sluggish response to rainfall. However, these hydraulic conductivities are highly variable as a result of fracturing and fault zones within the formation.

The outcropping Alum Mountain Volcanics are generally considered to be impermeable but localised fractures may provide pathways for localised groundwater flow paths (McVicar et al., 2014). These flow paths may be expressed as springs along the margins of the basin, driven by localised circulation of meteoric water.

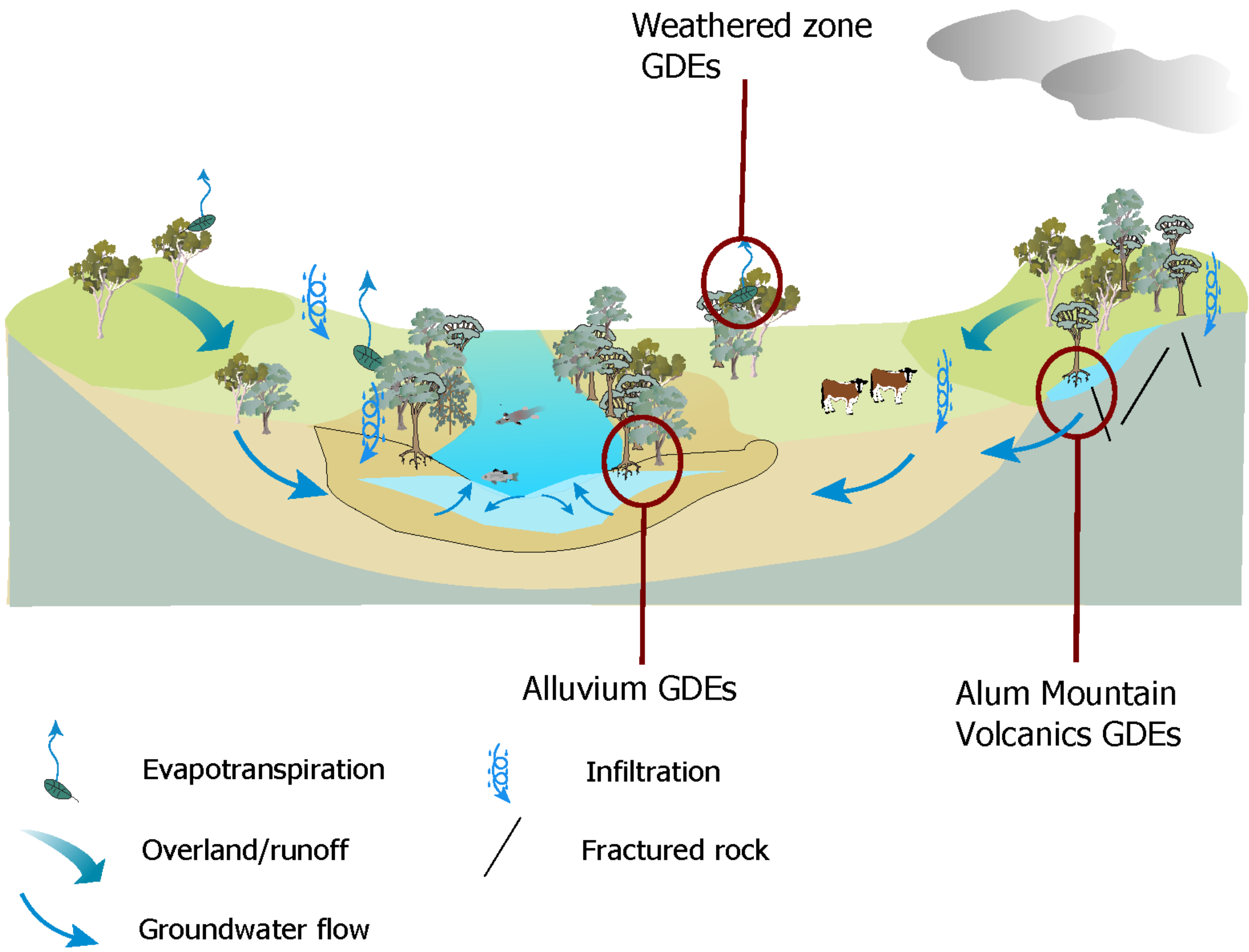

Figure 23 Conceptual model of the major groundwater processes in the Gloucester subregion

GDE = groundwater-dependent ecosystem

The water requirements of GDEs are poorly understood and there is large uncertainty as to the frequency, timing and duration of groundwater use by GDEs within the Gloucester subregion. In general, transpiration of groundwater is expected to decline as the depth to groundwater increases, but there is very limited evidence to support this assumption within Australia. O'Grady et al. (2010) reviewed estimates of groundwater discharge in Australia and concluded that there is considerable variation in the relationship between transpiration of groundwater and depth to groundwater. Factors such as the rooting depth of a particular species (which is usually not known), hydroclimatic environment and groundwater salinity all impact on groundwater use by vegetation. Zolfaghar et al. (2014) examined the structure and productivity of eucalypt forest across a depth-to-watertable gradient in the upper Nepean catchment in NSW. They found that where groundwater was shallow, vegetation had significantly higher biomass and productivity than sites where groundwater was deeper than approximately 10 m. The relationships between depth to groundwater and the structural and functional attributes of the vegetation communities were highly non-linear, with steep declines in leaf area index and biomass over a range of 5 to

10 m depth to groundwater. However, it is important to note that the study was largely correlative and did not quantify the groundwater requirements of the vegetation.

Specific studies of GDEs within the Gloucester subregion are limited. Existing mapping of GDEs is based on a multiple-lines-of-evidence approach that incorporated existing vegetation mapping, modelled groundwater levels and remote sensing (Kuginis et al., 2012). Modelled depths to groundwater (Summerell and Mitchell, 2011) for the subregion are generally shallow (within 16 m of the ground surface).

Of the five GDE landscape classes that were identified as likely to be groundwater dependent in the Gloucester subregion, qualitative models were developed for three landscape classes: 'Forested wetlands', 'Wet sclerophyll forests' and 'Dry sclerophyll forests'. A qualitative model for rainforests was not developed owing to its small area within the subregion and lack of proximity to coal resource development. GDEs occur within each of the three hydrogeological units described above but they are predominantly associated the weathered/fractured rock zone and alluvial aquifers (Table 22). Few GDEs are present above the Alum Mountain Volcanics. The distribution of GDEs within the assessment extent (AE) of the Gloucester subregion is illustrated in Figure 6 of Section 2.7.2. The structure and composition of the forested wetland landscape has been described in detail in the 'Riverine' landscape group (see Section 2.7.3.1).

Table 22 Area (ha) of groundwater-dependent ecosystem landscape classes within each of three hydrogeological units within the entire assessment extent (AE) of the Gloucester subregion

Landscape class	Alluvium (ha)	Weathered/fractured rock zone (ha)	Alum Mountain Volcanics (ha)
Dry sclerophyll forests	0.8	19	0.1
Forested wetlands	60	138	6.9
Rainforests	80	61	3.3
Wet sclerophyll forests	0	12	5.8

The wet sclerophyll forests of NSW occur on moderately fertile soils in high rainfall areas, and are characterised by a tall, open, sclerophyllous tree canopy and a luxuriant understorey of soft-leaved, mesophyllous, shrubs, fern and herbs (Keith, 2004). Many understorey plants are rainforest species or have close rainforest relatives. Rainforests may be embedded within a matrix of wet sclerophyll forest and the two often blend together as intermediate forms. More than 30% crown cover of emergent, non-rainforest species (including eucalypts, brushbox and turpentine) results in a classification of wet sclerophyll forest rather than rainforest (DECC, 2007). The main vegetation communities are described in Table 23.

Table 23 Main vegetation communities within the 'Wet sclerophyll forests', 'Rainforests' and 'Dry sclerophyll forests' landscape classes in the Gloucester subregion

Vegetation community	Source
North coast wet sclerophyll forests have a subdominant stratum of mesophyllous small trees or tall shrubs up to 15 m tall and a second understorey layer of mesophyllous shrubs above a continuous ground stratum of ferns and herbs. Vines are also present on shrubs and smaller trees. They occur both in coastal ranges and foothills, and on alluvium in sheltered creek flats. They grade into both northern hinterland forests (with decreasing shelter or moisture) and subtropical rainforests (with increasing shelter, moisture or fertility). Dominant canopy species include *Eucalyptus acmenioides* (white mahogany), *E. microcorys* (tallowwood), *E. pilularis* (blackbutt), *E. saligna* (Sydney blue gum), *Lophostemon confertus* (brush box) and *Syncarpia glomulifera* (turpentine) which occur in various combinations.	NSW Office of Environment and Heritage (n.d. a)
Northern warm temperate rainforests consist of closed forest up to 30 m tall, generally lacking emergents. The canopy is comprised of 4–15 species but is dominated by *Acmena smithii* (lilly pilly), *Ceratopetalum apetalum* (coachwood) and *Doryphora sassafras* (sassafras). It occurs in sheltered gullies and slopes in the hilly to steep terrain of the coast and escarpment on moderately fertile soils in high rainfall areas, extending above 1000 m in elevation, on granites, rhyolites, syenites or sedimentary substrates that yield acid soils with moderate levels of nutrients. Occasional lianas and epiphytes, open shrub/sapling stratum and variable fern/herb groundcover occur amongst copious leaf litter. Mosses, liverworts and lichens may be conspicuous on tree trunks or the forest floor.	NSW Office of Environment and Heritage (n.d. b)
Hunter-Macleay dry sclerophyll forests are dry open eucalypt forests to 30 m tall that are associated with the major coastal river valleys along the NSW coast. They have a mixed sclerophyll and mesophyll shrub stratum, and grassy ground layer. They occur below 400 m elevation in foothills and undulating terrain in rain-shadow valleys, on well-drained loams derived from shales. Main overstorey species include *Corymbia maculata* (spotted gum), *Eucalyptus crebra* (narrow-leaved ironbark), *E. moluccana* (grey box), *E. propinqua* (grey gum), *E. siderophloia* (grey ironbark) and *Syncarpia glomulifera* (turpentine).	NSW Office of Environment and Heritage (n.d. c)

Wet sclerophyll forests are tall, dense forests (30 to 60 m height) dominated by *Eucalyptus* trees. There are only small amounts of the 'Wet sclerophyll forests' landscape class within the AE for the Gloucester subregion and these are restricted to the weathered/fractured rock and Alum Mountain Volcanics land zones. Wet sclerophyll forests are divided into two subgroups (subformations) depending on whether their understorey is shrubby or grassy (NSW Office of Environment and Heritage, n.d. d). Both have a tall, straight-trunked eucalypt canopy and a mesophyllous understorey; however, the grassy subformation has a more-open form with fewer shrubs and small trees, and occurs in slightly drier habitats. Within the AE, wet sclerophyll forests are dominated by the Keith vegetation class 'North Coast wet [shrubby subformation] sclerophyll forests' (Dawes et al., 2018). Rainforests within the AE are primarily Keith vegetation class 'Northern warm temperate rainforests' (Keith, 2004). Note that the NSW-listed (*Threatened Species Conservation Act 1995* (TSC Act)) 'Lowland Rainforest in the NSW North Coast and Sydney Basin Bioregions' and Commonwealth-listed (*Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act)) 'Lowland Rainforests of Subtropical Australia', are associated with both north coast wet sclerophyll forests and northern warm temperate rainforests.

The 'Wet sclerophyll forests' and 'Rainforests' landscape classes provide habitat for a diverse range of plant and animal species. A number of EPBC Act-listed species included in the water-dependent asset register for the Gloucester subregion (McVicar et al., 2015) are known to occur in both landscape classes including the swift parrot (*Lathamus discolor*), giant barred frog

(*Mixophyes iteratus*), giant burrowing frog (*Heleioporus australiacus*), stuttering frog (*Mixophyes balbus*), grey-headed flying fox (*Pteropus poliocephalus*), koala (*Phascolarctos cinereus*) and trailing woodruff (*Asperula asthenes*). Others, such as Charmhaven apple (*Angophora inopina*), regent honeyeater (*Anthochaera phrygia*), Guthrie's grevillia (*Grevillia guthrieana*), Hastings River mouse (*Pseudomys oralis*), leafless tongue orchid (*Cryptostylis hunteriana*), red goshawk (*Erythrotriorchis radiatus*), and slaty red gum (*Eucalyptus glaucina*) occur only in wet sclerophyll forest.

The 'Dry sclerophyll forests' landscape class is predominantly confined to the weathered/fractured rock zone in the south of the AE. The majority of the landscape class is dominated by dry sclerophyll forests of the Keith vegetation class 'Hunter-Macleay dry sclerophyll forests' (Table 23), with smaller areas of 'Sydney coastal dry sclerophyll forests' and 'Coastal dune dry sclerophyll forests' (Dawes et al., 2018). Structurally these community types are classified as open forests, occurring on soils of lower fertility and characterised by an overstorey to 30 m dominated by *Corymbia maculata* and a range of *Eucalyptus* species including *E. crebra*, *E. fibrosa* and *E. umbra*. Understories are mixed and contain a range of shrubs with a more or less continuous ground layer. Typical shrub species include *Acacia parvipinnula*, *Allocasuarina torulosa* along with smaller shrubs such as *Breynia oblongifolia*, *Daviesia ulicifolia*, *Lissanthe strigosa*, *Notelaea longifolia, Persoonia linearis, Pultenaea villosa* and *Rapanea variabilis.* The dry sclerophyll forests may provide habitat for a range of EPBC Act-listed plant species identified in the asset register for the Gloucester subregion (McVicar et al., 2015) including Charmhaven apple (*Angophora inopina*), leafless tongue orchid (*Cryptostylis hunteriana*), and slaty red gum (*E. glaucina*). EPBC Act-listed animal species that might use this forest type as habitat include the grey-headed flying fox (*Pteropus poliocephalus*), Hastings River mouse (*Pseudomys oralis*), koala (*Phascolarctos cinereus*), regent honeyeater (*Anthochaera phrygia*) and the swift parrot (*Lathamus discolor*).

2.7.4.2 'Forested wetlands' landscape class

2.7.4.2.1 Qualitative mathematical model

A qualitative model was developed to describe the forest communities in landscape classes that are in floodplains and wetlands (Figure 24). Drawdown of groundwater by coal mines and coal seam gas (CSG) development in the AE for the Gloucester subregion is predicted to impact the supply of both deep and shallow groundwater (DGW and SGW, respectively in Figure 24) to these forest communities. In some instances, the coal mine footprint will also have a direct impact on the remaining amount of forested wetlands in the AE, which will lead to impacts via forest fragmentation (FF).

The principal ecosystem components, processes and functions attributed to wetland forests were the roles that their canopies offered in providing flower nectar (FN), which is a food resource for bird and mammal consumers such as the swift parrot (SP), regent honeyeater (RHE), arboreal mammals (AM) and grey-headed flying fox (GHFF; Commonwealth of Australia, 2015; Saunders and Tzaros, 2011), as well as insects, and habitat structure, such as tree hollows for nesting (Commonwealth of Australia, 2015; Saunders and Tzaros, 2011), and also in providing habitat for various predatory diurnal and nocturnal raptors (DR and NR, respectively), such as the red goshawk (*Erythrotriorchis radiatus*). Contiguous unfragmented forest canopies were described as being an especially critical habitat feature for aggressive native honeyeaters (ANHE), such as the noisy miner (*Manorina melanocephala*), noisy friarbird (*Philemon corniculatus*) and red wattlebird (*Anthochaera carunculata*), which exert a strong competitive hierarchy on the community of nectar consumers. Koalas (Koa) also benefit from forest canopies (FWOS) for all aspects of their life history requirements. On the one hand, the supply of deep groundwater was thought to be critical for the survival of forested wetlands, and it was suggested that vegetation accesses these stores through deep root systems. On the other hand, shallow groundwater, along with rainfall (Ppt), was described as being a main factor in the magnitude of flower and nectar production, and shallow groundwater was also critical for the presence of a herbaceous wetland vegetation (HWV). In a recent study of riparian *Tamarix*, Anderson and Nelson (2013) failed to find any relationship between depth to groundwater and noted: 'The extent to which a reduction in soil water availability will affect riparian plant floral ecology, riparian pollinators, and plant pollinator interactions is largely unknown, because we lack information on most plant species' response to shifts in depth to groundwater'.

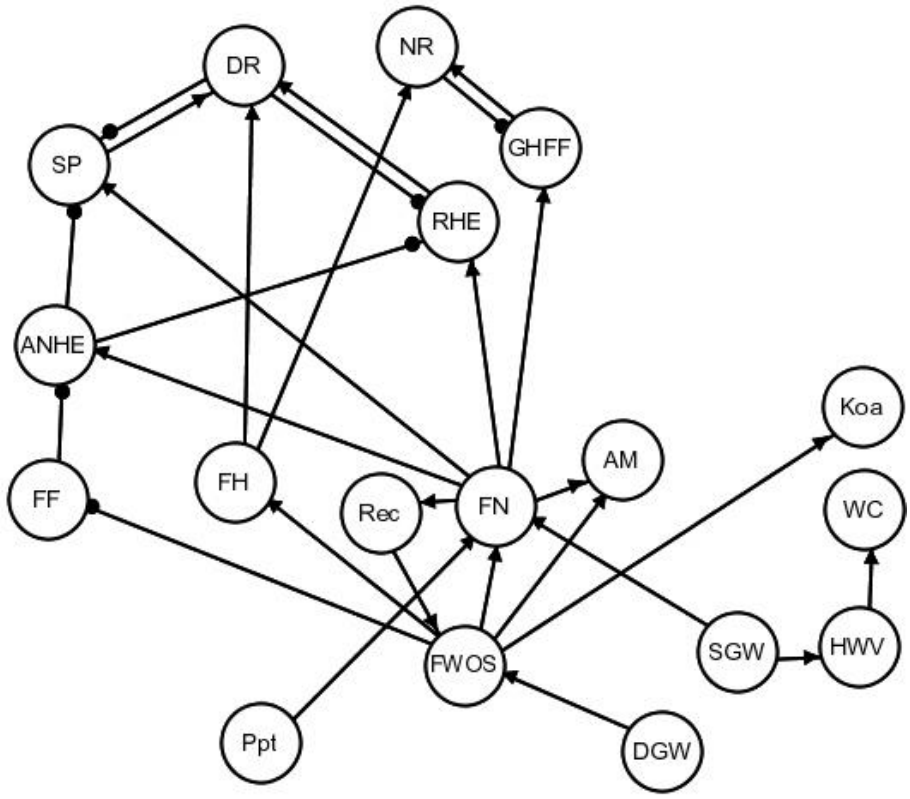

Figure 24 Signed digraph of the 'Forested wetlands' landscape class in the Gloucester subregion

Variables are: arboreal mammals (AM), aggressive native honeyeaters (ANHE), deep groundwater (DGW), diurnal raptor (DR), forest fragmentation (FF), forest habitats (FH), flowers & nectar (FN), forested wetland overstorey (vegetation)(FWOS), grey-headed flying fox (GHFF), herbaceous wetland vegetation (HWV), koala (Koa), nocturnal raptor (NR), precipitation (Ppt), recruitment (Rec), regent honeyeater (RHE), shallow groundwater (SGW), swift parrot (SP), wetland community (WC).
Data: Bioregional Assessment Programme (Dataset 1)

Surface water and groundwater modelling predict potential impacts of coal mining to both deep and shallow groundwater stores, and a single cumulative impact scenario (C1) was developed based on a simultaneous decrease in both these sources of groundwater (Table 24).

Table 24 Summary of the cumulative impact scenarios for the 'Forested wetlands' landscape class in the Gloucester subregion

Cumulative impact scenario	Deep groundwater	Shallow groundwater
C1	–	–

Cumulative impact scenarios are determined by combinations of no change (0) or a decrease (–) in the following signed digraph variables: deep groundwater (DGW), shallow groundwater (SGW). Scenario C1 shows the changes to these variables under the coal resource development pathway (CRDP).
Data: Bioregional Assessment Programme (Dataset 1)

Qualitative analysis of the signed digraph model (Figure 24) generally indicates an ambiguous or negative response prediction for biological variables within the forested wetlands community as a consequence of a decrease in available nectar production and quality of forest habitats (Table 25). Ambiguity in the response predictions for swift parrots, diurnal raptors and the regent honeyeater arise from positive effects associated with the potential release from competitive dominance by aggressive native honeyeaters matched by negative effects resulting from reduced nectar production. An ambiguous response prediction for grey-headed flying foxes stems from a potential decrease in nectar resources and a possible decline in the abundance of their nocturnal raptor predators due to habitat loss.

Table 25 Predicted response of the signed digraph variables in the 'Forested wetlands' landscape class to cumulative changes in hydrological response variables for the Gloucester subregion

Signed digraph variable		Cumulative impact scenario
Full name	Shortened form	C1
Diurnal raptor	DR	?
Nocturnal raptor	NR	–
Aggressive native honeyeaters	ANHE	–
Swift parrot	SP	?
Regent honeyeater	RHE	?
Grey-headed flying fox	GHFF	?
Forest habitats	FH	–
Forest fragmentation	FF	+
Flowers and nectar	FN	–
Precipitation	Ppt	0
Koala	Koa	–
Arboreal mammals	AM	–
Forested wetland overstorey (vegetation)	FWOS	–
Herbaceous wetland vegetation	HWV	–
Recruitment	Rec	–
Wetland community	WC	–

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 determinancy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinancy are denoted by a question mark. Zero denotes completely determined predictions of no change.
Data: Bioregional Assessment Programme (Dataset 1)

2.7.4.3 'Wet sclerophyll forests' landscape class

2.7.4.3.1 Qualitative mathematical model

A qualitative model was developed for wet sclerophyll forests based on the model structure for forested wetlands, with the overstorey (WSOS in Figure 25 and Figure 26) providing the same ecosystem functions as for forested wetlands. An added feature of this model was the effect of the overstorey in creating a microclimate (MC) that supported ground-layer and mid-storey vegetation (WSGL and WSMS, respectively). Overstorey vegetation was described as also being an important habitat for grey-headed flying foxes (GHFF), which utilise wet sclerophyll forest, dry sclerophyll forest and rainforest canopies as camp areas (Lunney and Moon, 1997). Deep groundwater (DGW) is suggested as being important to the survival of the trees, which access stores of water through deep roots, but it was recognised that this is likely only happening in the alluvial deposits of river floodplains or on lower slopes within the area of interest. There was even greater uncertainty as to whether stores of shallow groundwater (SGW) benefited mid-storey vegetation, which led to two alternative models: one with (model 1 in Figure 25) and one without (model 2 in Figure 26) a positive link from shallow groundwater to mid-storey vegetation.

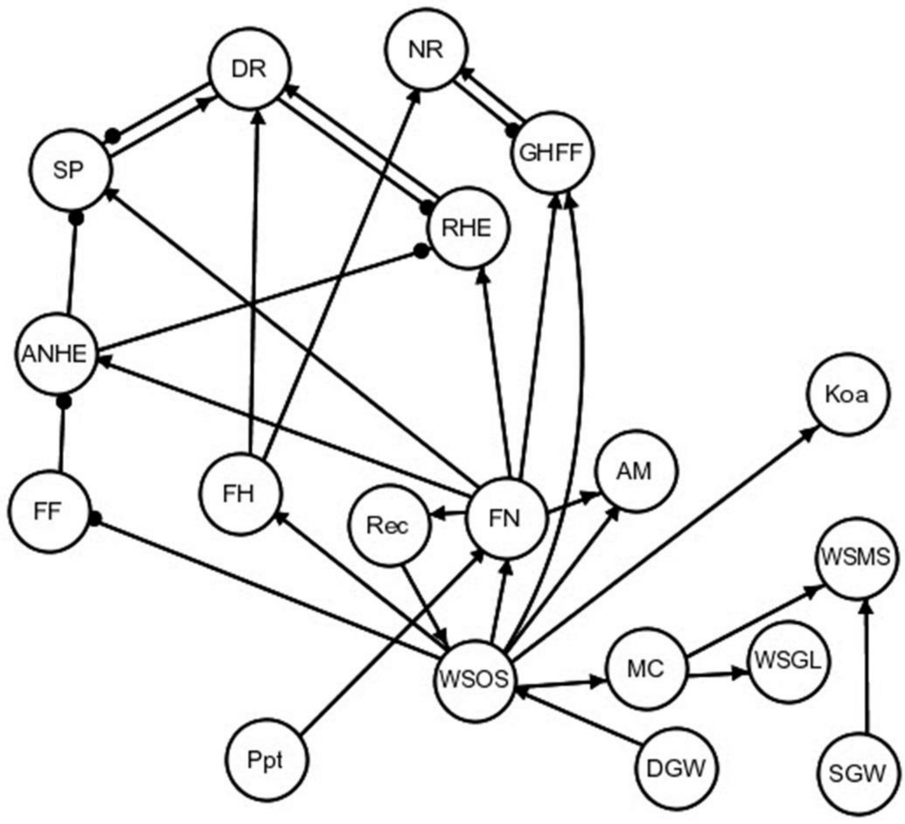

Figure 25 Signed digraph of the 'Wet sclerophyll forests' landscape class (model 1) in the Gloucester subregion

Variables are: arboreal mammals (AM), aggressive native honeyeaters (ANHE), deep groundwater (DGW), diurnal raptor (DR), forest fragmentation (FF), forest habitats (FH), flowers & nectar (FN), grey-headed flying fox (GHFF), koala (Koa), microclimate (MC), nocturnal raptor (NR), precipitation (Ppt), recruitment (Rec), regent honeyeater (RHE), shallow groundwater (SGW), swift parrot (SP), wet sclerophyll ground layer (vegetation) (WSGL), wet sclerophyll mid-storey (vegetation) (WSMS), and wet sclerophyll overstorey (vegetation) (WSOS).
Data: Bioregional Assessment Programme (Dataset 1)

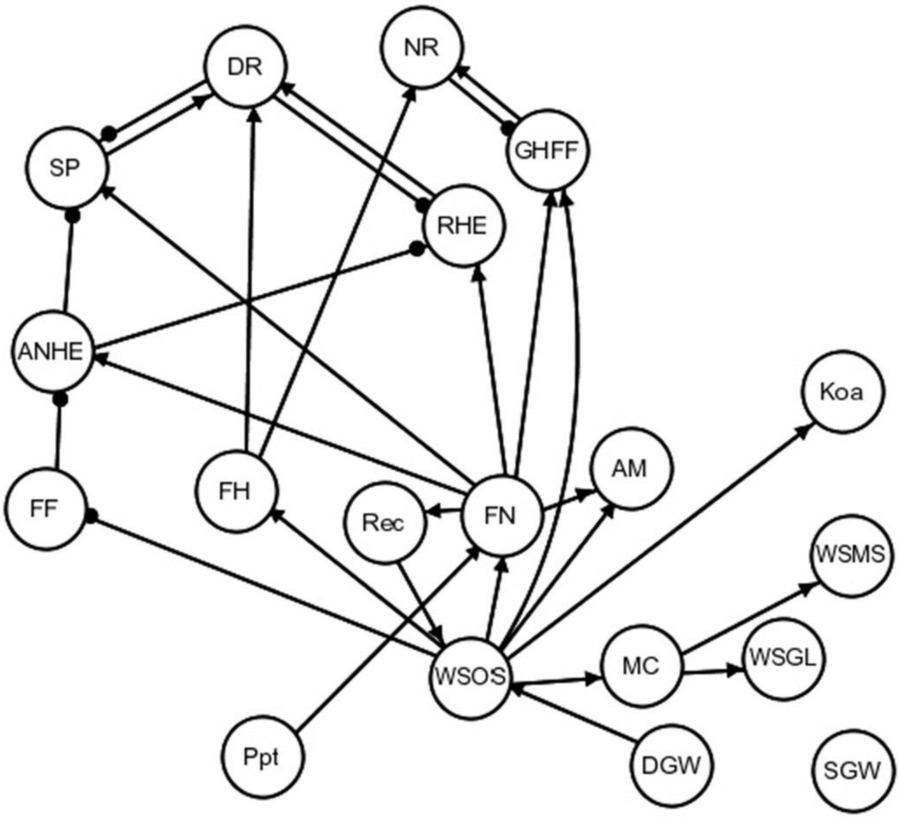

Figure 26 Signed digraph of the 'Wet sclerophyll forests' landscape class (model 2) in the Gloucester subregion

Variables are: arboreal mammals (AM), aggressive native honeyeaters (ANHE), deep groundwater (DGW), diurnal raptor (DR), forest fragmentation (FF), forest habitats (FH), flowers & nectar (FN), grey-headed flying fox (GHFF), koala (Koa), microclimate (MC), nocturnal raptor (NR), precipitation (Ppt), recruitment (Rec), regent honeyeater (RHE), shallow groundwater (SGW), swift parrot (SP), wet sclerophyll ground layer (vegetation) (WSGL), wet sclerophyll mid-storey (vegetation) (WSMS), and wet sclerophyll overstorey (vegetation) (WSOS).
Data: Bioregional Assessment Programme (Dataset 1)

Surface water and groundwater modelling predict potential impacts of coal mining to both deep and shallow groundwater stores, and a single cumulative impact scenario (C1) was developed based on a simultaneous decrease in both these sources of groundwater in models 1 and 2 (Table 26).

Table 26 Summary of the cumulative impact scenarios for the 'Wet sclerophyll forests' landscape class in the Gloucester subregion

Cumulative impact scenario	Deep groundwater	Shallow groundwater
C1 model 1	–	–
C1 model 2	–	–

Cumulative impact scenarios are determined by combinations of no change (0) or a decrease (–) in the following signed digraph variables: deep groundwater (DGW), shallow groundwater (SGW). Scenario C1 shows the changes to these variables under the coal resource development pathway (CRDP).
Data: Bioregional Assessment Programme (Dataset 1)

Qualitative response predictions were the same for both models depicting wet sclerophyll forest communities (Table 27). Response predictions for these two models also matched those for forested wetlands (Table 25), with the same dynamics of the effects for release from competitive dominance and release from predation contributing to ambiguous response predictions for diurnal raptors, swift parrots, regent honeyeaters and grey-headed flying foxes.

Table 27 Predicted response of the signed digraph variables of the 'Wet sclerophyll forests' landscape class to cumulative changes in hydrological response variables for the Gloucester subregion

Signed digraph variable		Cumulative impact scenario	
Full name	Shortened form	C1 model 1	C1 model 2
Diurnal raptors	DR	?	?
Nocturnal raptor	NR	–	–
Aggressive native honeyeaters	ANHE	–	–
Swift parrot	SP	?	?
Regent honeyeater	RHE	?	?
Grey-headed flying fox	GHFF	?	?
Forest habitats	FH	–	–
Forest fragmentation	FF	+	+
Flowers and nectar	FN	–	–
Precipitation	Ppt	0	0
Koala	Koa	–	–
Arboreal mammals	AM	–	–
Wet sclerophyll overstorey (vegetation)	WSOS	–	–
Microclimate	MC	–	–
Recruitment	Rec	–	–
Wet sclerophyll ground layer (vegetation)	WSGL	–	–
Wet sclerophyll mid-storey (vegetation)	WSMS	–	–

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 determinancy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinancy are denoted by a question mark. Zero denotes completely determined predictions of no change.
Data: Bioregional Assessment Programme (Dataset 1)

2.7.4.4 'Dry sclerophyll forests' landscape class

2.7.4.4.1 Qualitative mathematical model

A model for dry sclerophyll forests was developed based on the model structure of wet sclerophyll forests. All features of this model were the same as for wet sclerophyll forests, but with added uncertainty in the role of microclimate (MC) in supporting understorey vegetation components. This uncertainty was whether the microclimate created by the dry sclerophyll forest overstorey (DSOS) was beneficial to mid-storey (DSMS) and ground-layer (DSGL) vegetation, which led to two alternative models, one with (model 1 in Figure 27) and one without (model 2 in Figure 28) positive links from microclimate to mid-storey and ground-layer vegetation. There was also uncertainty between two experts as to whether or not dry sclerophyll trees could effectively access stores of deep groundwater (DGW) outside of alluvial deposits, which involves the positive link from deep groundwater to the dry sclerophyll overstorey variable. Omitting this link would essentially mean that the system was not a groundwater-dependent ecosystem. It would also remove any possible impact from coal mining on groundwater stores. This uncertainty in model structure was therefore not propagated through the qualitative analysis of perturbation response.

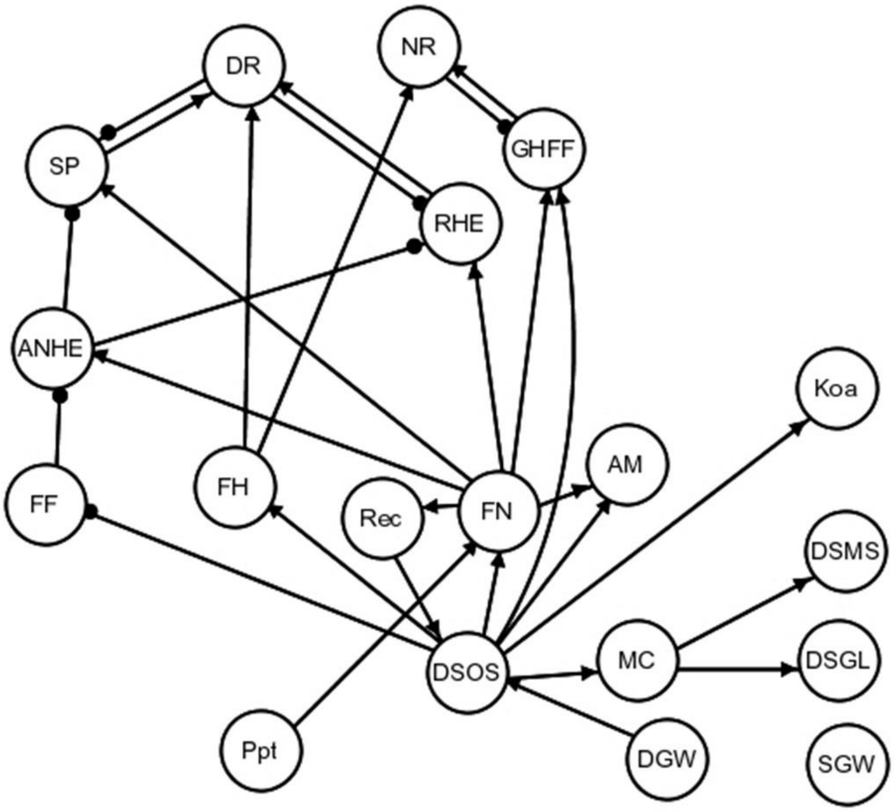

Figure 27 Signed digraph of the ‘Dry sclerophyll forests’ landscape class (model 1) in the Gloucester subregion

Variables are: arboreal mammals (AM), aggressive native honeyeaters (ANHE), deep groundwater (DGW), diurnal raptor (DR), dry sclerophyll ground layer (vegetation) (DSGL), dry sclerophyll mid-storey (vegetation) (DSMS), dry sclerophyll overstorey (vegetation) (DSOS), forest fragmentation (FF), forest habitats (FH), flowers & nectar (FN), grey-headed flying fox (GHFF), koala (Koa), microclimate (MC), nocturnal raptor (NR), precipitation (Ppt), recruitment (Rec), regent honeyeater (RHE), shallow groundwater (SGW), and swift parrot (SP).
Data: Bioregional Assessment Programme (Dataset 1)

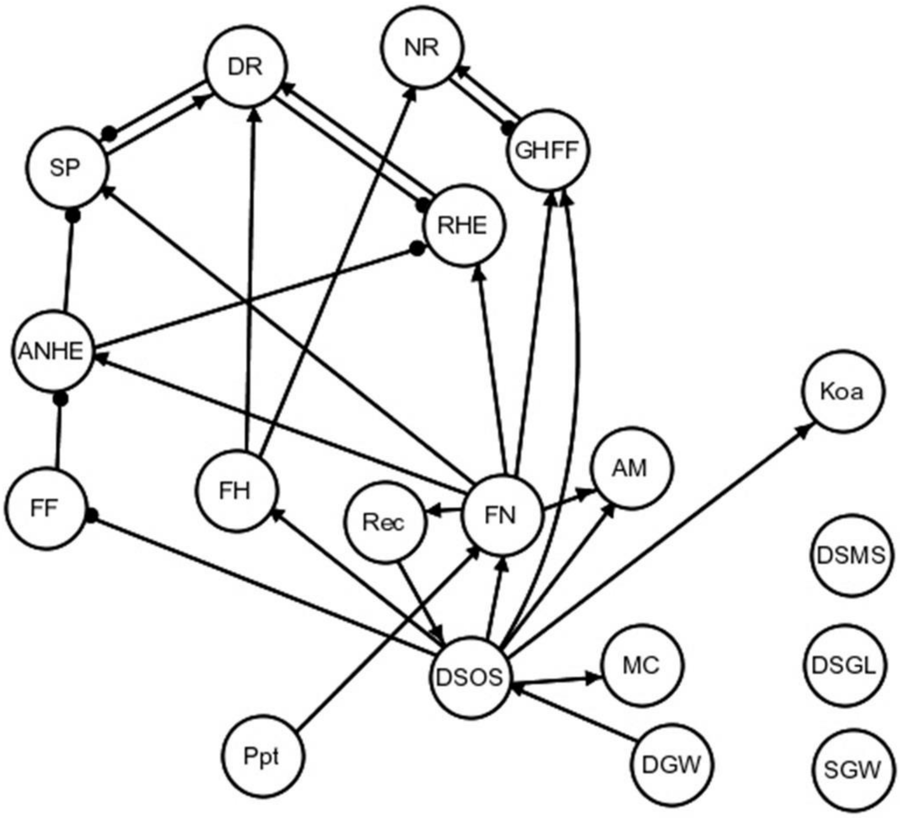

Figure 28 Signed digraph of the 'Dry sclerophyll forests' landscape class (model 2) in the Gloucester subregion

Variables are: arboreal mammals (AM), aggressive native honeyeaters (ANHE), deep groundwater (DGW), diurnal raptor (DR), dry sclerophyll ground layer (vegetation) (DSGL), dry sclerophyll mid-storey (vegetation) (DSMS), dry sclerophyll overstorey (vegetation) (DSOS), forest fragmentation (FF), forest habitats (FH), flowers & nectar (FN), grey-headed flying fox (GHFF), koala (Koa), microclimate (MC), nocturnal raptor (NR), precipitation (Ppt), recruitment (Rec), regent honeyeater (RHE), shallow groundwater (SGW), and swift parrot (SP).
Data: Bioregional Assessment Programme (Dataset 1)

As for the other GDEs in this region, surface water and groundwater modelling predict potential impacts of coal mining to both deep and shallow groundwater stores. A single cumulative impact scenario (C1) was developed based on a simultaneous decrease in both sources of groundwater in models 1 and 2 (Table 28).

Table 28 Summary of the cumulative impact scenarios for the 'Dry sclerophyll forests' landscape class for the Gloucester subregion

Cumulative impact scenario	Deep groundwater	Shallow groundwater
C1 model 1	–	–
C1 model 2	–	–

Cumulative impact scenarios are determined by combinations of no-change (0) or a decrease (–) in the following signed digraph variables: deep groundwater (DGW), shallow groundwater (SGW). Scenario C1 shows the changes to these variables under the coal resource development pathway (CRDP).
Data: Bioregional Assessment Programme (Dataset 1)

Qualitative response predictions were the same for both models depicting dry sclerophyll forest communities (Table 29), except for the predicted response of ground-layer and mid-storey vegetation, which in model 2 had a predicted response of zero (no change). Other than these zero-response predictions, the response predictions for these two models matched those for forested wetlands (Table 25) and wet sclerophyll forests (Table 27), with the same dynamics contributing to ambiguous response predictions noted above.

Table 29 Predicted response of the signed digraph variables of the 'Dry sclerophyll forests' landscape class to cumulative changes in hydrological response variables for the Gloucester subregion

Signed digraph variable		Cumulative impact scenario	
Full name	Shortened form	C1 model 1	C1 model 2
Diurnal raptors	DR	?	?
Nocturnal raptor	NR	–	–
Aggressive native honeyeaters	ANHE	–	–
Swift parrot	SP	?	?
Regent honeyeater	RHE	?	?
Grey-headed flying fox	GHFF	?	?
Forest habitats	FH	–	–
Forest fragmentation	FF	+	+
Flowers and nectar	FN	–	–
Precipitation	Ppt	0	0
Koala	Koa	–	–
Arboreal mammals	AM	–	–
Dry sclerophyll overstorey (vegetation)	DSOS	–	–
Microclimate	MC	–	–
Recruitment	Rec	–	–
Dry sclerophyll ground layer (vegetation)	DSGL	–	0
Dry sclerophyll mid-storey (vegetation)	DSMS	–	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 determinancy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinancy are denoted by a question mark. Zero denotes completely determined predictions of no change.
Data: Bioregional Assessment Programme (Dataset 1)

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2.7.5 Limitations and gaps

Summary

This product concludes with the construction and interpretation of receptor impact models. The predictions of receptor impact variables at assessment units occurs in the impact and risk analysis product.

Limitations of the Gloucester subregion bioregional assessment (BA) receptor impact models and the knowledge gaps that prevented qualitative models for some potentially impacted landscape classes being developed into quantitative models are summarised. Limitations identified suggest that that opportunities to build on the receptor impact modelling include, considering water quality as a driver of potential change in receptor impact variables, extending the qualitative mathematical models developed for wet and dry sclerophyll forests or forested wetlands to receptor impact modelling, and exploring the implications of a drawdown up to 2m on the groundwater-dependent landscape classes. There are also opportunities to consider additional receptor impact variables and models given that the receptor impact variables used may speak more directly to some part of the ecosystem than others.

2.7.5.1 Prediction of receptor impact variables

Figure 3 in Section 2.7.1.2 summarises the receptor impact modelling workflow, starting from the identification of landscape classes that occur within the Gloucester subregion zone of potential hydrological change and that may be impacted, through to the prediction of receptor impact variables at assessment units. This product concludes with the construction and interpretation of receptor impact models, and the relationship between the receptor impact variable and one or more hydrological response variables used in the model. While this 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. Receptor impact variable prediction at assessment units occurs in the impact and risk product, 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 class.

2.7.5.2 Limitations of the receptor impact modelling

Section 2.7.1 and companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018) detail the strengths and limitations of the expert elicitation process used in BAs for building qualitative ecosystem models and quantitative receptor impact models. 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 in the zone of potential hydrological change for the Gloucester subregion reflect the subjectivity and bias inherent in the knowledge base of the assembled experts (e.g. in defining the scope of the model;

its components and connections; 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 class or ecosystem; a view that might brook argument about some of the specifics, but would generally be accepted as an adequate, high-level conceptualisation of the important components of the ecosystem(s) it represents.

However, some knowledge gaps and limitations were identified at the expert elicitation workshops, which limit the assessment of potential impacts from hydrological changes due to additional coal resource development for some landscape classes or components of landscape classes within the zone of potential hydrological change. In other words, they limit this BA and must be flagged as areas requiring further investigation.

While some models include salinity and/or nutrient components, the expert elicitations to define the results space for the receptor impact models are premised on changes in hydrology. Changes in water quality parameters that could occur with a shift in the relative contributions of surface runoff and groundwater to streamflow or due to enhanced connectivity between aquifers of differing water quality, for example, are not represented. Thus, the potential ecological impacts due to additional coal resource development reported in companion product 3-4 (impact and risk analysis) for the Gloucester subregion (Post et al., 2018) reflect the risk from hydrological changes only; they could differ if changes in key water quality parameters had been included in the model formulation.

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.

The signed digraphs for Gloucester subregion were elicited from participants present at the time of the qualitative modelling workshop, with a review process to confirm that the models reflected the knowledge conveyed. The purpose of the workshop was to provide a general description of the system that could be used as a focus for subsequent receptor impact modelling in follow-up workshops. Some of the variables ultimately used in the receptor impact modelling are not shown in the sign-directed graphs or are examples of more generic functional components. For instance, hydropsychids can be seen as an example of ‘high-flow macroinvertebrates’ in perennial streams. While the focus in the receptor impact modelling workshops across the Bioregional Assessment Programme closely followed the elements in the signed digraphs from the preceding qualitative modelling workshops, there were changes for some landscape classes in the Gloucester subregion. This reflected refinements to the receptor impact modelling process (the Gloucester subregion was the first) and the differences in the collective expertise between the two workshops.

There are opportunities for further refinement of the riverine signed digraphs, with some links and components subsequently identified that may be important. For example, with the intermittent landscape class some follow-up discussion as part of the review process has indicated that the ‘surface water regime’ (SWR) could also be linked with other components such as fine sediments (FS) and upstream recruitment (UR). Other discussion focused on the relationship between carp on submerged macrophytes, and the need to consider a predator-prey link between carp and small native fish (GS NF) or invertebrates (SW MI) in the signed digraph.

The canopy cover of woody vegetation, density of Hydropsychidae larvae, density of eel-tailed catfish and richness of hyporheic invertebrate taxa receptor impact variables for the perennial streams and intermittent streams were selected as indicators of instream 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 reflect those criteria and 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 instream ecosystems across the Gloucester subregion has not been established. The interpretation of results of the receptor impact models presented in companion product 3-4 for the Gloucester subregion (Post et al., 2018) is couched in terms of risk to instream habitat, rather than risks to the receptor impact variables themselves.

Qualitative models were developed for the ‘Forested wetlands’, ‘Wet sclerophyll forests’ and ‘Dry sclerophyll forests’. The ‘Forested wetlands’ landscape class focused on the role that the forest canopies play in providing flower nectar, habitat structure for nesting, and general habitat for various bird predators. There are opportunities for further refinement of the signed digraphs, including a stronger representation of the intrinsic responses of vegetation to groundwater even though the information on individual plant species response to shifts in depth to groundwater is limited. Discussion as part of the review process has focused on the link between forest fragmentation (FF) and forested wetland overstorey (FWOS), extending potential links from forest habitats' (FH) and flowers and nectar (FN) to other fauna (e.g. other birds, flying foxes), considering the potential absence of links to herpetofauna (e.g. frogs, reptiles) or insects, and the ecological role of organic matter cycling. Analogous opportunities around the qualitative modelling typically extend to ‘Wet sclerophyll forests’ and ‘Dry sclerophyll forests’. Receptor impact modelling could be conducted for ‘Forested wetlands’, ‘Wet sclerophyll forests’ and ‘Dry sclerophyll forests’.

The groundwater-dependent landscape classes cover fairly small areas within the zone of potential hydrological change, and none of these landscape classes are subject to drawdowns greater than 2 m. While there is uncertainty as to the frequency, timing and duration of groundwater use in the Gloucester subregion, the analysis would benefit from an additional elicitation process with experts around the potential implications of up to 2 m of drawdown.

A more comprehensive listing of the gaps and opportunities that have emerged during the Gloucester subregion BA is provided in Section 3.7 of companion product 3-4 (Post et al., 2018).

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Glossary

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

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

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

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).

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

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

baseflow index: the ratio of baseflow to total streamflow over a long period of time (years)

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

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

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

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

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

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

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

conceptual model: abstraction or simplification of reality

connectivity: a descriptive measure of the interaction between water bodies (groundwater and/or surface water)

consequence: synonym of impact

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

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

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

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

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.

ecosystem function: the biological, geochemical and physical processes and components that take place or occur within an ecosystem. It refers to the structural components of an ecosystem (e.g. vegetation, water, soil, atmosphere and biota) and how they interact with each other, within ecosystems and across 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).

EventsR0.3: 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 0.3 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 overbench flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development.

EventsR3.0: 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 3.0 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.

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).

Gloucester subregion: The Gloucester subregion covers an area of about 348 km^2. The Gloucester subregion is defined by the geological Gloucester Basin. It is located just north of the Hunter Valley in NSW, approximately 85 km north-north-east of Newcastle and relative to regional centres is 60 km south-west of Taree and 55 km west of Forster.

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

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 develoment 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.

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).

Kurosols: Soils other than Hydrosols with a clear or abrupt textural B horizon and in which the major part of the upper 0.2 m of the B2 horizon (or the major part of the entire B2 horizon if it is less than 0.2 m thick) is strongly acid.

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).

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 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.

material: pertinent or relevant

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 overbench flow: high-flow condition where a river channel is partially or completely filled for a period of weeks to months. All habitats within the river channel will be wet including boulders, logs and lateral benches, and the entire length of the channel is connected with relatively deep water, allowing movement of biota freely along the river.

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.

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'.

QBFI: ratio of total baseflow generation to total streamflow generation, averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.

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

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.

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

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

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. (Note that for the Gloucester subregion, only eight hydrological response variables were used to define the surface water zone.) 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.

Tenosols: Soils that do not fit the requirements of any other soil orders and generally with one or more of the following: i. A peaty horizon. ii. A humose, melacic or melanic horizon, or conspicuously bleached A2 horizon, which overlies a calcrete pan, hard unweathered rock or other hard materials; or partially weathered or decomposed rock or saprolite, or unconsolidated mineral materials. iii. A horizons which meet all the conditions for a peaty, humose, melacic or melanic horizon except the depth requirement, and directly overlie a calcrete pan, hard unweathered rock or other hard materials; or partially weathered or decomposed rock or saprolite, or unconsolidated mineral materials. iv. A1 horizons which have more than a weak development of structure and directly overlie a calcrete pan, hard unweathered rock or other hard materials; or partially weathered or decomposed rock or saprolite, or unconsolidated mineral materials. v. An A2 horizon which overlies a calcrete pan, hard unweathered rock or other hard materials; or partially weathered or decomposed rock or saprolite, or unconsolidated mineral materials. vi. Either a tenic B horizon, or a B2 horizon with 15% clay (SL) or less1, or a transitional horizon (C/B) occurring in fissures in the parent rock or saprolite which contains between 10 and 50% of B horizon material (including pedogenic carbonate). vii. A ferric or bauxitic horizon >0.2 m thick. viii. A calcareous horizon >0.2 m thick.

tmax: year of maximum change

tmaxRef: the year that the maximum difference in drawdown relative to the reference period (1983 to 2012) (dmaxRef) occurs.

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

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

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

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

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

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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