Australian Government

BIOREGIONAL ASSESSMENTS

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

Receptor impact modelling for the Hunter subregion

Product 2.7 for the Hunter 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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Authorship is listed in relative order of contribution.

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Cover photograph

Oblique view west of Muswellbrook showing Bengalla coal storage (left foreground) with irrigated agriculture and riparian vegetation either side of the Hunter River and Mount Arthur coal mine in the distance (right background), NSW, 2014

© Google earth (2015), Sinclair Knight Merz Imagery date 16 December 2008. Position 32°17′58′′ S, 150°48′51′′ E, elevation 136 m, eye altitude 1.59 km

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Executive summary

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

A receptor impact model describes the relationship between:

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

Receptor impact modelling for the Hunter subregion applies the two potential coal resource development futures considered in the bioregional assessments:

- *baseline coal resource development (baseline)*: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as at December 2012. In the Hunter subregion the baseline includes 42 mining operations, comprising 22 open-cut mines and 20 underground mines
- *coal resource development pathway (CRDP)*: a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012. In the Hunter subregion as of September 2015, the *additional coal resource development* includes a further 22 proposals for coal resource developments, including 3 new open-cut coal mines, 3 new underground coal mines and 16 expansions to baseline mining operations. As of May 2015, there is no CSG production in the Hunter subregion, nor any proposals for CSG development in the future.

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 products 2.6.1 (surface water modelling) and 2.6.2 (groundwater modelling); the process of developing qualitative mathematical models and receptor impact models is summarised in this product.

To simplify the impact and risk analysis for this additional coal resource development, the Hunter subregion is broken into five landscape groups – 'Riverine', 'Groundwater-dependent ecosystem (GDE)', 'Coastal lakes and estuaries', 'Non-GDE vegetation' and 'Economic land use' – which comprise 26 landscape classes, broadly differentiated by ecohydrological characteristics. Only landscape classes that intersect the zone of potential hydrological change were candidates for qualitative models.

Two modelling workshops were held to build the qualitative mathematical models and receptor impact models and required input from experts in these landscapes and/or the Hunter subregion. Receptor impact models were developed for landscape classes that experts considered more likely to be at risk from hydrological changes due to additional coal resource development, and for which they had the expertise to inform model development.

Six receptor impact models were developed: 'Perennial streams – riffle-breeding frogs', 'Perennial streams – Hydropsychidae larvae', 'Intermittent streams – riffle-breeding frogs', 'Intermittent streams – hyporheic invertebrate taxa', 'Forested wetlands (riverine forest) – projected foliage cover' and 'Wet and dry sclerophyll forests – projected foliage cover'. They quantify relationships between components of four qualitative models, representing five landscape classes.

Qualitative models were developed for a further seven landscape classes: 'Highly intermittent or ephemeral' streams, 'Rainforest', 'Freshwater wetland', 'Lakes', 'Lagoons', 'Saline wetlands', and 'Seagrass'. Quantitative models of ecosystem response were not progressed for these landscape classes because the project team and experts at the qualitative modelling workshops considered it unlikely that these landscape classes would be impacted by hydrological changes due to additional coal resource development, or were too uncertain about ecosystem responses to potential hydrological changes to provide meaningful quantitative estimates (e.g. in the 'Freshwater wetland' landscape class). The qualitative model for the 'Rainforest' landscape class, was premised on rainforests in sheltered gullies and slopes in hilly-to-steep terrain, which were considered unlikely to be affected by drawdown of the regional watertable. This does not take into account the 10 km^2 of rainforests that overlaps with the alluvium in the Hunter subregion suggesting that, despite their topographic position, these rainforest communities may have some dependence on alluvial groundwater in some circumstances. This rainforest community represents a gap in the receptor impact modelling.

Four landscape classes that intersect the zone of potential hydrological change do not have qualitative models. They are 'Heathland', 'Grassy woodland', 'Semi-arid woodland' and 'Creeks' (part of the 'coastal lakes and estuaries' landscape group). These landscape classes generally depend on rainfall and/or local groundwater and are considered *very unlikely* (less than 5% chance) to be impacted by hydrological changes due to additional coal resource development.

Descriptions of the qualitative mathematical models and receptor impact models are provided under the landscape group headings. To define the results space for the receptor impact variables, elicitation scenarios were chosen to represent the range of modelled hydrological results under baseline and additional coal resource development. The receptor impact variables serve as indicators of potential impact to the ecosystems they represent. Riffle-breeding frogs, for example, are not found along every reach of intermittent and perennial stream in the Hunter subregion, and the models do not assume this. Rather the models predict whether, everything else being equal, a given hydrological change will enhance or diminish the habitat suitability of a reach of stream for riffle-breeding frogs, and by extension other components of the ecosystem that have similar flow dependencies or depend on components that do. Results from application of the receptor impact models to modelled hydrological changes in the Hunter subregion are reported in Section 3.4 of companion product 3-4 (impact and risk analysis) for the Hunter subregion.

'Riverine' landscape group

In the qualitative mathematical model for the 'Permanent or perennial' streams landscape class, experts identified groundwater levels, riffle flow, overbench flow, overbank flow and zero-flow days as critical determinants of instream and riparian habitat condition. Reductions in groundwater levels and streamflow, resulting in increases in zero-flow days, are generally considered to have negative impacts on riparian and subsurface habitats.

Two instream receptor impact models were developed, reflecting the response of riffle-breeding frogs and flow-dependent macroinvertebrates to changes in zero-flow days. As the number of zero-flow days increases, experts generally considered that:

- the probability of presence of riffle-breeding frogs would drop quite dramatically, with the model reflecting a chance of no presence under extremely dry conditions
- the density of Hydropsychidae (net-spinning caddisflies) larvae would drop dramatically, with the model reflecting the possibility of less than 1 per m^2 under increasingly intermittent flow regimes.

In the qualitative mathematical model for the 'Lowly to highly intermittent' streams landscape, the same hydrological variables as for the perennial streams were identified as critical to habitat condition, with flow reductions and lowering of the watertable generally assumed to result in negative impacts.

The two receptor impact models represent the response of hyporheic invertebrate taxa (organisms found where surface water and groundwater mix below the bed of a stream) and riffle-breeding frogs to changes in zero-flow days and the duration of zero-flow spells. With increasing zero-flow days, experts generally considered that:

- the probability of presence of riffle-breeding frogs would drop quite dramatically, with the possibility of no presence under extremely dry conditions
- the hyporheic invertebrate taxa richness would fall, with the chance of fewer than 10 in 6 L of water under extremely dry conditions.

'Groundwater-dependent ecosystem' landscape group

Eight of nine GDE landscape classes occur within the zone of potential hydrological change. The 'Spring' landscape class does not intersect the zone and can be ruled out as *very unlikely* to be impacted by additional coal resource development.

The qualitative model for the 'Forested wetland' landscape class was based on the biological processes and environmental factors that regulate tree, shrub and herb composition in riparian systems of inland and coastal rivers of the Hunter subregion. The model recognises the possibility for coal resource development to impact the groundwater regimes that support these forest communities. Qualitative analysis generally indicates a negative predicted response on trees, seeds and seedlings to changes in hydrology, with a corresponding decline in shade, habitat structure, bank stability and orchids and fungi.

The receptor impact model for the ‘Forested wetland’ landscape class quantifies the response of projected foliage cover of riverine forests of central and western Hunter to changes in hydrology. Coastal swamp oak communities are not represented by this model, nor riverine forests along the regulated Hunter River and Glennies Creek. Experts generally thought that:

- initial foliage cover in the reference period has a positive effect on the likelihood of future foliage cover
- groundwater extraction has a negative effect on projected foliage cover
- increased frequency of both overbench and overbank flows has a positive effect on projected foliage cover.

Experts at the Hunter subregion qualitative modelling workshop determined that ‘Wet sclerophyll forest’ and ‘Dry sclerophyll forest’ landscape classes could be represented in a single model. Groundwater was assumed to be the dominant water source. The qualitative model assumes trees, seedlings and shrubs are adversely affected by groundwater depletion, with reductions in shade, habitat structure, nectar, nectar consumers, predators, sap-eating and leaf-eating insects, gliders and koalas. Insects are shown as potentially increasing due to reduced predation.

The ‘Wet and dry sclerophyll forests’ receptor impact model reflects the experts’ view that:

- initial foliage cover in the reference period has a positive effect on future foliage cover
- groundwater extraction has a negative effect on projected foliage cover.

A qualitative mathematical model for the ‘Rainforest’ landscape class was developed based on a modified version of the wet and dry sclerophyll forests model. Experts assumed that rainforests generally occupy sheltered gullies and slopes in hilly-to-steep terrain, that they might use groundwater opportunistically, and that the groundwater would be from local sources (e.g. perched watertables), not connected to a regional watertable. Thus, the rainforests were considered unlikely to be affected by coal resource development and a quantitative model was not progressed.

The ‘Freshwater wetland’ landscape class is described as a complex of marsh and pond habitats. These wetlands are reported in the literature as largely dependent on local, perched groundwater systems. They were considered unlikely to be impacted by coal resource developments higher in the catchment and quantitative models were not progressed for this landscape class. However, given some uncertainty about freshwater wetland connections with regional groundwater, it is recommended that an assessment of the potential for impacts on a freshwater wetland be informed by understanding of the local and regional hydrology.

‘Coastal lakes and estuaries’ landscape group

Qualitative models were developed for subtidal benthos and intertidal wetland communities, which pertain to ‘Seagrass’, ‘Lakes’, ‘Lagoons’ and ‘Saline wetlands’ landscape classes. The subtidal benthos qualitative model reflects the view that seagrass beds are sensitive to subsidence from underground mining, leading to an increase in water depth, hence reduced light penetration, to the seagrass beds. As the proposed Wallarah 2 and Mandalong Southern Extension mines are not under the coastal lakes, there is no risk of subsidence of the lake beds from these developments. The proposed Chain Valley extension does involve coal extraction from under Lake Macquarie, but not within the high water mark subsidence barrier, as required under existing regulations to minimise risks from subsidence in these areas. A quantitative model was not developed for subtidal benthos.

The qualitative model for intertidal wetlands identified an interaction between groundwater and saltmarsh, which was very local in scale. There was considerable uncertainty about interactions with regional groundwater, if any. Modelling of groundwater drawdown due to additional coal resource development indicated a small chance of drawdown in areas of mapped saline wetlands on the eastern side of Lake Budgewoi, the Dora Creek inflow to Lake Macquarie and around the Lake Macquarie entrance. A quantitative model was not developed for intertidal wetlands.

The receptor impact modelling described in this product guides how companion product 3-4 (impact and risk analysis) for the Hunter subregion is framed. This product will describe the difference between results for the CRDP and the baseline (due to the additional coal resource development) for only those developments that can be modelled in the Hunter subregion.

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This technical product was reviewed by several groups:

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

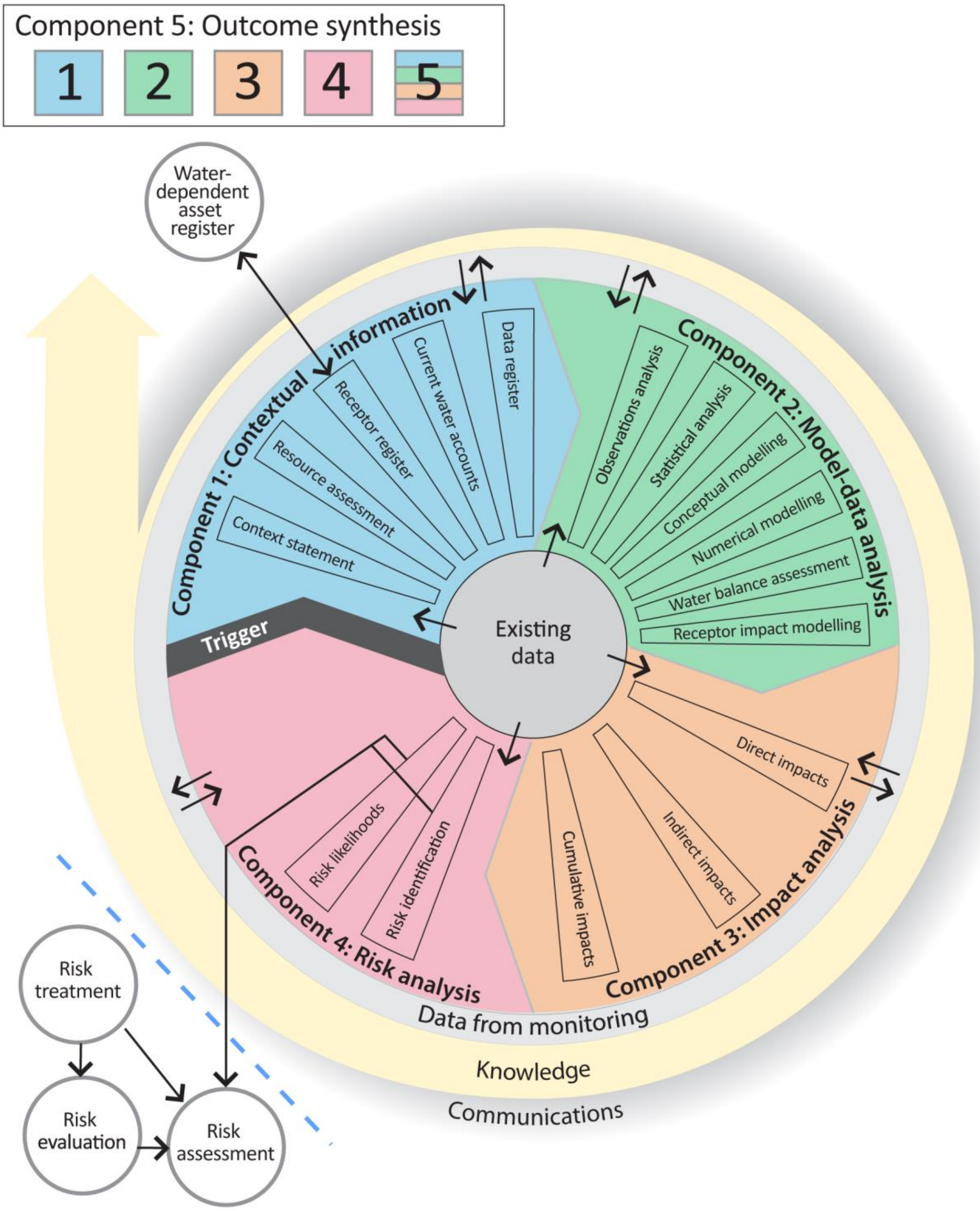

Figure 1 Schematic diagram of the bioregional assessment methodology

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.

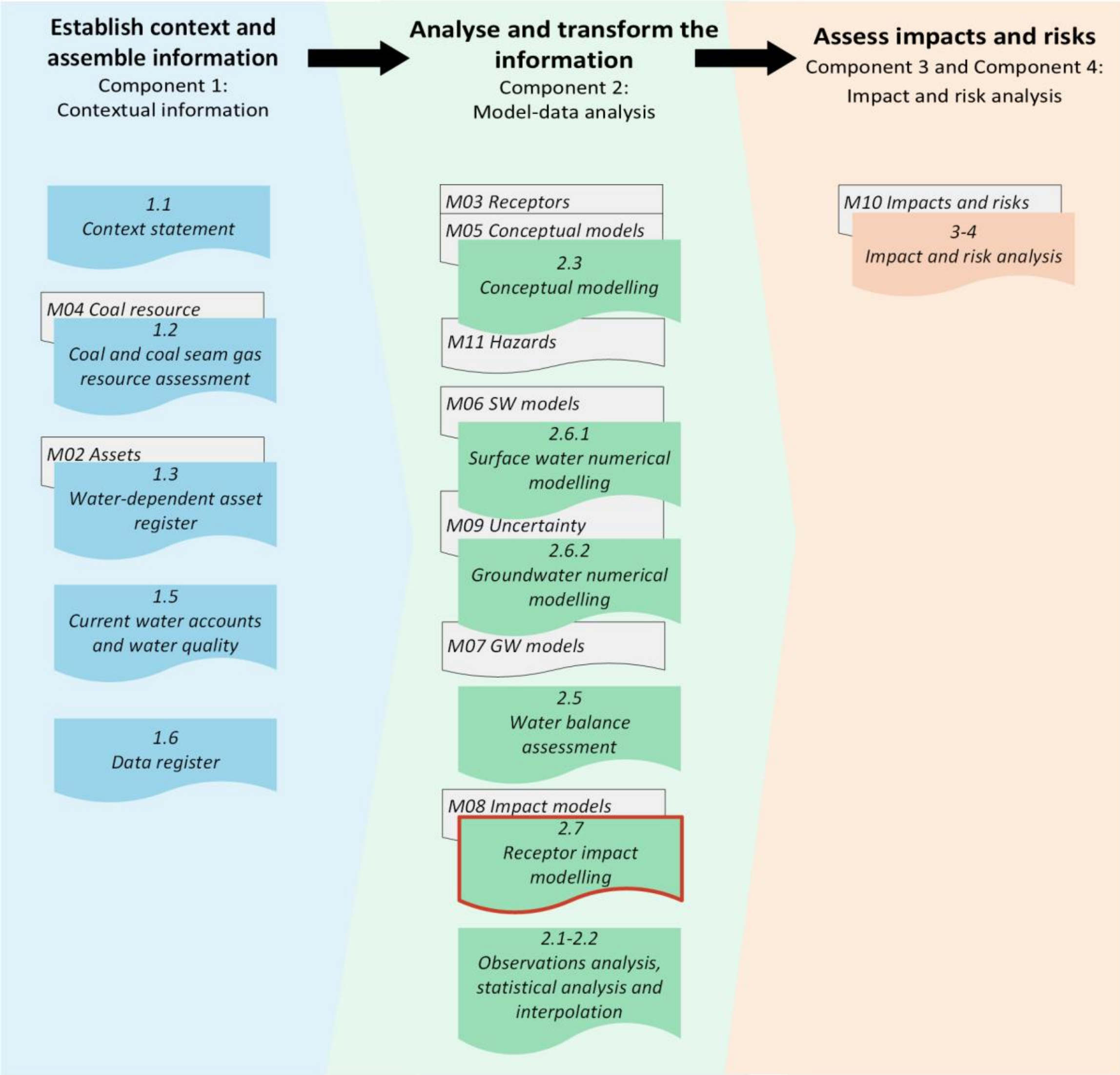

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 Hunter 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 Hunter 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 Hunter 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 Hunter subregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3	PDF, HTML
Component 5: Outcome synthesis for the Hunter 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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2.7 Receptor impact modelling for the Hunter subregion

This product presents receptor impact modelling for the Hunter 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 Hunter 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 Hunter 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 changes to specific components of an ecosystem that may result from hydrological changes predicted in response to coal resource development. A receptor impact model is constructed for one or more landscape classes. A landscape class represents ecosystems with similar water dependencies that are expected to respond similarly to changes in groundwater and/or surface water. Only landscape classes that intersect the zone of potential hydrological change are considered 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 elicited from independent experts and contain key components and processes of the landscape class ecosystems, and the hydrological variables that support them. They are then used to qualitatively predict (reported as increase, decrease or no change) how the landscape class ecosystem will respond to changes in hydrology that may occur as a result of coal resource development.

The receptor impact modelling process continues with selection of receptor impact variables from the ecological components identified in the qualitative mathematical model and hydrological response variables to represent the hydrological regimes that support these components. Thus, the landscape classification and qualitative mathematical models form the bases for carefully structured elicitations that use expert opinion to quantify the potential changes in receptor impact variables in response to (often simultaneous) changes in hydrological response variables. Importantly, the elicitations capture experts’ uncertainty in this response and allow for variability in the response within the landscape class.

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. The statistical model describes the conditional probability of the receptor impact variable taking specific values given specified values of the hydrological response 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 the defined landscape classes. The aim of receptor impact modelling is to convert the potentially abstract information about hydrological changes into predictions about impacts on values (risk assessment endpoints) that ideally stakeholders care about and can more readily understand and interpret. The receptor impact models should 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 Hunter 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 2102).

This product presents the receptor impact modelling for the Hunter subregion. The modelling is described in detail in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018). Section 2.7.1.2 of this document describes how this methodology is applied to the Hunter 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 M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016) and companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

- *receptor impact variable* – a characteristic of the system that, according to the conceptual modelling, potentially changes due to changes in hydrological response variables (for example, condition of the breeding habitat for a given species, or biomass of river red gums)
- *receptor impact model* – a receptor impact model predicts a relationship between a receptor impact variable (for example annual mean percent 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 or subregion 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 (companion product 2.6.2 (Herron et al., 2018b); companion product 2.6.1 (Zhang et al., 2018) for the Hunter 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.

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 Hunter 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 (Stage 1 in Figure 3) 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 defined (using a precautionary approach) 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 Hunter subregion, the relevant aquifer is the regional watertable.

The surface water zone of potential hydrological change is defined in a similarly precautionary manner. The area contains those river reaches where a change in at least one of nine 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 6 in companion product 3-4 for the Hunter subregion (Herron et al., 2018a)). That is, if 5% or more of model runs show a maximum change in results under CRDP of 1% relative to baseline. For four of the frequency-based hydrological response variables – high-flow days (FD), low-flow days (LFD), length of low-flow spell (LLFS) and zero-flow days (ZFD) – the threshold is a 5% chance of a change of 3 days per year. For the final frequency-based hydrological response variable (low-flow spells, LFS), the threshold is a 5% chance that the maximum difference in the number of low-flow spells between the baseline and CRDP futures is at least two spells per year (companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)).

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, on the grounds that the latter are predicted to experience negligible (or insignificant) exposure to hydrological change due to coal resource development.

2.7.1.2.2 Qualitative mathematical modelling of landscape classes

BAs use qualitative mathematical models to describe landscape class ecosystems, and to predict (qualitatively) how coal resource development will directly and indirectly affect these ecosystems. Qualitative mathematical models were constructed in dedicated workshops, attended by experts familiar with these landscapes and/or the Hunter 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 that will become the focus of the quantitative receptor impact models.

Table 3 Name and organisation of external experts who participated in the Hunter subregion qualitative mathematical modelling (QMM) and receptor impact modelling (RIM) workshops

Organisation	Number of attendees at the QMM workshop	Number of attendees at the RIM workshop
Department of the Environment and Energy	1	1
Eco Logical Australia	0	3
Edith Cowan University	1	0
La Trobe University	1	1
Macquarie University	2	1
NSW Department of Primary Industries	1	1
NSW Office of Environment and Heritage	4	1
University of Canberra	1	0
University of New England	1	1
University of New South Wales	2	0
University of Newcastle	2	1
University of Technology Sydney	0	1

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 (Dambacher et al., 2002, 2003). 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.

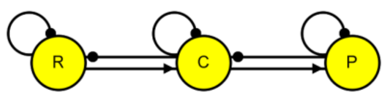

Figure 4 Signed digraph depicting a straight-chain system with a basal resource (R), consumer (C) and predator (P)

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 it would be expected to return relatively quickly to its previous state or equilibrium.

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

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

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

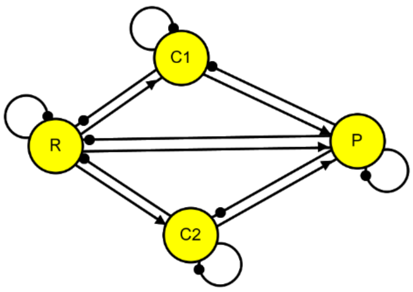

Figure 5 Signed digraph depicting a more complex system containing an additional consumer and a predator that feeds on more than one tropic level

Here the predicted response of R due to an input that causes P to increase 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) described a statistical approach that estimates the probability of sign determinacy for each response prediction. In 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 the approach described by Dambacher et al. (2003), in the system depicted in Figure 5, R is predicted to increase 77% of the time because of the ratio of the net to the total number of paths.

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

2.7.1.2.3 Choice of hydrological response variables and receptor impact variables

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

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

Hydrological response variables are derived from the numerical surface water and groundwater model results to represent these ecologically important water requirements. The surface water hydrological response variables in the receptor impact models are defined in terms of mean annual values for two 30-year periods: 2013 to 2042 and 2073 to 2102 (e.g. mean number of zero-flow days per year between 2013 and 2042). The hydrological response variables are generalised for the assessment extent and thus serve as indicators of change in ecologically important flows, rather than accurate characterisation of flow regimes at local scales. They differ from the hydrological response variables defined in companion product 2.6.1 for surface water modelling in the Hunter subregion (Zhang et al., 2018), which represent the maximum difference between the CRDP and baseline simulations over the 90-year simulation period (e.g. the maximum difference in zero-flow days per year between 2013 and 2102).

Receptor impact variables are selected according to the following criteria:

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

Receptor impact variables are chosen as indicators about the response of a landscape class. Changes in the receptor impact variables (e.g. foliage cover; taxa richness) imply changes to the ecology of the landscape class. A decrease in projected 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. A receptor impact variable that is not an asset 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 and subregions to address within the operational constraints of the programme. The design must also respect, as much as possible, the predicted hydrological regimes as summarised by hydrological modelling outputs. Without this information, design points may present hydrological scenarios that are unrealistically beyond bounds suggested by the landscape class definition. Alternatively, insufficiently wide bounds on hydrological regimes lead to an overextrapolation problem when receptor impact model predictions are made conditional on hydrological simulations at the risk-estimation stage (Stage 6 in Figure 3). The design must further respect the feasibility of the design space, which may be constrained by mathematical relationships between related hydrological response variables. The design must accommodate the requirement to predict to past and future assessment years. The design must also allow for the estimation of potentially important interactions and nonlinear impacts of hydrological response variables on the receptor impact variable.

2.7.1.2.4 Construction and estimation of receptor impact models

BAs address the question ‘How might selected receptor impact variables change under various scenarios of change for the hydrological response variables?’ through formal elicitation of expert opinion. This is a difficult question to tackle and presents a challenging elicitation task. BAs implement a number of processes that are designed to help meet this challenge: (i) persons invited to the receptor impact modelling workshops are selected based on the relevance of their domain expertise; (ii) all experts are provided with pre-workshop documents that outline the approach, the expectations on the 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 (as listed in Table 1) for receptor impact modelling (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.

As described in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018) (Section 5.1.1), all models used in BAs are forms of log-linear models and the receptor impact model coefficients therefore can be interpreted in terms of multiplicative change. On the transformed scale (log or complementary log-log) the coefficients are unitless weights that show the predicted change to the expected value of the response variable follow a change of one unit of the predictor variable holding all other predictor variables constant. Taken together, the model coefficients determine the combine effect of changes to the predictor variables on the expected value of the response variable. On the transformed scale this combined effect is assumed to be linear. On the absolute scale this combined effect would be multiplicative.

2.7.1.2.5 Receptor impact model prediction

This stage (Stage 7 in Figure 3) applies the receptor impact model methodology to predict the response of the receptor impact variables. The general framework allows for the receptor impact model to be applied either at single or multiple receptor locations. The receptor impact model can therefore be applied at multiple receptor locations that are representative of a landscape class within a bioregion or subregion. The primary endpoint considered, however, is predicting receptor impact variable response to the BA future across an entire landscape class, which is accomplished by including all receptors that represent the hydrological characteristics of the landscape class. The uncertainty from the hydrology modelling is propagated through the receptor impact model at each receptor location to 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 for the Hunter subregion (Herron et al., 2018a). 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

The 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 these assumptions for the results, and how these implications are acknowledged through the BA products.

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

Assumptions of receptor impact modelling	Implications	Acknowledgement
Discretisation of continuous landscape surface	Provided a defined spatial scope for experts to address. Connections between landscape classes broken. Changes in one landscape class may have implications for adjacent landscape classes.	Identify 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 is sufficient and correct	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 for receptor impact models	Acknowledge issues with data in the impact and risk product (also done in the conceptual modelling product). In companion product 3-4 for the Hunter subregion (Herron et al., 2018a) acknowledge that mapped results reflect the mapped inputs
Areas of landscape classes are constant over modelling period	Provides a defined spatial scope for expert assessment of change. 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	Acknowledge in Methods
Other developments and users of water (e.g. agriculture) are constant over time	Provided a defined context for experts to consider. BA is about 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	Acknowledge in Methods

Assumptions of receptor impact modelling	Implications	Acknowledgement
Landscape characteristics other than hydrological variables are not represented in quantitative receptor impact models	Limits hydrological response variables used in receptor impact models to those that may be derived from 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	Identify as knowledge gap when the hydrological response variables used in the model represent a subset of the key dependencies. Acknowledge importance of local (vs regional) analyses where the concern is over particular parts of a landscape class
Experts available adequately represent the state of knowledge for relevant landscape classes	Experts provided domain expertise and experience that informed both model structure and also provided quantifiable predictions of receptor impact variable response 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 in the room	Acknowledge that the receptor impact variable is an ‘indicator’ of the potential ecosystem response. Identify as knowledge gap where part of the landscape class is not represented
The simplification of complex systems is appropriate for the task	Provided formal approach to model identification and selection of candidate receptor impact variables. Not all components and relationships are represented by receptor impact models	Acknowledge 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
A common set of modelled hydrological response variables is appropriate across different landscape classes	Limits hydrological response variables used in receptor impact models to those that may be derived from hydrological models developed by BA. Enables some simplification of complex systems. Loss of local specificity in predictions of receptor impact variables	The need for local-scale information is identified (in multiple places)
Receptor impact variables are good indicators of ecosystem response	The qualitative models informed the selection of receptor impact variables within the additional constraints imposed by expert availability given project timelines. Focus of the quantified relationships within the landscape class	The need for local-scale information is identified (in multiple places)

Assumptions of receptor impact modelling	Implications	Acknowledgement
Extrapolation of predictions beyond elicitation scenarios	The 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. However, 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	Identify as a limitation for the appropriate landscape class in the impact and risk product 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 models may not accurately-represent impacts of shorter-term hydrological changes (pulse perturbations) on ecosystems and landscape classes	Describe rationale for the focus on press perturbations in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018). Note that many potential pulse perturbations are caused by accidents and managed by site-based processes. Identify as a limitation / knowledge gap. Note that quantitative receptor impact models do account for pulse perturbations

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2.7.2 Prioritising landscape classes for receptor impact modelling

Summary

Landscape classes that intersect the zone of potential hydrological change could potentially be impacted by hydrological changes due to additional coal resource development. Most of the ecological landscape classes in the Hunter subregion intersect the zone; only the 'Spring', 'Barrier river' and 'Drowned valley' landscape classes do not and can be ruled out as *very unlikely* (less than 5% chance) to be impacted by hydrological changes due to additional coal resource development.

Six quantitative models (receptor impact models) have been developed for five landscape classes in the 'Riverine' and 'Groundwater-dependent ecosystem (GDE)' landscape groups: perennial streams, intermittent streams, forested wetlands, and wet and dry sclerophyll forests. The quantitative model developed for the 'Forested wetland' is specific to riverine forests, and should not be applied to coastal vegetation classes within the 'Forested wetland' landscape class.

Qualitative models have been developed for a further five landscape classes, but the experts' and/or project team's view was that they are unlikely to be impacted by hydrological changes due to additional coal resource development and quantitative models were not progressed. These qualitative models, which represent ephemeral streams, rainforests, freshwater wetlands, subtidal benthos and intertidal wetlands, have been developed for the 'Highly intermittent or ephemeral', 'Rainforest', 'Freshwater wetland', 'Seagrass', and 'Lakes', 'Lagoons' and 'Saline wetlands' landscape classes, respectively.

Four landscape classes that intersect the zone of potential hydrological change do not have qualitative models. They are 'Heathland', 'Grassy woodland', 'Semi-arid woodland' and 'Creeks'. These landscape classes generally depend on rainfall and/or local groundwater and are considered *very unlikely* (less than 5% chance) to be impacted by hydrological changes due to additional coal resource development.

2.7.2.1 Potentially impacted landscape classes

Prior to the qualitative modelling workshop, the zone of potential hydrological change was used to (i) identify ecological landscape classes that intersect it and are potentially impacted by the modelled hydrological changes due to additional coal resource development, and (ii) rule out landscape classes that do not intersect the zone and are therefore considered *very unlikely* (less than 5% chance) to be impacted by changes in hydrology. Qualitative and/or receptor impact models are only needed for those ecological landscape classes that are potentially impacted.

Qualitative models and receptor impact models were not built for 'Economic land use' and 'Non-GDE vegetation' landscape groups, which are not considered water dependent in the definition adopted for the bioregional assessments (BAs). Potential impacts on water-dependent economic assets are covered in companion product 3-4 (impact and risk analysis) for the Hunter subregion (Herron et al., 2018).

The zone of potential hydrological change, defined in Section 3.3.1 of companion product 3-4 for the Hunter subregion (Herron et al., 2018), encompasses the area where the predicted changes in groundwater drawdown and/or surface water hydrological response variables due to additional coal resource development could potentially impact water-dependent landscape classes and assets. The total area of the zone of potential hydrological change is 3213 km^2 and comprises four distinct groundwater drawdown areas linked by a potentially impacted surface water corridor in the Hunter river basin, and a fifth groundwater area and associated surface water corridor in the Macquarie-Tuggerah lakes basin (see Figure 17 in companion product 3-4 for the Hunter subregion (Herron et al., 2018)).

Table 5 lists the 19 ecological landscape classes in the Hunter subregion (see companion product 2.3 for the Hunter subregion (Dawes et al., 2018)) and identifies those that do and do not intersect the zone of potential hydrological change. All riverine landscape classes and eight of the nine groundwater-dependent ecosystem (GDE) landscape classes are present within the zone of potential hydrological change, although some GDE landscape classes are only represented by very small areas, such as the ‘Grassy woodland’, ‘Heathland’ and ‘Semi-arid woodland’ landscape classes. The ‘Spring’ landscape class is one of two landscape classes that do not intersect the zone and is ruled out of further consideration. Of the ‘Coastal lakes and estuaries’ landscape group, all landscape classes except ‘Drowned valleys’ are present within the zone, although several are only represented by very small areas, such as the ‘Creeks’ and ‘Barrier river’ landscape classes. Maps showing the landscape classes within each landscape group that are in the zone of potential hydrological change are provided in Section 3.4 of companion product 3-4 for the Hunter subregion (Herron et al., 2018).

Table 5 Length or area of each landscape class within the zone of potential hydrological change (zone)

Landscape class names as shown in companion product 2.3 for the Hunter subregion (Dawes et al., 2018). Also indicated is whether the landscape class is represented in a qualitative model (shown by model name) and/or a receptor impact model (RIM).

Landscape group	Landscape class	In the zone	Length (km) / area (km^2) in the zone	Qualitative model	RIM
Riverine (km)	Permanent or perennial	Yes	634	Perennial streams	1. Perennial streams – riffle-breeding frogs 2. Perennial streams – Hydropsychidae larvae
	Lowly to highly intermittent[a]	Yes	518	Intermittent streams	1. Intermittent streams – riffle-breeding frogs 2. Intermittent streams – hyporheic invertebrate taxa
	Highly intermittent or ephemeral	Yes	1985	Ephemeral streams	No
GDE (km^2)	Rainforest	Yes	23.9	Rainforests	No
	Wet sclerophyll forest	Yes	4.5	Wet and dry sclerophyll forests	Wet and dry sclerophyll forests
	Dry sclerophyll forest	Yes	14.6		
	Freshwater wetland	Yes	1.1	Freshwater wetlands	No
	Forested wetland	Yes	57.8	Forested wetlands	Forested wetland – riverine forest
	Grassy woodland	Yes	0.2	No	No
	Heathland	Yes	0.2	No	No
	Semi-arid woodland	Yes	<0.1	No	No
	Spring	No	na	No	No
Coastal lakes and estuaries (km^2)	Lakes	Yes	76.2	Intertidal wetlands	No
	Lagoons	Yes	3.8		
	Seagrass	Yes	15.6	Subtidal benthos	No
	Saline wetlands	Yes	1.5	Intertidal wetlands	No
	Creeks	Yes	<0.1	No	No
	Barrier river	Yes	0.4	No	No
	Drowned valleys	No	na	No	No

[a]The 'Lowly to moderately intermittent' and 'Moderately to highly intermittent' landscape classes from companion product 2.3 for the Hunter subregion (Dawes et al., 2018) are treated as one landscape class, listed here as 'Lowly to highly intermittent'.
GDE = groundwater-dependent ecosystem, na = not applicable
Data: Bioregional Assessment Programme (Dataset 1)

Table 5 also identifies for those landscape classes within the zone of potential hydrological change, whether a qualitative model was built (indicated by the model name) or not and whether a receptor impact model was built. Six receptor impact models were built, representing five landscape classes; seven landscape classes have qualitative models, but not receptor impact models; five landscape classes that intersect the zone of potential hydrological change do not have qualitative models. Details of the qualitative models and receptor impact models are provided in Sections 2.7.3, 2.7.4 and 2.7.5 of this product, while the results from modelling the effects of baseline and additional coal resource development on landscape classes using these models are presented in Section 3.4 of companion product 3-4 for the Hunter subregion (Herron et al., 2018). The reasons for not building qualitative and/or receptor impact models for some landscape classes are outlined in Section 2.7.2.2, Section 2.7.2.3 and Section 2.7.2.4.

2.7.2.2 'Riverine' landscape group

The total length of streams in the riverine landscape group within the zone of potential hydrological change is 3138 km, 63% of which is in highly intermittent or ephemeral streams, which were considered predominantly rainfall-dependent and not encompassed in the definition of water-dependent adopted for the BAs. For BA purposes, an ephemeral stream is defined as a stream that flows only briefly during and following a period of rainfall, and has no baseflow component. Thus groundwater changes due to additional coal resource development are unlikely to have a significant impact on ephemeral stream hydrology. Interception and storage of local runoff on a mine site can impact ephemeral streamflow; however, since communities associated with ephemeral streams are adapted to high runoff variability and respond opportunistically to water when it is there, they are considered less vulnerable to changes in catchment runoff. A qualitative model was developed for streams in the 'Highly intermittent or ephemeral' landscape class (ephemeral streams; Table 5), but was not progressed to a receptor impact model.

The qualitative models for the perennial, intermittent and ephemeral streams all include a riparian habitat component. For perennial streams, this model node (circles in the signed digraphs in the subsequent sections) serves as a linking node to the forested wetland GDE qualitative model. Along intermittent and ephemeral streams, this node could represent the connection to a dry sclerophyll forest, rainforest or other landscape class qualitative model. Similarly, the frog nodes in the perennial river model and the forested wetland model represent another point of connection, reflecting the interconnectedness of the landscape classes. In other words, while the riverine qualitative models are largely self-contained, they include components that enable them to be linked to other qualitative models, representing other parts of the landscape. Of course, not all possible interconnections between the riverine qualitative models and other landscape class models are represented, as this was not the objective of the model building process.

Receptor impact modelling, described in Section 2.7.3, focuses on perennial streams and intermittent streams (Table 5). The 'Lowly to highly intermittent' landscape class designation in Table 5 combines the two intermittent riverine landscape classes ('Lowly to moderately intermittent' and 'Moderately to highly intermittent') that were defined from the flow regime classification methodology (see Section 2.3.3 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018)) on the basis that both are variably connected to groundwater. For the purposes of developing the qualitative model, it was agreed at the workshop that a single model could represent both landscape classes.

The discretisation of the stream network into landscape classes, based on flow regimes that broadly reflect connection to groundwater, was considered useful for differentiating between different instream ecosystems. In some streams, the modelled hydrological changes indicate the possibility of a switch from perennial to intermittent or ephemeral flow, or from intermittent to ephemeral flow. In other words, a change in landscape classification. The expert elicitations for the intermittent and perennial stream models include hydrological change scenarios consistent with these sorts of flow regime changes. Thus, a receptor impact model for, say, perennial streams can be used to predict the response of a receptor impact variable to a change to intermittent flow. The differences between the components and relationships represented in the perennial stream, intermittent stream and ephemeral stream qualitative models indicate potential ecosystem changes where the predicted hydrological change indicates a landscape class change.

2.7.2.3 'GDE' landscape group

The total area of GDE landscape classes within the zone of potential hydrological change is 102 km^2, most of which (57%) is 'Forested wetland', with smaller areas of 'Rainforest' (23%), 'Dry sclerophyll forest' (14%), 'Wet sclerophyll forest' (4%), and 'Freshwater wetland' (1%) landscape classes. Receptor impact modelling of GDE landscape classes is described in Section 2.7.4. Qualitative and quantitative models were developed for the 'Forested wetland' (Section 2.7.4.2), 'Dry sclerophyll forest' and 'Wet sclerophyll forest' landscape classes. Based on feedback from the qualitative modelling workshop, 'Wet sclerophyll forest' and 'Dry sclerophyll forest' landscape classes were represented by a single qualitative model and quantitative model (wet and dry sclerophyll forests, Table 5; Section 2.7.4.3).

A qualitative model was developed for all forested wetlands at the qualitative modelling workshop, which represented vegetation classes typical of both the coastal and inland parts of the Hunter subregion. As noted in the previous section, riverine forested wetlands are the predominant riparian habitat along perennial streams in the Hunter subregion, and this interconnection is reflected via the riparian habitat node in the perennial stream qualitative model. Other points of connection, such as frogs, are also reflected in the two models. Ecosystems represented in the forested wetlands qualitative model can be sensitive to changes in the flow regime of the perennial streams they occur along.

During the expert elicitation of quantitative relationships for the forested wetlands receptor impact model, the experts were explicit that their assessment related to riverine forests in the western and central uplands of the Hunter subregion, typically comprising *Eucalyptus camaldulensis* (river red gum), E. *tereticornis* and *Casuarina cunninghamii.* These correspond to 'Eastern riverine forest' and 'Coast and tableland riverine forest' vegetation classes in Table 5 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018). Thus, the quantitative model does not apply to 'Coastal swamp forests' and 'Coastal floodplain wetlands' vegetation classes. Riverine forests account for 50% of the 'Forested wetland' landscape class within the zone of potential hydrological change. The experts stipulated that the model should also not be applied to riverine forests along regulated rivers due to their altered flow regimes. In Section 3.4 of companion product 3-4 for the Hunter subregion (Herron et al., 2018), the potential impacts on 'Coastal floodplain wetlands' and 'Coastal swamp forests' vegetation classes are assessed using the qualitative model, while potential impacts on riverine forests along unregulated river sections are evaluated using results from the quantitative receptor impact modelling.

A qualitative model was developed for the 'Rainforest' landscape class (rainforests, Table 5; Section 2.7.4.4) and reflected the experts' shared view that in this area rainforests depend on the concentration of rainwater in upland gullies for their water supply, rather than regional groundwater; hence, a quantitative model was not progressed as it was considered *very unlikely* (less than 5% chance) that coal resource developments of these rainforests would impact their water supply. The rainforests within the Hunter subregion's zone of potential hydrological change are predominantly Keith's 'Northern warm temperate rainforests' vegetation class (Keith, 2004). These occur in sheltered gullies and slopes in hilly-to-steep terrain of the coast and escarpment on moderately fertile soils in high rainfall areas, extending above 1000 m elevation, on granites, rhyolites, syenites or sedimentary substrates that yield acid soils with moderate levels of nutrients (OEH, 2016). However, 10 km^2 of the distribution of Keith's (2004) 'Northern warm temperate rainforests' vegetation class overlaps with the alluvium in the Hunter subregion, which given their topographic position suggests they could have some dependence on alluvial groundwater in some circumstances. The rainforest model presented in Section 2.7.4.4 does not reflect this. The dependence on groundwater of riparian rainforests within this landscape class is considered a knowledge gap.

The 'Freshwater wetland' landscape class within the zone of potential hydrological change is represented entirely by Keith's (2004) 'Coastal freshwater lagoons' vegetation class. Keith's (2004) 'Coastal heath swamps', also represented by this landscape class, are outside the zone and *very unlikely* to be impacted by hydrological changes due to additional coal resource development. A qualitative model was developed for Keith's (2004) 'Coastal freshwater lagoons' vegetation class (see Section 2.7.4.5). Experts at the workshop were unable to agree whether groundwater dependence of these lagoons is regional or local, and hence whether hydrological changes from underground coal mining higher up in the catchment would affect lagoon hydrology. Experts thought that tidal fluctuations might be influencing water levels in the lagoons. A drop in regional groundwater was considered likely to lead to seawater intrusion and hence have little impact on lagoon water levels, but potentially cause large increases in the salinity of the wetland water and catastrophic change in its ecology. Understanding whether these lagoons are sustained by connection to a rainfall-fed local groundwater aquifer or to a fresh regional aquifer, and the connectivity between local and regional aquifers is important for determining possible impacts due to mining. For the assembled experts, the water-dependencies of the coastal freshwater lagoons in the Hunter subregion were a knowledge gap. A review of the literature was undertaken to obtain further insight.

Claus et al. (2011) developed two pertinent conceptual models for wetland types under the NSW Wetland Monitoring, Evaluation and Reporting program: one for 'Coastal freshwater lagoons and lakes' and the other for 'Coastal dune lakes or lagoons'. The former model identified overbank flow as the major source of water for the wetland, while the latter 'are perched above the general water-table in dune hollows created by wind action and sealed by organically cemented sand.' Both of these models indicate that the wetlands are unlikely to be dependent on regional groundwater aquifers. This is consistent with a study of Porters Creek Wetland in the Hunter subregion, which found that the wetland was associated with a shallow watertable that was replenished by rainfall (Payne et al., 2012). These studies suggest that coastal freshwater lagoons are likely to be dependent on local, perched groundwater systems that are disconnected from regional groundwater, and hence not particularly sensitive to drawdown caused by coal mining. Therefore, the assessment team decided that development of a quantitative model of Keith's

(2004) 'Coastal freshwater lagoons' vegetation class was not a major priority for this bioregional assessment. However, since the potential for adverse impacts from drawdown of regional groundwater might be lagoon specific, local assessments of the groundwater dependency of each lagoon within this landscape class are recommended to better resolve this issue.

Only small areas of the 'Heathland' landscape class were present in the zone of potential hydrological change (0.2 km^2) and it was the view of the experts in the qualitative modelling workshop that these were likely to be dependent on local, perched groundwater systems. Wet heathland and swamp sclerophyll shrubland occur in open depressions where the watertable is shallow after periods of high rainfall, whereas sedgeland is found in closed depressions where standing water accumulates (Rutherford et al., 2013). Hence, no qualitative or quantitative models were developed for the 'Heathland' landscape class.

Only very small areas of 'Grassy woodland' (0.2 km^2) and 'Semi-arid woodland' (<0.1 km^2) landscape classes were present in the zone of potential hydrological change, and it was the view of the experts in the qualitative modelling workshop that these were likely to only have an opportunistic dependence on groundwater. Grassy woodlands are associated with fertile soils on the western slopes of the Great Dividing Range (Keith, 2004) and include the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) critically endangered community 'White Box – Yellow Box – Blakely's Red Gum Grassy Woodland and Derived Native Grassland'. Salinity and rising groundwater levels threaten remnants of these woodlands at low elevations within the landscape (Yates and Hobbs, 1997).

The 'Semi-arid woodland' landscape class within the zone of potential hydrological change falls within Keith's (2004) 'Riverine plain woodlands' vegetation class. These acacia-dominated woodlands occur on grey clay soils on flats and shallow depressions of the riverine plain far from active drainage channels; they are typically beyond the extent of modern-day floods. These include the EPBC Act-listed endangered 'Weeping Myall Open Woodland', which may have some groundwater dependence. This is based on the *Draft conservation advice for Hunter Valley Weeping Myall (*Acacia pendula*) Woodland of the Sydney Basin Bioregion* (Department of the Environment, 2014), which states 'Alteration of groundwater and construction of roads through expansions to coal mining, or coal seam gas exploration and extraction … poses a potential clearing-related threat'. However, it appears likely to depend on accumulation of surface run-off in local lows and break-of-slope areas, indicated by this description from White et al. (2002):

> In higher rainfall areas it typically forms an open woodland. As rainfall decreases the ecological community becomes increasingly restricted, tending to sparse or scattered stands of woodland occurring in discrete bands fringing better-watered country. It can also occur as relatively narrow strips on the margins of floodplain woodland or on minor depressions or run-on areas adjacent to sandhills.

2.7.2.4 'Coastal lakes and estuaries' landscape group

Qualitative models were developed for subtidal benthos and intertidal wetlands, reflecting the continuum between fully submerged environments ('Seagrass' landscape class) and intermittently submerged environments ('Saline wetlands' landscape class) that are present within estuarine ecosystems. The qualitative model for subtidal benthos reflects expert opinion that seagrasses are particularly sensitive to subsidence resulting from underground mining, which leads to an increase in the depth of water above the seagrass beds and reduced light penetration. Only one (Chain Valley) of the three additional coal resource developments in this area is under a coastal lake. The delineation of subsidence control zones and requirement that mining components prepare subsidence management plans since 2004 (Mills, 2009) are regulatory measures intended to avoid or limit subsidence in the shallow, fringing zone of the coastal lakes, by restricting coal extraction options in these vulnerable areas. No quantitative model was developed for subtidal benthos based on an assessment that impacts on seagrasses from the additional coal resource developments were likely to be negligible.

The qualitative model for intertidal benthos identified an interaction between groundwater and saltmarsh. Saltmarsh tolerates less inundation than mangrove, and groundwater extraction can potentially result in subsidence owing to reduced soil volume and more prolonged inundation (Saintilan et al., 2009), which would favour mangrove over saltmarsh. Both saltmarsh and mangrove provide similar ecosystem services although the model indicated the saltmarshes could be preferred roosting habitat for migratory wading birds. Subsidence of saltmarsh resulting from groundwater removal is of the scale of millimetres (Rogers and Saintilan, 2008), which is a much finer scale than modelling undertaken as part of the BA. The impacts of such fine-scale processes were judged to be so local and uncertain that no quantitative model was developed for intertidal benthos.

The very small areas of the ‘Creeks’ landscape class (<0.1 km^2) are upstream of any development; hence there is little potential for development to directly impact on these streams and no qualitative or quantitative models were developed.

The small areas of the ‘Barrier river’ landscape class within the zone of potential hydrological change are all upstream of the tidal limit and overlap with the distribution of perennial rivers defined in the ‘Riverine’ landscape group. Hence, no model was developed for the ‘Barrier river’ landscape class.

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Datasets

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2.7.3 'Riverine' landscape group

Summary

The 'Riverine' landscape group is dominated by ephemeral streams (63%) with the remainder roughly equally divided between intermittent and perennial streams. Qualitative models were developed for each landscape class, but receptor impact models were only developed for perennial and intermittent streams. Ephemeral streams in this subregion were considered predominantly rainfall dependent and less vulnerable to hydrological changes from coal mining.

The qualitative model for perennial streams is premised on a flow- and habitat-based classification of aquatic macroinvertebrates (i.e. free-swimming macroinvertebrates in pool habitats and fast-water macroinvertebrates in riffle habitats). Groundwater levels, riffle flow, overbench flow, overbank flow and zero-flow days were identified as critical determinants of instream and riparian habitat condition. Reductions in groundwater levels and streamflow, resulting in increases in zero-flow days, are generally considered to have negative impacts on riparian and subsurface habitats. Potential changes in water quality from changes in hydrology are not represented in the model.

Receptor impact models were designed to focus on the response of riffle-breeding frogs and flow-dependent macroinvertebrates (Hydropsychidae larvae) to changes in the number of zero-flow days and duration of zero-flow spells. As the number of zero-flow days increase, experts were of the opinion that:

- the probability of presence of riffle-breeding frogs would drop quite dramatically, with the model reflecting a chance of no presence under extremely dry conditions
- the density of Hydropsychidae larvae would drop dramatically, with the model reflecting the possibility of less than 1 per m^2 under increasingly intermittent flow regimes.

A qualitative model for intermittent streams was developed through modifications to the perennial streams model. The model lacks pool-breeding frog species, a group which is instead replaced with non-specialist breeding frogs. The model also lacks perennial flow over riffle substrate as a main driver for success of riffle-breeding frog eggs, flow-dependent macroinvertebrates and fishes preferring fast-water habitats. The same hydrological variables critical to habitat condition in perennial streams are relevant to intermittent stream habitats, with flow reductions and lowering of the watertable generally assumed to result in negative impacts. Again, the potential changes in water quality from changes in hydrology are not represented in the model.

The receptor impact models focus on the response of hyporheic invertebrate taxa to changes in zero-flow days and the duration of zero-flow spells, and the response of riffle-breeding frogs to changes in zero-flow days and the duration of zero-flow spells. As the number of zero-flow days increase, experts consider that:

- mean hyporheic invertebrate taxa richness would fall, with the chance of fewer than 10 in 6 L of water under extremely dry conditions
- the probability of presence of riffle-breeding frogs would drop quite dramatically, with the possibility of no presence under extremely dry conditions.

2.7.3.1 Description

Four landscape classes were defined within the ‘Riverine’ landscape group in the Hunter subregion preliminary assessment extent (companion product 2.3 for the Hunter subregion (Dawes et al., 2018)) as follows:

- Permanent or perennial
- Lowly to moderately intermittent
- Moderately to highly intermittent
- Highly intermittent or ephemeral.

Of the 3137 km of river in the zone of potential hydrological change within the Hunter subregion, 634 km were ‘Permanent or perennial’, 518 km were either ‘Lowly to moderately intermittent’ or ‘Moderately to highly intermittent’ and 1986 km were ‘Highly intermittent or ephemeral’.

The ‘Permanent or perennial’ riverine landscape class broadly corresponds to the ‘stable baseflow’ classes from Kennard et al. (2010; Classes 1, 2 and 3) while the ‘Lowly to moderately intermittent’ and ‘Moderately to highly intermittent’ riverine landscape classes (dealt with together as ‘Lowly to highly intermittent’ streams; see Section 2.7.2.1 Table 4) correspond broadly to the ‘unpredictable baseflow’ and ‘intermittent’ classes from Kennard et al. (2010; Classes 4 and 5–8). Permanent or perennial streams have flow at least 80% of the year, and an appreciable contribution of groundwater to baseflows. Kennard et al. (2008) report baseflow indices in the range of 0.15 to 0.4 for perennial streams. Lowly to highly intermittent streams are characterised by streams that cease flowing more often than perennial streams and have a smaller baseflow contribution (0.07–0.25) due to an intermittent connection with groundwater (Kennard et al., 2008). Highly intermittent streams are characterised by an infrequent connection to groundwater and large numbers of zero-flow days.

River basins in the Hunter subregion include the Hunter, Macquarie-Tuggerah Lakes, Upper Namoi and Lower Karuah (see Figure 4 in companion product 3-4 for the Hunter subregion (Herron et al., 2018)). Only the Hunter river basin and Macquarie-Tuggerah lakes basin intersect the zone of potential hydrological change. The Hunter River is the largest river in the subregion and is fed by a number of significant tributaries, including Pages River, Dart Brook, Goulburn River, Glennies Creek, Wollombi Brook, Glendon Brook, Paterson River and Williams River. The total Hunter river basin area is 21,437 km^2, of which 14,886 km^2 is in the subregion. The Hunter River descends 1397 m over its 468-km course from its upper reaches in the Barrington Tops (outside the subregion), through the Hunter Valley, and out to sea.

The Macquarie-Tuggerah lakes basin includes three main river basins: Dora Creek, Wyong River and Ourimbah Creek. The Macquarie-Tuggerah lakes basin covers an area of 1836 km^2 and is bordered by the Hunter river basin in the north. Dora Creek runs south-east for 25 km to meet Lake Macquarie at the township of Dora Creek. The major tributaries of Dora Creek include Moran, Tobins, Jigadee, Blarney and Deep creeks. Wyong River runs south-east for 48 km to meet Tuggerah Lake at Tacoma. The Wyong River's main tributaries include Jilliby Jilliby and Cedar Brush creeks. Ourimbah Creek runs south-east for 31 km to meet Tuggerah Lake at Chittaway. Ourimbah Creek's major tributaries include Elliots, Bumbles, Toobys, and Bangalow creeks, which drain the southern-most corner of the subregion.

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 6. Longitudinal, lateral and vertical connectivity are enhanced with increasing flow. Increasing flow increases connectivity between habitats and enables greater movement of aquatic biota, 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 for 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. A lack of vertical connection to groundwater can result in cease-to-flow periods 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). The limited lateral, vertical and longitudinal connectivity associated with the zero-flow condition is illustrated in Figure 7, where an isolated pool persists between dry riffle beds and the groundwater level is below the channel bed.

During periods of low flow (Figure 8), 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). The hyporheic zone is defined as the saturated interstitial areas beneath the streambed and into the banks that contain some channel water (White, 1993). Low flows 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 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 is a primary driver of ecological responses, especially in pools. Riffle habitats are not only affected by changes in water quality but also reduced habitat area, as riffles dry out and contract. For example, Chessman et al. (2012) reported that aquatic macroinvertebrate assemblages that had been exposed to severe flow reduction or cessation 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.

Although lateral connectivity is limited under no- and low-flow conditions, riparian vegetation may directly access alluvial groundwater, in addition to perched watertables within the stream bank, or 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).

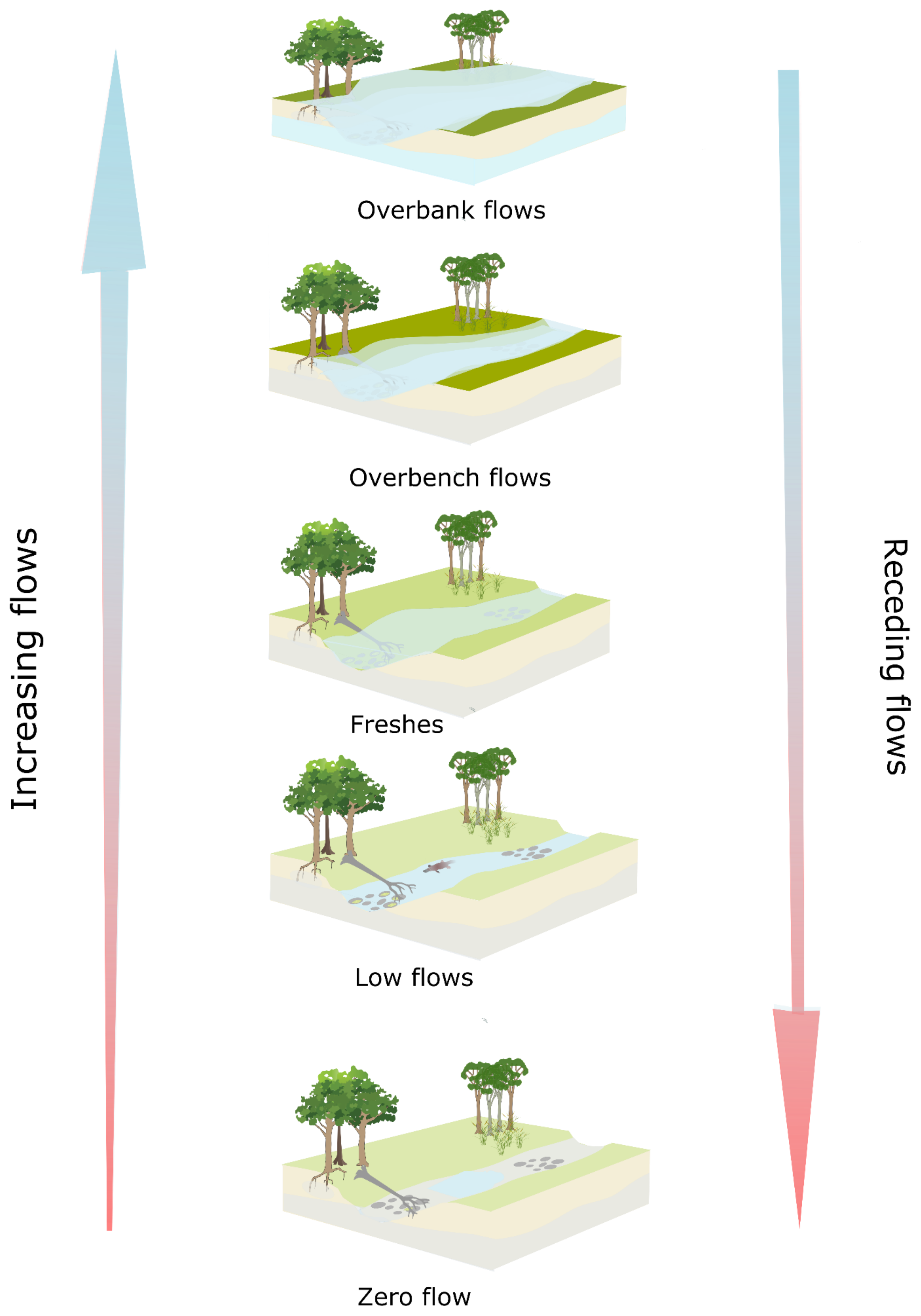

Figure 6 Conceptual representation of components of the hydrograph during wetting and drying cycles in streams

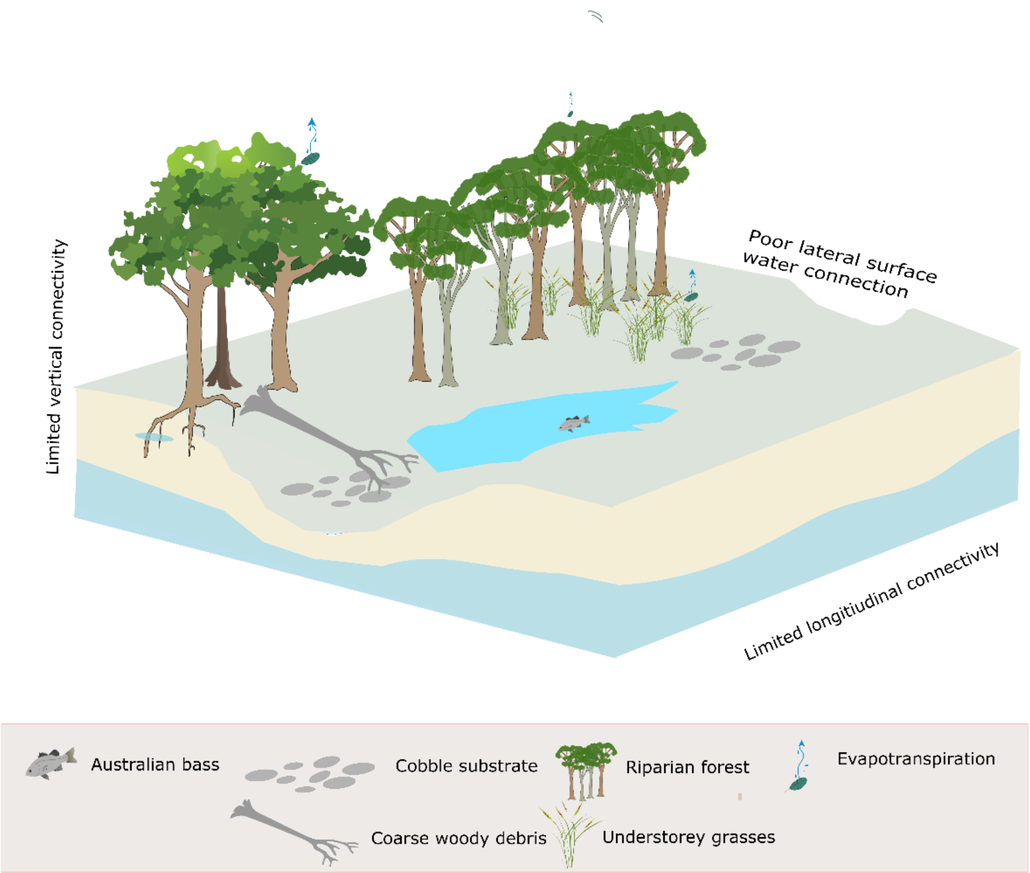

Figure 7 Conceptual model of streams during periods of zero flow when stream is disconnected from groundwater

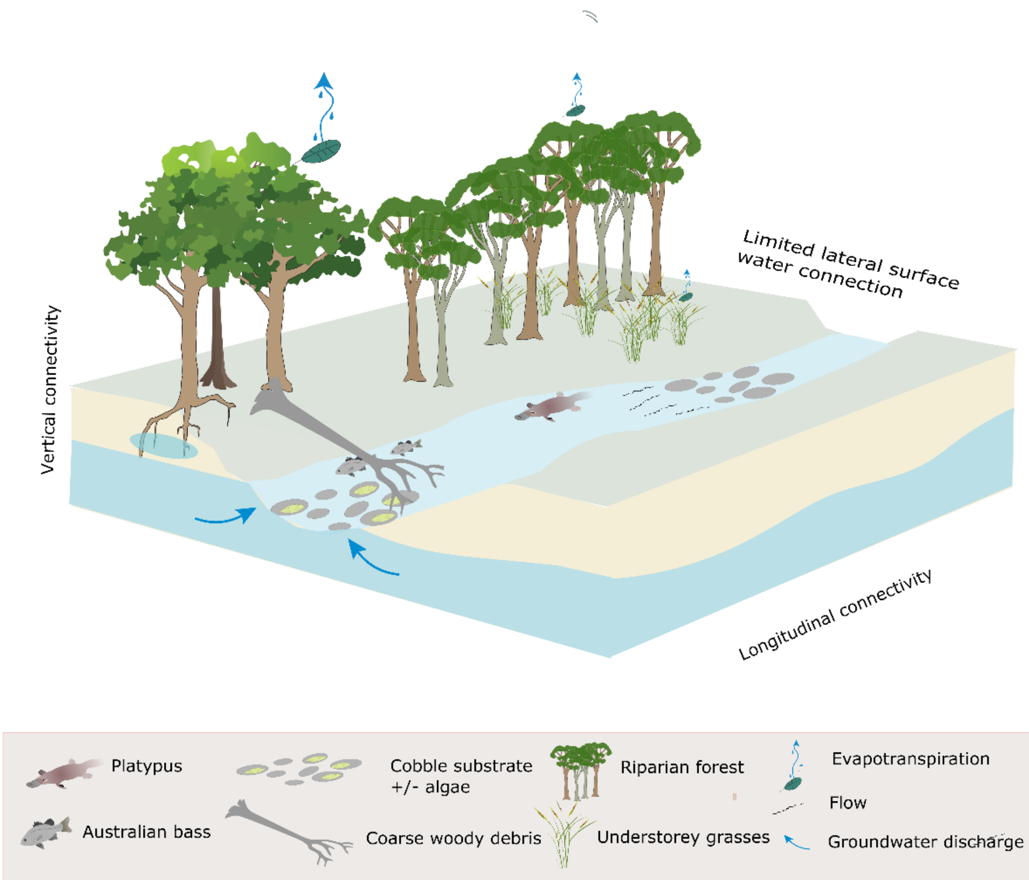

Figure 8 Conceptual model of streams during periods of low flow when baseflows predominate

Freshes (Figure 9) 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 play an important role in the regulation of water quality through inputs of freshwater. 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). Freshes increase lateral connectivity beyond that of low flows, and increase soil water availability in stream banks through increased bank recharge, helping to support the health and vigour of woody and herbaceous vegetation.

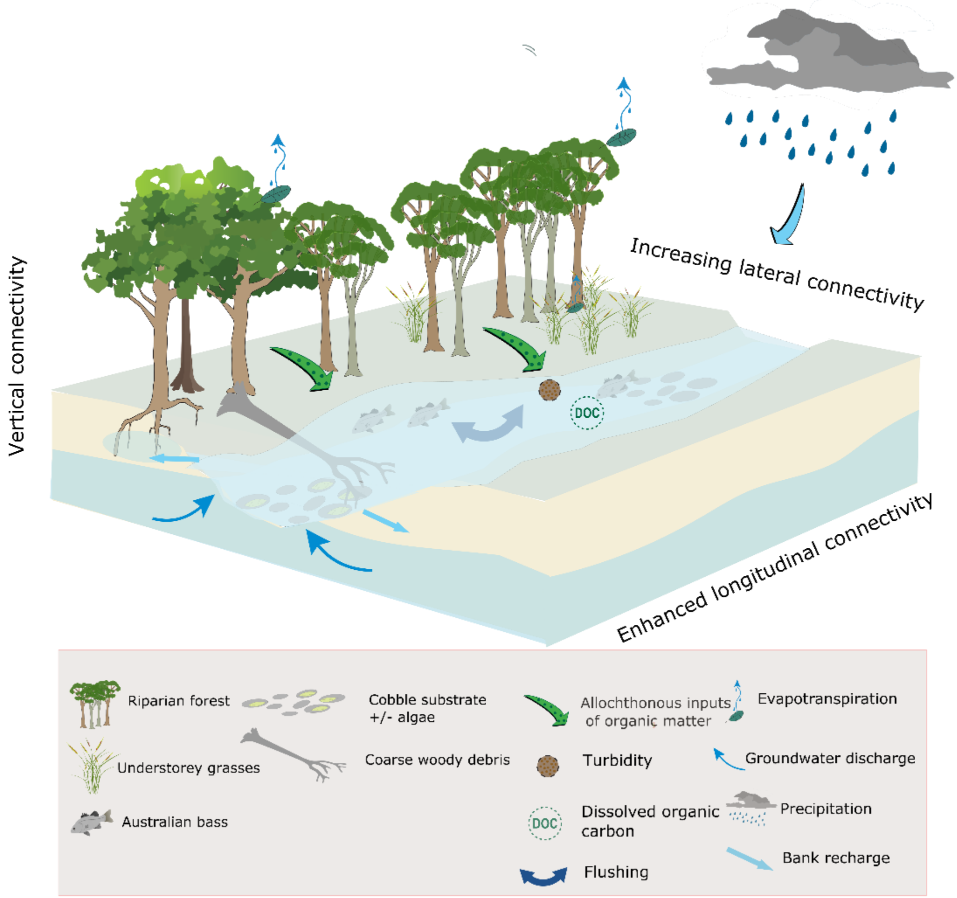

Figure 9 Conceptual model of streams during periods of freshes flow

The longitudinal connectivity is enhanced when compared to the low-flow conceptual model (Figure 8).

High flows (Figure 10 and Figure 11) inundate specific habitats and restore 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 '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), 'overbench flow' is used to represent both wet-season baseflows and bank-full flows. A bench is a bank-attached, narrow, relatively flat 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 habitat components 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 diadromous (migrates between fresh and estuarine waters) and potamodromous (migrates wholly within fresh waters) species.

Increased flow rates, such as during bank-full flows, scour banks and river substrate, and increase stream bank erosion. Bank erosion is accentuated under high discharge (bank-full conditions), 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 the main source of energy for higher trophic levels, can temporarily reduce stream primary production (Davie et al., 2012). Benthic algal communities often recover rapidly and grazing macroinvertebrates are able to 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 10) inundate the surrounding floodplains, providing lateral connectivity, freshwater, nutrients and particulate matter to floodplain wetlands. 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 promote health of the forested wetlands. However, Chalmers et al. (2009) also note that scouring of the floodplain can substantially increase seedling mortality. Connectivity to offstream wetlands, via overbank flows, enables replenishment of freshwater 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).

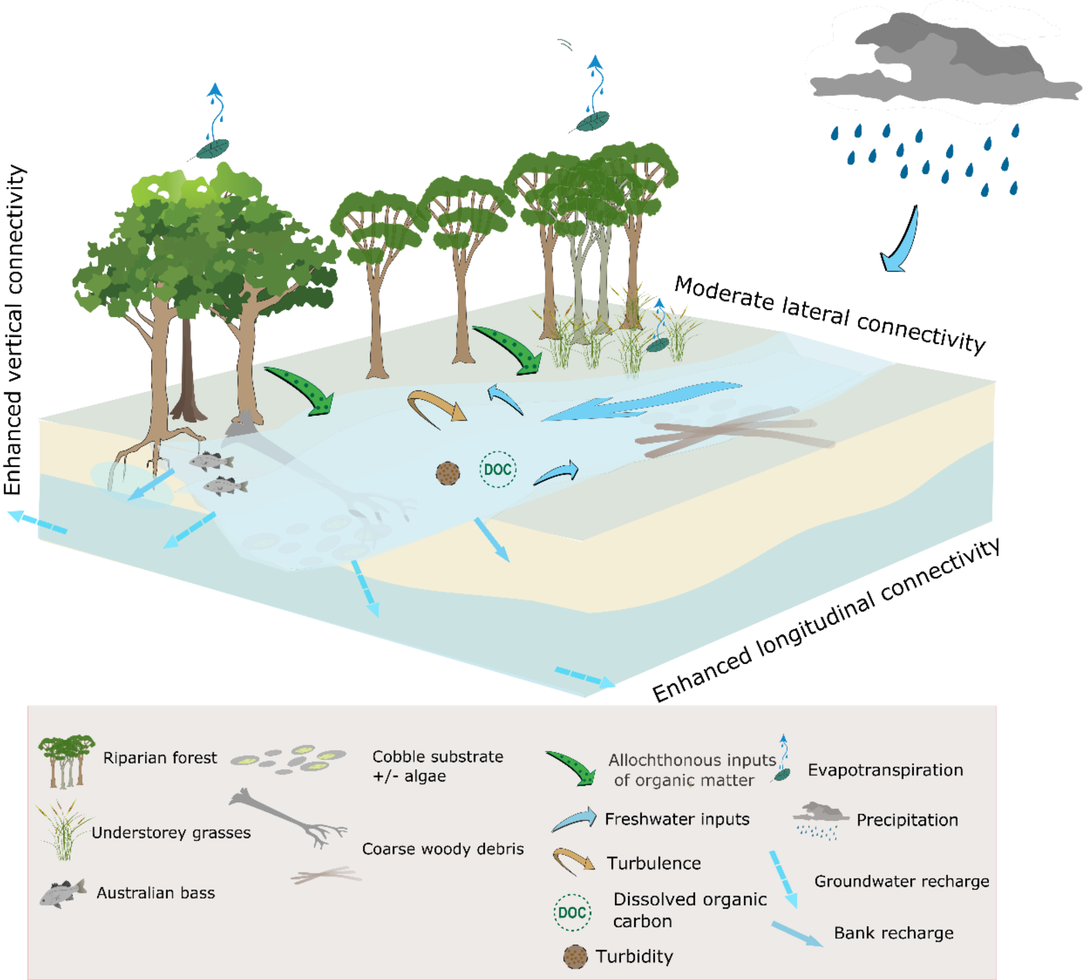

Figure 10 Conceptual model of streams during periods of overbench flow

Dashed arrows represent high uncertainty in relation to the flux. The enhanced connectivity is when compared to the freshes flow conceptual model (Figure 9).

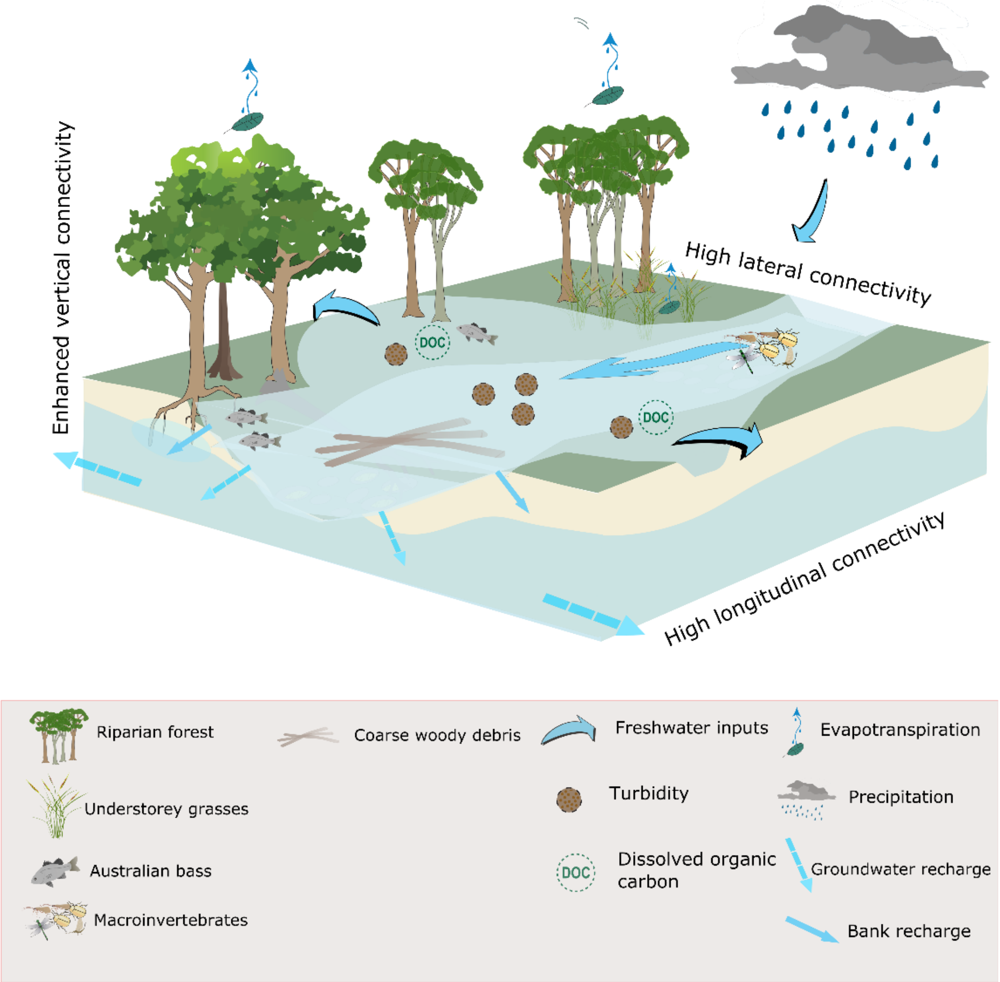

Figure 11 Conceptual model of streams during periods of overbank flow

The 'high' and 'enhanced' connectivity states are relative to the overbench flow model (Figure 10).

2.7.3.2 Perennial streams

2.7.3.2.1 Qualitative mathematical model

A model for perennial stream reaches was developed based on the stream velocity and habitat preferences of aquatic macroinvertebrates (Figure 12). The model is applicable to other stream biota with a preference for slow or fast flowing water, such as frogs and fish as described below. Water quality variables were purposely not represented in the model, although water quality is acknowledged as an important component of instream habitat. Riparian habitat (RH in Figure 12) in this model primarily pertains to the 'Forested wetland' landscape class in the Hunter subregion, for which a separate qualitative model was developed (Section 2.7.4.2). Thus, riparian habitat represents a linking node between the perennial streams and forested wetlands qualitative models. The vegetative canopy of riparian habitat contributes to allochthonous (i.e. found in a different place from its source) stores of detritus (Det) and, through the effect of shade, suppresses the growth of stream macrophytes (Mac) and algae (Alg). Allochthonous inputs of organic matter, in turn drive production of various macroinvertebrate populations (Boulton et al., 2014). Overbench and overbank flows in perennial streams are ecologically important for riparian habitat.

Stream macroinvertebrates were classified into groups based on their affinity for different aspects of stream velocity and flow (i.e. macroinvertebrates which occupy pool habitats and macroinvertebrates associated with fast-water habitats). Flow-dependent invertebrates (LFI and HFI) generally use the upper and interstitial surfaces of riffle substrates, and are considered to be sensitive to changes in the volume and velocity of water flowing over and through riffles (Chessman et al., 2012; Boulton, 2003); hence, flow over riffle substrate was described as a key driver of the productivity of high-flow macroinvertebrates (Q A in Figure 12). There was uncertainty as to whether this is also a strong driver for the success of the egg life stage of riffle-breeding frogs (RBF E) and fishes that prefer fast-water habitats (FWPF E), which led to the development of two alternative signed digraph models that do not (model 1, Figure 12) and do (model 2, Figure 13) include the effect of this driver to frogs and fishes. The effect of zero-flow days (ZFD) on flow-dependent invertebrates is represented via indirect pathways as a result of reduced subsurface habitat, subsurface fauna and algae.

Where present, gravel bars (GB) within the wetted stream channel play a critical role by providing subsurface habitat (SSH) for subsurface fauna and through the filtration of sediment and nutrient cycling, which provides nutrients for primary production (i.e. algae). A group for pool invertebrates (PI) was described for those invertebrates occupying pool habitats. Subsurface fauna (SSF; hyporheos) were defined as those within pool or riffle sediments from 10 cm to 2.5 m depth. The hyporheos feeds mainly on biofilms and includes many types of crustaceans, segmented worms, flatworms, rotifers, water mites, and juvenile stages of aquatic insects (Boulton et al., 1998). The chemical composition of downwelling water travelling through the hyporheic zone is altered by biogeochemical processes mediated by microbial biofilms on sediment particles. The chemically transformed upwelling water can promote growth of periphyton at the streambed surface, creating localised 'hotspots' of productivity (Boulton, 2007).

Amphibians and fish were also divided into those preferring riffle or slow-water habitats. An example of a riffle-breeding frog (RBF) is the stuttering frog (*Mixophyes balbus*), which breeds in streams during summer after heavy rain. Its eggs are laid on rock shelves or shallow riffles in small, flowing streams. The tadpoles are free-swimming benthic grazers, foraging amongst stones and leaf litter in riffle and pool sections of the stream channel (Anstis, 2002). As the tadpoles grow they move to deep, permanent pools and take approximately 12 months to metamorphose. In contrast, the giant burrowing frog (*Heleioporus australiacus*) is a pool-breeding frog (PBF) that lays its eggs in burrows or under vegetation in small pools. After rains, tadpoles are washed into larger pools where they complete their development in ponded areas.

The climbing galaxias (*Galaxias brevipinnis*) is an example of a fish that prefers fast water (FWPF) in the headwaters of streams flowing through forested land. This species eats a range of invertebrates including aquatic insects such as mayfly and caddisfly larvae, terrestrial invertebrates such as millipedes, flies and beetles, and crustaceans such as amphipods (Australian Museum, 2013). By contrast, the Australian smelt (*Retropinna semoni*) is usually found in slow-flowing streams (SWPF) where it schools near the surface. Eggs are laid amongst aquatic vegetation and breeding activity is concentrated into the months preceding summer storms and high, variable stream discharges (Milton and Arthington, 1985). A group of herbivores (Her) was included that consume stream macrophytes and algae. The model includes a group of generalist carnivores (Car) that prey on all of the macroinvertebrate groups and frog tadpoles (RBF T and PBF

ET). Top predators in the system, carnivores and omnivores (Omn), generally consume all groups of macroinvertebrates and tadpoles, with omnivores also consuming macrophytes and algae.

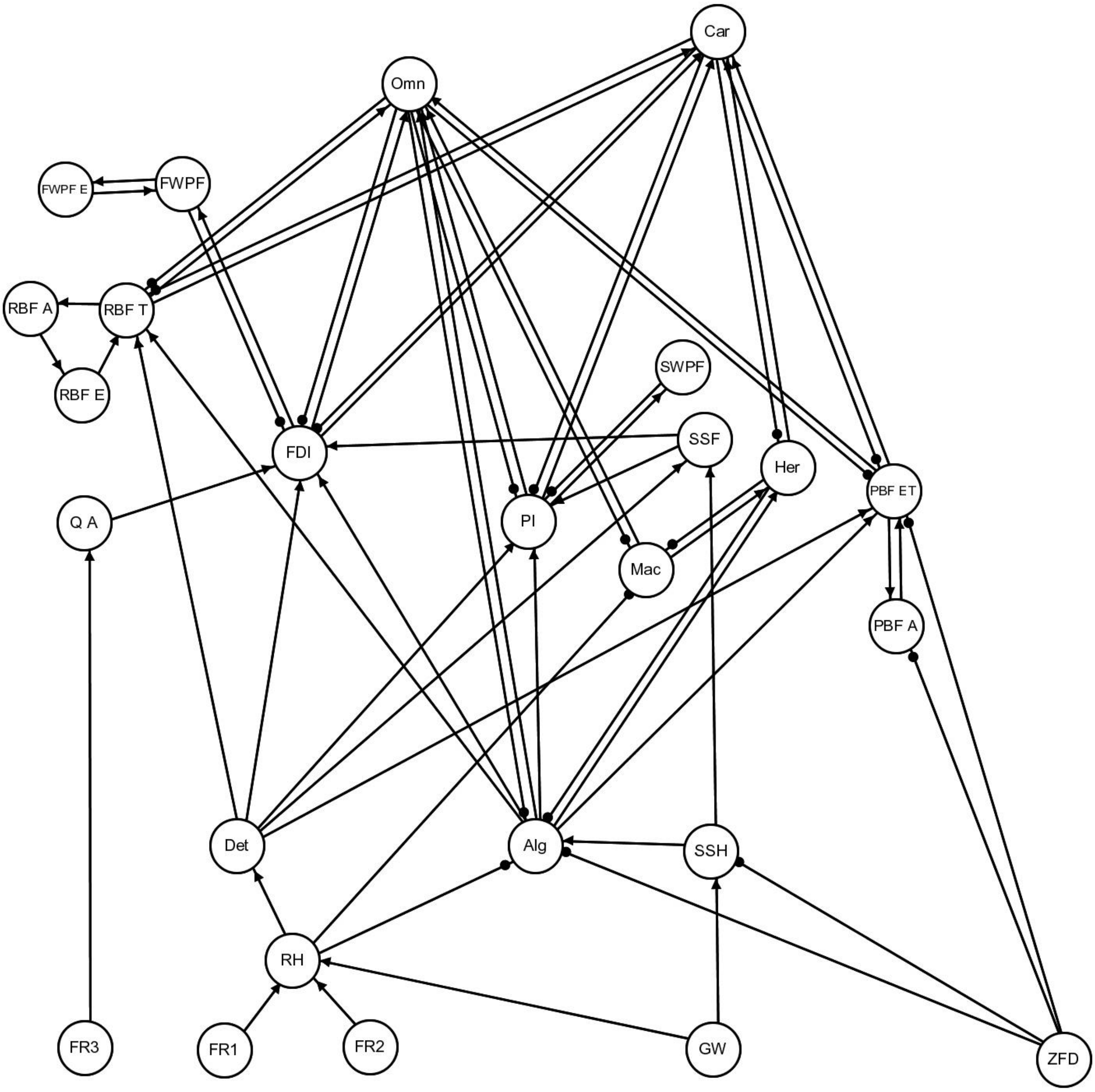

Figure 12 Model 1 signed digraph of perennial stream communities of the Hunter Valley

Algae (Alg), carnivores (Car), detritus (Det), eggs of fast water preferred fishes (FWPF E), fast water preferred fishes (adults) (FWPF), herbivores (Her), flow-dependent invertebrates (FDI), macrophytes (Mac), omnivores (Omn), adults of pool-breeding frogs (PBF A), eggs and tadpoles of pool-breeding frogs (PBF ET), pool invertebrates (PI), flow above riffle substrate (Q A), adults of riffle-breeding frogs (RBF A), eggs of riffle-breeding frogs (RBF E), tadpoles of riffle-breeding frogs (RBF T), riparian habitat (RH), subsurface fauna (SSF), subsurface habitat (SSH), slow water preferred fishes (SWPF). Hydrological variables added subsequent to the qualitative modelling workshop are flow regimes 1, 2 and 3 (FR1, FR2, FR3), depth to groundwater (GW) and zero-flow days (ZFD).

Data: Bioregional Assessment Programme (Dataset 1)

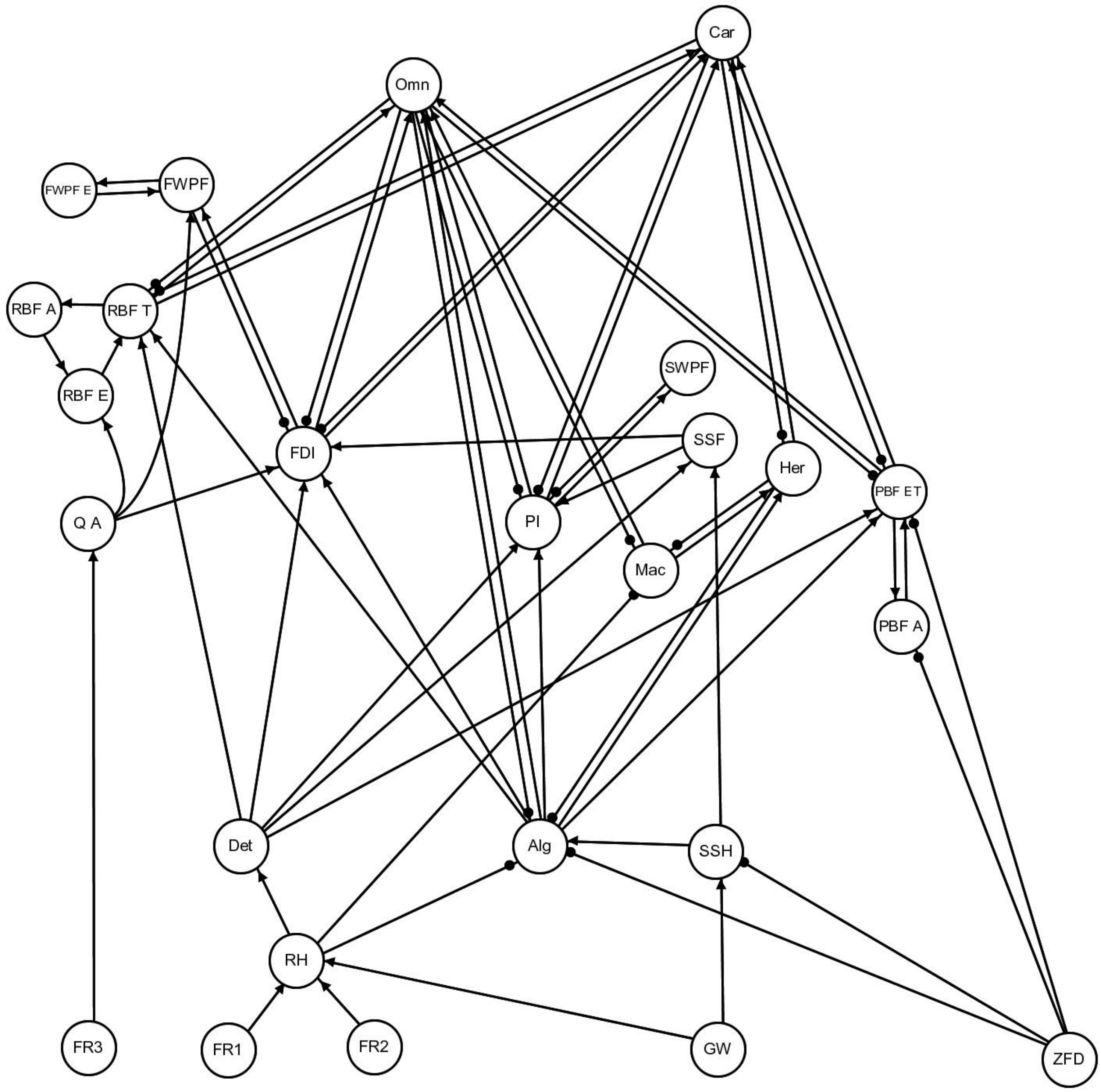

Figure 13 Model 2 signed digraph of perennial stream communities of the Hunter Valley

Algae (Alg), carnivores (Car), detritus (Det), eggs of fast water preferred fishes (FWPF E), fast water preferred fishes (adults) (FWPF), herbivores (Her), flow-dependent invertebrates (FDI), macrophytes (Mac), omnivores (Omn), adults of pool-breeding frogs (PBF A), eggs and tadpoles of pool-breeding frogs (PBF ET), pool invertebrates (PI), flow above riffle substrate (Q A), adults of riffle-breeding frogs (RBF A), eggs of riffle-breeding frogs (RBF E), tadpoles of riffle-breeding frogs (RBF T), riparian habitat (RH), subsurface fauna (SSF), subsurface habitat (SSH), slow water preferred fishes (SWPF). Hydrological variables added subsequent to the qualitative modelling workshop are flow regimes 1, 2 and 3 (FR1, FR2, FR3), depth to groundwater (GW) and zero-flow days (ZFD).
Data: Bioregional Assessment Programme (Dataset 1)

Apart from the volume of flow that connects pools by maintaining over-riffle flow, the other hydrological variables that maintain and support the perennial streams ecosystem were identified subsequent to the qualitative modelling workshop. Based on experience gained during the Gloucester subregion assessment, and comments received by experts following the Hunter subregion qualitative modelling workshop, depth to groundwater (GW), frequency, timing and duration of overbench flow (flow regime 1, FR1) and overbank flow (flow regime 2, FR2) were identified as the critical hydrological determinants of riparian habitat condition. Zero-flow days

(ZFD in Figure 12 and Figure 13) was also subsequently identified as the most important hydrological determinant of pool-breeding frogs and subsurface habitat.

Over-riffle flow proved more difficult to define, given it varies with channel and substrate morphology, but was broadly agreed to refer to flow above some 'low-flow' volume (flow regime 3, FR3). To remove the ambiguity in this term, this volume was identified as the inflection point in a flow-duration curve that indicates a rapid transition from a flowing state to a non-flowing state. By way of example, the flow-duration curve calculated from the Coggan gauging station at the Goulburn River suggests that this flow is 0.03 to 0.06 cm^3/s (~2.6–5 ML/day). It was noted, however, that further analysis of flow-duration curves from perennial and intermittent streams in the Hunter subregion would be required to provide further confidence in this definition of 'low flow'.

In the qualitative models for this landscape class, a diminishment in FR1 and FR2 were both projected to have a negative effect on riparian habitat (RH), while a decrease in FR3 was treated as reducing the flow level above riffle substrates (Q A). An increase in the number of zero-flow days was described as having a negative effect on pool-breeding frogs (PBF), subsurface fauna (SSF), flow-dependent invertebrates (FDI), the quality of subsurface habitat (SSH) and algae (Alg). Finally, a decrease in groundwater level (i.e. an increase in depth to groundwater, GW), was described as having a negative impact on riparian habitat and subsurface habitat. For this landscape class, it was determined that impacts to FR1 and FR2 could not be distinguished in perturbation analyses, and so their effect on the ecosystem could be considered together. Based on all possible combinations of these impacts, with FR1 and FR2 considered in unison, a total of 15 cumulative impact scenarios were developed for qualitative analyses of response predictions (Table 6).

Table 6 Summary of the cumulative impact scenarios (CISs) for perennial streams for the Hunter subregion

CIS	FR1	FR2	FR3	ZFD	GW
C1	–	–	0	0	0
C2	0	0	–	0	0
C3	0	0	0	0	+
C4	0	0	0	+	0
C5	–	–	–	0	0
C6	–	–	0	0	+
C7	–	–	0	+	0
C8	0	0	–	0	+
C9	0	0	–	+	0
C10	0	0	0	+	+
C11	–	–	–	0	+
C12	0	0	–	+	+
C13	–	–	0	+	+
C14	–	–	–	+	0
C15	–	–	–	+	+

Pressure scenarios are determined by combinations of no change (0), increase (+) or decrease (–) in the following hydrologic response variables: flow regime 1 (FR1, overbench and bank-full flow), flow regime 2 (FR2, overbank flow), flow regime 3 (FR3, low flow), zero-flow days (ZFD), depth to groundwater (GW).

Data: Bioregional Assessment Programme (Dataset 1)

Qualitative analysis of the signed digraph models (Figure 12 and Figure 13) generally indicate a negative response prediction for variables within the riparian-dependent community of perennial streams across the 15 cumulative impact scenarios (Table 7 and Table 8). Exceptions include the predicted positive response of macrophytes (Mac) and herbivores (Her), which is primarily a consequence of decreased suppression of macrophytes by riparian habitat. The predicted response of both pool-breeding and riffle-breeding frogs appeared to have a high degree of ambiguity across many of the cumulative impact scenarios, but in a number of scenarios they were predicted to have an increase in density, which was due, in part, to a release from predation as a consequence of a predicted decrease in their omnivore and carnivore predators.

Table 7 Predicted response of the signed digraph variables (model 1) in perennial streams to (cumulative) changes in hydrological response variables

Signed digraph variable (full name)	Signed digraph variable (shortened form)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Flow-dependent invertebrates	FDI	(–)	(–)	–	–	–	–	–	–	–	–	–	–	–	–	–
Pool invertebrates	PI	(–)	?	–	(–)	(–)	–	–	(–)	(–)	–	–	–	–	–	–
Subsurface fauna	SSF	–	0	–	–	–	–	–	–	–	–	–	–	–	–	–
Eggs and tadpoles of pool-breeding frogs	PBF ET	?	?	?	?	?	?	?	(+)	?	?	?	?	?	?	?
Adults of pool-breeding frogs	PBF A	?	?	?	?	?	?	?	(+)	?	?	?	?	?	?	?
Eggs of riffle-breeding frogs	RBF E	?	?	?	(+)	?	?	(+)	(+)	+	+	?	+	+	+	+
Tadpoles of riffle-breeding frogs	RBF T	?	?	?	(+)	?	?	(+)	(+)	+	+	?	+	+	+	+
Adults of riffle-breeding frogs	RBF A	?	?	?	(+)	?	?	(+)	(+)	+	+	?	+	+	+	+
Eggs of fast water preferred fishes	FWPF E	(–)	(–)	–	–	–	–	–	–	–	–	–	–	–	–	–
Fast water preferred fishes	FWPF	(–)	(–)	–	–	–	–	–	–	–	–	–	–	–	–	–
Omnivores	Omn	(–)	?	–	–	(–)	–	–	–	–	–	–	–	–	–	–
Slow water preferred fishes	SWPF	(–)	?	–	(–)	(–)	–	–	(–)	(–)	–	–	–	–	–	–
Carnivores	Car	?	?	(–)	(–)	?	(–)	(–)	(–)	(–)	–	(–)	–	–	(–)	–
Herbivores	Her	+	?	+	(+)	+	+	+	+	(+)	+	+	+	+	+	+
Detritus	Det	–	0	–	0	–	–	–	–	0	–	–	–	–	–	–
Riparian habitat	RH	–	0	–	0	–	–	–	–	0	–	–	–	–	–	–
Subsurface habitat	SSH	0	0	–	–	0	–	–	–	–	–	–	–	–	–	–
Macrophytes	Mac	(+)	?	(+)	+	(+)	+	+	+	+	+	+	+	+	+	+
Algae	Alg	(+)	?	?	–	(+)	?	(–)	?	–	–	?	–	–	(–)	–

The cumulative impact scenarios (C1 to C15) are determined by combinations of no-change (0), increase (+) or decrease (–) in hydrologic response variables (see Table 6). Qualitative model predictions show the predicted response of the signed digraph variable. 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)

Table 8 Predicted response of the signed digraph variables (model 2) in perennial streams to (cumulative) changes in hydrological response variables

Signed digraph variable (full name)	Signed digraph variable (shortened form)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Flow-dependent invertebrates	FDI	(–)	?	–	–	(–)	–	–	(–)	–	–	–	–	–	–	–
Pool invertebrates	PI	(–)	?	–	(–)	(–)	–	–	(–)	(–)	–	–	–	–	–	–
Subsurface fauna	SSF	–	0	–	–	–	–	–	–	–	–	–	–	–	–	–
Eggs and tadpoles of pool-breeding frogs	PBF ET	?	(+)	?	?	?	?	?	(+)	?	?	(+)	?	?	?	?
Adults of pool-breeding frogs	PBF A	?	(+)	?	?	?	?	?	(+)	?	?	(+)	?	?	?	?
Eggs of riffle-breeding frogs	RBF E	?	(–)	?	(+)	(–)	?	(+)	(–)	?	+	(–)	?	+	?	?
Tadpoles of riffle-breeding frogs	RBF T	?	(–)	?	(+)	(–)	?	(+)	(–)	?	+	(–)	?	+	?	?
Adults of riffle-breeding frogs	RBF A	?	(–)	?	(+)	(–)	?	(+)	(–)	?	+	(–)	?	+	?	?
Eggs of fast water preferred fishes	FWPF E	(–)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fast water preferred fishes	FWPF	(–)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Omnivores	Omn	(–)	?	–	–	(–)	–	–	–	–	–	–	–	–	–	–
Slow water preferred fishes	SWPF	(–)	?	–	(–)	(–)	–	–	(–)	(–)	–	–	–	–	–	–
Carnivores	Car	?	?	(–)	(–)	(–)	(–)	(–)	(–)	(–)	–	(–)	–	–	–	–
Herbivores	Her	+	?	+	(+)	+	+	+	+	(+)	+	+	+	+	+	+
Detritus	Det	–	0	–	0	–	–	–	–	0	–	–	–	–	–	–
Riparian habitat	RH	–	0	–	0	–	–	–	–	0	–	–	–	–	–	–
Subsurface habitat	SSH	0	0	–	–	0	–	–	–	–	–	–	–	–	–	–
Macrophytes	Mac	(+)	?	(+)	+	(+)	+	+	(+)	+	+	+	+	+	+	+
Algae	Alg	(+)	?	?	–	(+)	?	(–)	?	–	–	?	–	–	(–)	–

The cumulative impact scenarios (C1 to C15) are determined by combinations of no-change (0), increase (+) or decrease (–) in hydrologic response variables (see Table 6). Qualitative model predictions show the predicted response of the signed digraph variable. 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)

2.7.3.2.2 Temporal scope, hydrological response variables and receptor impact variables

In bioregional assessments (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 numerical model predictions in a defined assessment interval that precedes the assessment year. In all cases these predictions allow for the possibility that the future result can depend on the state of the receptor impact variable in the reference year 2012, and consequently this is also quantified by conditioning on the predicted hydrological conditions in a reference interval that precedes 2012 (see companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)).

For surface water and groundwater variables in the Hunter subregion, the reference assessment interval is defined as the 30 years preceding 2012 (i.e. 1983 to 2012). For surface water variables in the Hunter 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 (i.e. 2013 to 2102) as time to maximum can occur at any time during the modelling period.

In BA, 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 (see companion submethodology M10 (as listed in Table 1) for analysing impacts and risks (Henderson et al., 2018)). Choices should be 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 (see companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)). Unambiguous responses to hydrological changes and the requirement for expertise to assess these in the BA workshops is critical.

For perennial streams, the qualitative modelling workshop identified five variables (three flow regimes, zero-flow days and groundwater levels) as the key hydrological variables that were thought to: (i) be instrumental in maintaining and shaping the components, functions and processes provided by the landscape class ecosystem; and, (ii) have the potential to change due to coal resource development (Figure 12 and Figure 13). All of the ecological components and processes represented in the qualitative model are potential receptor impact variables and all of these are predicted to vary as the hydrological factors vary either individually or in combination (Table 7 and Table 8). Following advice from participants during (and after) the qualitative modelling workshop, and guided by the availability of experts for the receptor impact modelling workshop, and the receptor impact variable selection criteria (Section 2.7.1.2.3), the receptor impact models were initially conceived to focus on the relationship between flow-dependent macroinvertebrates and riffle-breeding frogs to changes in FR3.

The hydrological factors identified by the participants after the Hunter subregion qualitative modelling workshop have to be 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 above. However, due to the reservations surrounding the definition of 'low flow', and its sensitivity to the stream channel geometry (which varies across the landscape class), the experts at the receptor impact modelling workshops elected to change the hydrological response variable for the perennial streams from FR3 to zero-flow days (Table 9). The precise definition of the receptor impact variable, typically a species or group of species represented by a qualitative model node, was also determined by the experts during the receptor impact modelling workshop.

Using zero-flow day hydrological response variables, and the receptor impact variable definitions derived during the receptor impact modelling workshop, the relationships identified in the qualitative modelling workshop were formalised into two receptor impact models that predict the response of:

1. Mean density of larvae of the Hydropsychidae family (net-spinning caddisflies) in a 1 m^2 sample of riffle habitat, to changes in the number of zero-flow days (averaged over 30 years) (ZQD, subsequently referred to in this Section as 'zero-flow days') and the maximum length of spells (in days per year) with zero flow averaged over a 30-year period (ZME)
2. Mean probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in a 100-m transect, to changes in ZQD and ZME.

Note that a receptor impact model for investigating the relationship between the annual mean percent projected foliage cover of woody riparian vegetation (*Eucalyptus tereticornis*, *Casuarina cunninghamiana*, *Eucalyptus camaldulensis*; the riparian habitat (RH) node in the perennial streams qualitative model) and FR1, FR2 and groundwater is presented in the 'Forested wetland' landscape class analysis (Section 2.7.4.2).

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

2.7.3.2.3 Receptor impact models

2.7.3.2.3.1 Presence of riffle-breeding frogs

The density and diversity of frogs in streams responds to local, ground-level stream and vegetation variables (Parris and McCarthy, 1999). Many frogs that breed in permanent water bodies are excluded from temporary ones because their larval stage is longer than the persistence of water in these habitats. Therefore, the mix of frog species found in different streams can be partially explained by the different periods of water availability needed by each species in order to breed successfully (Brisbane City Council, 2010).

Elicitation scenarios

Table 10 summarises the elicitation matrix for the presence of the riffle-breeding frog in perennial streams in the landscape class. The first seven design points – design point identifiers 1 to 7 – address the predicted variability in ZQD and ZME across the perennial streams in the landscape class during the reference interval (1983–2012). The design points 1, 2, 4 and 6 capture the combination of the extremes of each hydrological response variable, whilst design points 3, 5 and 7 represent intermediate points in each hydrological response variable axis.

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. The high and low values for Yref (the value of the receptor impact variable in 2012 on the linear predictor scale) were again calculated during the receptor impact modelling workshop. (Note designs for the reference and future-assessment periods are produced separately and identifiers are not unique across the two.)

Table 10 Elicitation design matrix for the receptor impact model of probability of presence of the riffle-breeding frog (*Mixophyes balbus*), over a 100-m transect in perennial streams in the Hunter subregion

Design point identifier	ZME	ZQD	Yref	Year
5	80.0	335	na	2012
6	245	335	na	2012
2	0.755	157	na	2012
4	11.2	335	na	2012
1	0.0	0.0	na	2012
3	80.0	157	na	2012
7	2.0	5.0	na	2012
12	220	350	0.8	2042
2	0.70	150	0.5	2042
7	0.0	0.0	0.8	2042
9	37.0	150	0.8	2042
22	220	350	0.8	2102
23	37.0	350	0.8	2102
20	0.70	150	0.8	2102
13	0.0	0.0	0.5	2102

Design points for Yref in the future (short- and long-assessment periods) are calculated during the receptor impact modelling elicitation workshop using elicited values for the receptor impact variable in the reference period. Yref is value of receptor impact variable in the reference assessment year on the linear predictor scale; it has no value if the design case is in the reference assessment year. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling. na = not applicable, ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period, ZQD = the number of zero-flow days per year, averaged over a 30-year period
Data: Bioregional Assessment Programme (Dataset 1)

Receptor impact model

The fitted model for the probability of presence of the riffle-breeding frog takes the form

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \beta_{h_1} x_{h_1} + \beta_{h_2} x_{h1}^2 + \beta_{h_3} x_{h_3} \quad (1)$$

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 future period (i.e. short- or long-assessment year), x_l is a binary indicator variable scored 1 for the case of an assessment in the long-assessment year, x_r is a continuous variable that represents the value of the receptor impact variable on the link transformed scale in the reference year (Yref; set to zero if the design case is in the reference assessment year), x_{h_1} is the integer value of ZQD and x_{h_3} is the integer value of ZME, all with corresponding fitted β coefficients (see Table 3 in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018)). The (marginal) mean and 80% central credible intervals of the two hydrological response variable coefficients are summarised in the partial regression plots in Figure 14, whilst Table 11 summarises the same information for all seven model coefficients.

The hydrological response variables in this receptor impact model vary during the reference interval and the future interval. The model indicates that the experts’ elicited information strongly supports the assertion that ZQD has a negative effect on the density of riffle-breeding frogs despite the experts being quite uncertain about its average value. The model suggests that the probability of presence can vary across the landscape class from less than 0.4 to 0.8 under conditions of constant flow (ZQD = 0), holding all other covariates at their mid-values. As the number of zero-flow days increase, however, experts were of the opinion that the probability of presence would drop quite dramatically with the model suggesting some chances of probability of presence near zero under extremely dry conditions (ZQD > 350 days) (Figure 14).

There was very little evidence in the elicited data to suggest that this effect would be substantially different in the future-assessment years. This is indicated by the somewhat identical partial regression plots in the reference, short- and long-assessment years (Figure 14), and the relatively large negative 10th and positive 90th percentiles for the future1 coefficients in Table 11. The model does, however, suggest that the experts’ uncertainty increased for predictions in the long-assessment year (2102) relative to the reference year and that the mean probability of presence in 2102 will be slightly lower (if all other variables remain unchanged).

The elicitation was carried out with the experts deciding to provide responses for scenarios 1 and 7 only. The argument was that under the reference period, the other scenarios were not describing the hydrological conditions of the perennial stream landscape class. Figure 14 reflects this as the dashed vertical lines for the reference period only describe small intervals for both ZME and ZQD.

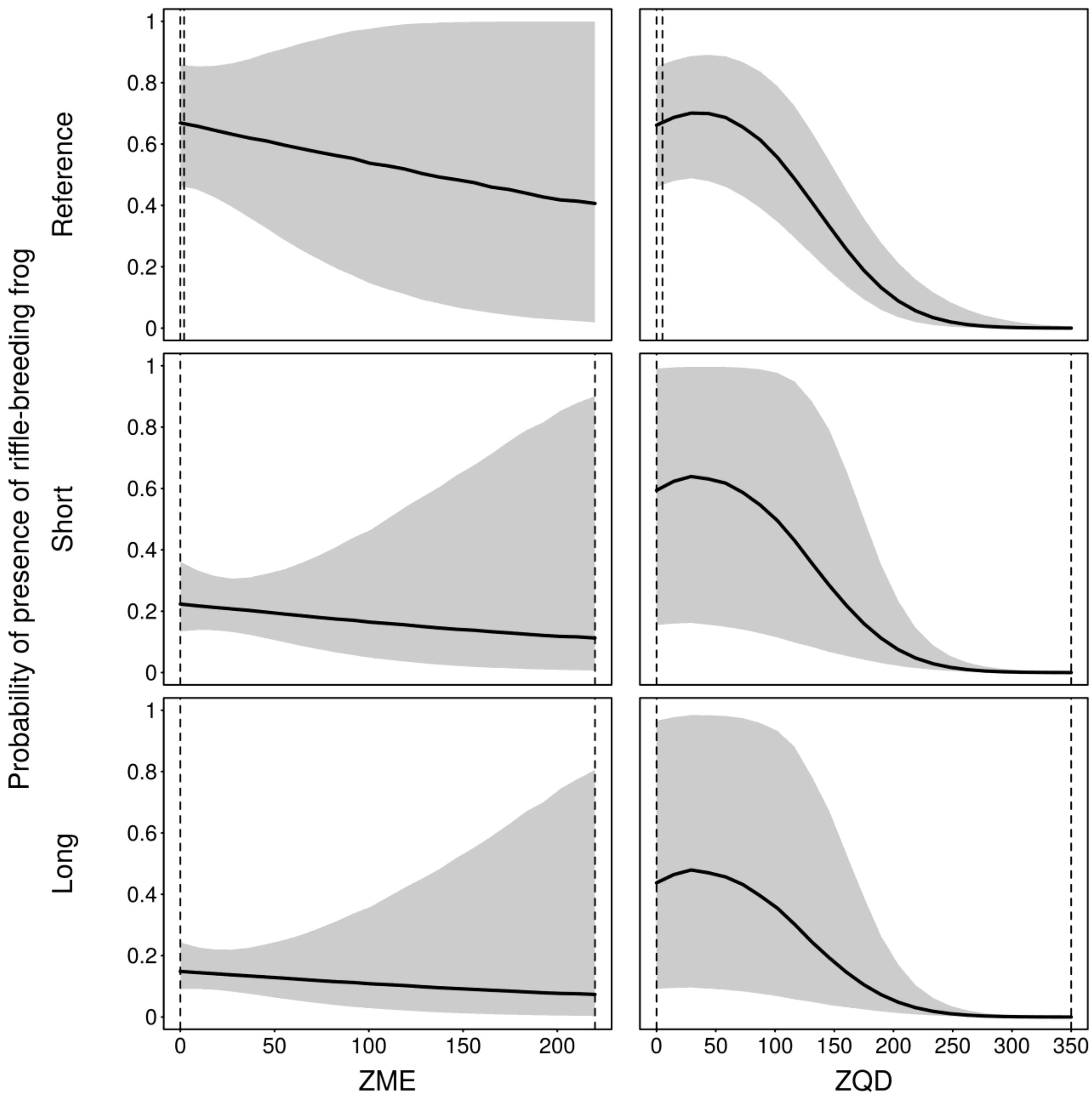

Figure 14 (Top row) Predicted mean (black line) and 80% central credible interval (grey polygon) of mean probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in a 100-m transect in perennial streams in the Hunter subregion under reference hydrological conditions; (middle and bottom rows) predicted future effects (mean = black line, 80% central credible interval = grey polygon)

In middle and bottom rows, all other hydrological response variables are held constant at the midpoint 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), ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period
Data: Bioregional Assessment Programme (Dataset 1)

The best-fitting model in this case indicates that the probability of presence of the riffle-breeding frog in the reference years has an influence on its probability of presence in the future years. This is indicated by the fact that $\beta_r > 0$ for all presented quantiles in Table 11. This suggestion is consistent with a belief on the part of experts that development would be unlikely to greatly alter the presence of suitable habitat, such that if suitable habitat exists at a location to support a relatively large number of frogs in the reference period then that habitat would be likely to 'persist' and continue to support a relatively large number of frogs in the future, despite development.

Table 11 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in perennial streams in the Hunter subregion

	Mean	q10	q90
(Intercept)	0.0827	–0.487	0.653
future1	0.142	–0.494	0.779
long1	–0.447	–0.82	–0.074
Yref	0.531	0.0897	0.973
ZME	–0.00349	–0.0183	0.0113
ZQD	0.0064	–0.000937	0.0137
I(ZQD^2)	–9.04e–05	–0.000138	–4.32e–05

Yref is value of receptor impact variable in the reference assessment year on the linear predictor scale; it has no value if the design case is in the reference assessment year. Future is a binary variable scored 1 if the analysis case is in a short- or long-assessment year. Long is a binary variable scored 1 if the analysis case is in the long assessment year. ZQD = the number of zero-flow days per year, averaged over a 30-year period, ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period, I(ZQD^2) = zero-flow days quadratic term
Data: Bioregional Assessment Programme (Dataset 1)

2.7.3.2.3.2 Density of Hydropsychidae larvae

Hydropsychidae are a family of the order Trichoptera (caddisflies), whose larvae are not usually found in polluted or saline water. Their larval populations can be large in many Australian river systems. The larvae live on rocks, boulders or submerged logs in moderate to fast-flowing waters. Larvae are omnivorous, and a capture net is used to filter food particles from the water column, including algae, organic particles and small invertebrates (Hawking et al., 2009). Along with other benthic invertebrates, they are integral to the movement of energy and matter from the benthos (periphyton) both to higher trophic levels (as a food source for other aquatic biota) and from aquatic systems to terrestrial food webs (as emergent adults) (Runck, 2007). Common genera of caddisflies in south-eastern Australia include *Notalina*, *Hellyethira* and *Cheumatopsyche*.

Elicitation scenarios

Table 12 summarises the elicitation matrix for the density of Hydropsychidae larvae. The first eight design points – design point identifiers 1 to 8 – address the predicted variability in ZQD and ZME across the landscape class in the reference interval, capturing the lowest and highest predicted values together with 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 9 to 23 inclusive (as listed in Table 12) represent scenarios that span the uncertainty in the predicted values of ZQD and ZME in the relevant time period of hydrological history associated with the short (2042) and long (2012) 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 12 Elicitation design matrix for the receptor impact model of density of *Cheumatopsyche* spp. (Hydropsychidae) larvae per m^2 of riffle habitat in perennial streams in the Hunter subregion

Design point identifier	ZME	ZQD	Yref	Year
5	80.0	335	na	2012
6	245	335	na	2012
2	0.756	157	na	2012
4	0.0	335	na	2012
1	0.0	0.0	na	2012
3	80.0	157	na	2012
7	5.0	150	na	2012
8	5.0	50.0	na	2012
12	220	350	3	2042
21	0.70	150	1	2042
17	0.0	0.0	3	2042
9	37.0	150	3	2042
22	23.3	350	3	2102
23	37.0	350	3	2102
20	0.70	150	3	2102
13	0.0	0.0	1	2102

Design points for Yref in the future (short- and long-assessment periods) are calculated during the receptor impact modelling elicitation workshop using elicited values for the receptor impact variable in the reference period. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling.
Yref is value of receptor impact variable in the reference assessment year on the linear predictor scale; it has no value if the design case is in the reference assessment year. na = not applicable, ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period, ZQD = the number of zero-flow days per year, averaged over a 30-year period
Data: Bioregional Assessment Programme (Dataset 1)

Receptor impact model

The fitted model for Hydropsychidae larval density takes the form

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_{h_1} x_{h_1} + \beta_{h_2} x_{h_1}^2 + \beta_{h_3} x_{h_3} + \beta_{i_1} x_f x_{h_3}^2 \quad (2)$$

where the terms x_0, x_f, x_l are as before, x_{h_1} is the integer value of ZQD, x_{h_3} is the integer value of ZME and h_2 Identifies the coefficient for the quadratic term $x_{h_1}^2$. 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 15, whilst Table 13 summarises the same information for all seven model coefficients.

The model indicates that the experts' elicited information strongly supports the assertion that ZQD has a negative effect on the density of Hydropsychidae larvae despite the experts being uncertain about its average value. The model suggests that mean larvae density can vary across the landscape class from about 50 per m^2 to 100 per m^2 under conditions of constant flow (ZQD = 0, ZME = 0), holding all other covariates at their mid-values. As the number of zero-flow days increase, however, experts were of the opinion that density would drop dramatically with the model suggesting values less than 1 per m^2 as flow conditions become increasingly intermittent (ZQD > 200 days) (Figure 15). Note that in this model the positive effect on mean larval density from the term $\beta_{h_1} x_{h_1}$ is overwhelmed by the negative effect of the $\beta_{h_2} x_{h_1}^2$ term. The slight increase in mean larval abundance when zero-flow days increase from 0 to 50 is likely an artefact of the model fitting process rather than an indication of an ecological phenomena. The selection of the quadratic term for both ZQD and ZME is most likely driven by the need to render the sharp decrease in larvae density. This induces a weak artefact signal of increase in larvae density for ZQD values from 0 to 50 days. This artefact signal stems from the need to best fit the elicited data with a shape-constrained curve. The uncertainty around this prediction though mitigates this conclusion and is advocating for a plateau-type signal for ZQD values between 0 and 120 days.

There was little evidence in the elicited data to suggest that this effect could be different in the future assessment years. This is indicated by the interaction between 'future' and 'ZME' which has been selected in the best model (Table 13), and the slightly increasing curvature in the marginal regression plot for ZME in the short- and long-assessment years (Figure 15). In effect the model is saying that the influence of ZME becomes slightly more curvilinear into the future.

Finally, in the canopy cover model for forested wetlands (Section 2.7.4.2) there was strong evidence within the experts' elicited values that average percent canopy cover in the reference year had a positive influence on the values in the future assessment years ($\beta_r > 0$). The model selection procedure in this case, however, has eliminated the possibility that the average density of Hydropsychidae larvae in the reference years has an influence on its abundance in the future years. This is indicated by the fact that β_r is not included within the best-fitting model (Table 13). This suggestion is consistent with the assertion that (over a 30-year period) there is likely to be very little lag in the response of short-lived species to changes in the hydrological response variables.

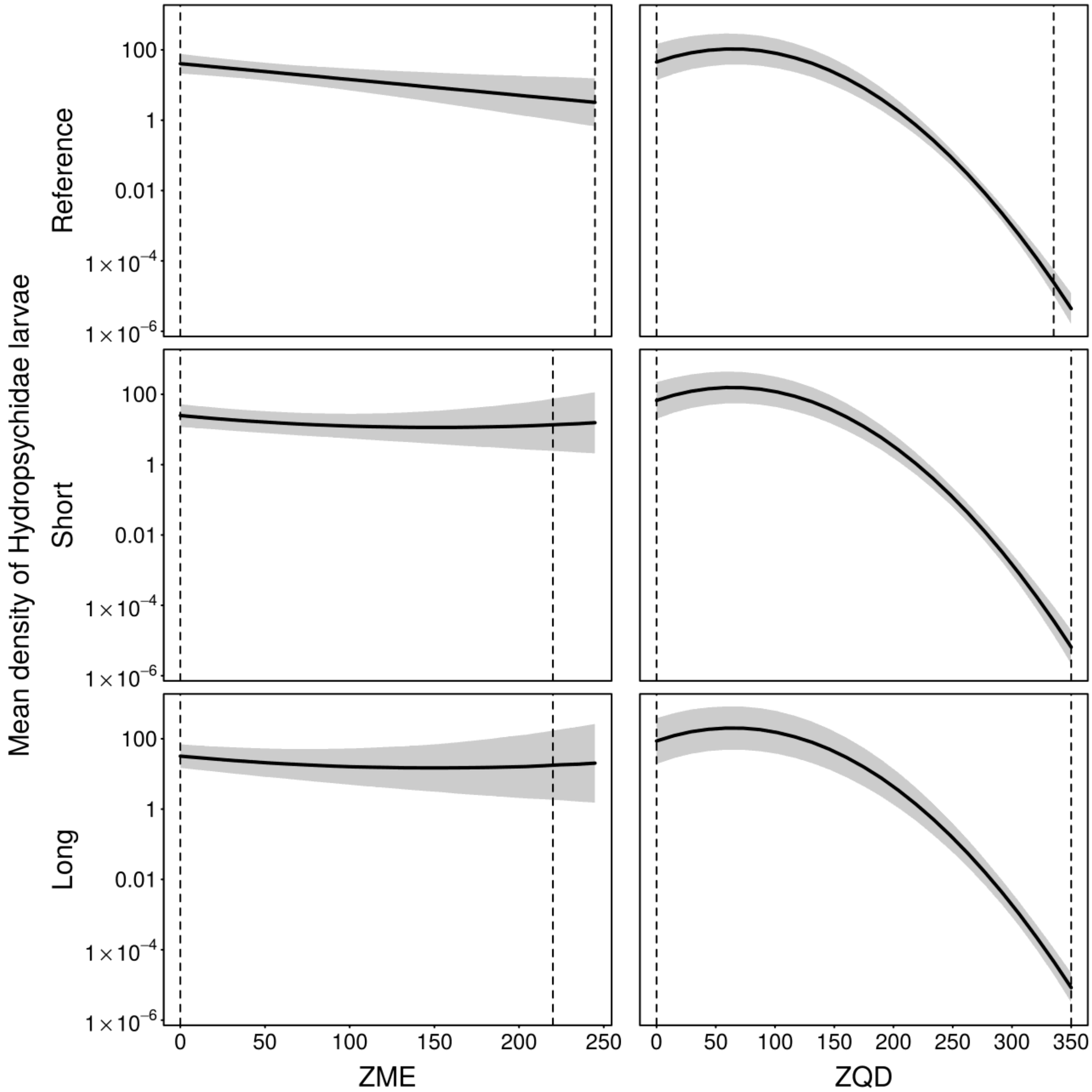

Figure 15 (Top row) Predicted mean (black line) and 80% central credible interval (grey polygon) of mean density of Hydropsychidae larvae in a 1 m^2 sample of riffle habitat in perennial streams in the Hunter subregion under reference hydrological conditions; (middle and bottom rows) predicted future effects (mean = black line, 80% central credible interval = grey polygon)

In middle and bottom rows, all other hydrological response variables are held constant at the midpoint 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 = the number of zero-flow days per year, averaged over a 30-year period, ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period
Data: Bioregional Assessment Programme (Dataset 1)

Table 13 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for the mean density of *Cheumatopsyche* spp. (Hydropsychidae) larvae per m^2 of riffle habitat in perennial streams in the Hunter subregion

	Mean	q10	q90
(Intercept)	5.08	4.1	6.06
future1	–0.156	–1.05	0.74
long1	0.255	–0.784	1.29
ZME	–0.0104	–0.0176	–0.00315
ZQD	0.0266	0.0163	0.0368
I(ZQD^2)	–0.000208	–0.00024	–0.000176
future1:I(ZME^2)	3.45e–05	7.67e–06	6.13e–05

Future is a binary variable scored 1 if the analysis case is in a short- or long-assessment year. Long is a binary variable scored 1 if the analysis case is in the long assessment year. ZQD = the number of zero-flow days per year, averaged over a 30-year period, ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period, I(ZQD^2) = zero-flow days quadratic term, future1:I(ZME^2) = interaction between future 1 and maximum length of zero-flow day spells quadratic term
Data: Bioregional Assessment Programme (Dataset 1)

2.7.3.3 Intermittent streams

2.7.3.3.1 Qualitative mathematical models

Workshop discussions on intermittent stream reaches determined that, while flowing, they could be adequately described by a modified version of the signed digraph for perennial streams (Figure 16). The model for this system lacks pool-breeding frog species, a group which is instead replaced with non-specialist breeding frogs, but otherwise is identical in its basic model components and linkages. This model also lacks the influence of the regime for perennial flow over riffle substrate as a main driver for success of riffle-breeding frog eggs, flow-dependent macroinvertebrates and fishes preferring fast-water habitats.

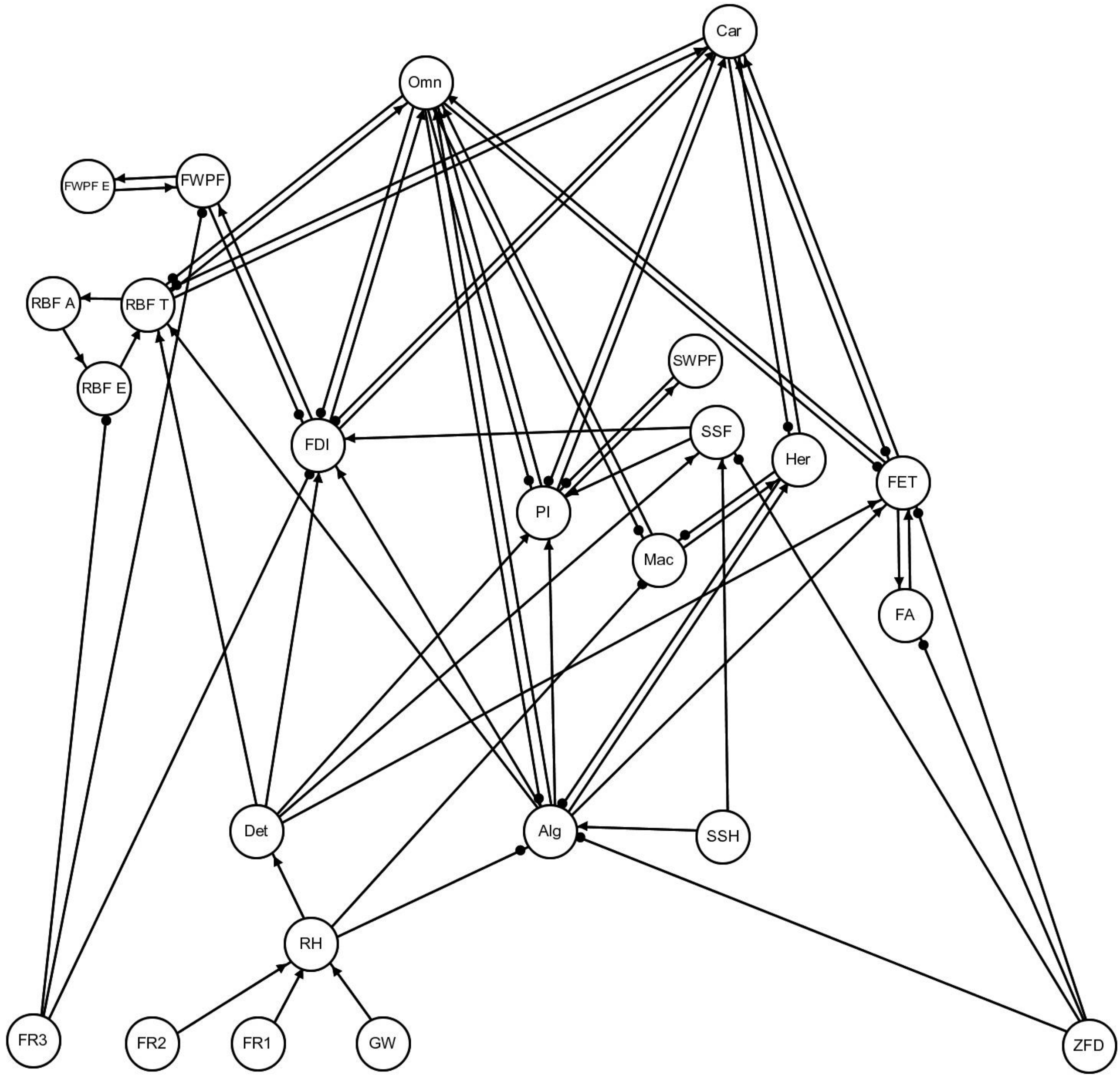

Figure 16 Signed digraph of intermittent stream communities of the Hunter Valley

Algae (Alg), carnivores (Car), detritus (Det), frog adults (FA), frog eggs and tadpoles (FET), eggs of fast water preferred fishes (FWPF E), fast water preferred fishes (adults) (FWPF), herbivores (Her), flow-dependent invertebrates (FDI), macrophytes (Mac), omnivores (Omn), pool invertebrates (PI), adults of riffle-breeding frogs (RBF A), eggs of riffle-breeding frogs (RBF E), tadpoles of riffle-breeding frogs (RBF T), riparian habitat (RH), subsurface habitat (SSH), subsurface fauna (SSF), slow water preferred fishes (SWPF). Hydrological variables added subsequent to the qualitative modelling workshop are flow regimes 1, 2 and 3 (FR1, FR2, FR3), depth to groundwater (GW) and zero-flow days (ZFD).
Data: Bioregional Assessment Programme (Dataset 1)

Surface water and groundwater modelling indicated significant potential impacts of coal mining to surface flow and groundwater for this landscape class. The impacts for this system are the same as for perennial streams, and include the same hydrological response variables of overbench flow (flow regime 1, FR1), overbank flow (flow regime 2, FR2), low flows (flow regime 3, FR3), zero-flow days (ZFD), and depth to groundwater (GW). As in the perennial streams model, water quality variables are not represented, although water quality is acknowledged as an important component of instream habitat.

In this system, a diminishment in FR1 and FR2 was treated as having a negative effect on riparian habitat (RH in Figure 16), while a decrease in FR3 was treated as having a negative effect on flow-dependent invertebrates (FDI), riffle-breeding frogs (RBF) and fast water preferred fishes (FWPF). An increase in the number of zero-flow days was described as having a negative effect on (non-specialist) frog eggs and tadpoles (FET), subsurface fauna (SSF), flow-dependent invertebrates (FDI), the quality of subsurface habitat (SSH) and algae (Alg). Finally, a decrease in groundwater levels was described as having a negative impact on riparian habitat and subsurface habitat. Based on all possible combinations of these impacts (again with FR1 and FR2 considered in unison), a total of 15 cumulative impact scenarios were developed for qualitative analyses of response predictions (Table 14). In practical terms, the structure of this model and the pathways of interaction effects of the hydrological response variables give a system that has equivalent response predictions to that of model 2 for perennial streams (Figure 13, Table 8).

Table 14 Summary of the cumulative impact scenarios (CISs) for intermittent streams for the Hunter subregion

CIS	FR1	FR2	FR3	ZFD	GW
C1	–	–	0	0	0
C2	0	0	–	0	0
C3	0	0	0	0	+
C4	0	0	0	+	0
C5	–	–	–	0	0
C6	–	–	0	0	+
C7	–	–	0	+	0
C8	0	0	–	0	+
C9	0	0	–	+	0
C10	0	0	0	+	+
C11	–	–	–	0	+
C12	0	0	–	+	+
C13	–	–	0	+	+
C14	–	–	–	+	0
C15	–	–	–	+	+

Pressure scenarios are determined by combinations of no-change (0), increase (+) or decrease (–) in the following hydrologic response variables: flow regime 1 (FR1, overbench and bank-full flow), flow regime 2 (FR2, overbank flow), flow regime 3 (FR3, low flow), zero-flow days (ZFD), depth to groundwater (GW).
Data: Bioregional Assessment Programme (Dataset 1)

Qualitative analysis of this signed digraph model confirms that the intermittent stream system (Figure 16, Table 15) has exactly the same qualitative response predictions as model 2 for perennial streams (Figure 13, Table 8). Most response predictions are negative, if not ambiguous, with only macrophytes and herbivores having positive response predictions across the 15 scenarios. As before, riffle-breeding frogs are predicted to increase in some scenarios in part due to release from predation.

Table 15 Predicted response of the signed digraph variables in intermittent streams to (cumulative) changes in hydrological responses variables

Signed digraph variable (full name)	Signed digraph variable (shortened form)	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15
Flow-dependent invertebrates	FDI	(–)	?	–	–	(–)	–	–	(–)	–	–	–	–	–	–	–
Pool invertebrates	PI	(–)	?	–	(–)	(–)	–	–	(–)	(–)	–	–	–	–	–	–
Subsurface fauna	SSF	–	0	–	–	–	–	–	–	–	–	–	–	–	–	–
Frog eggs and tadpoles	FET	?	(+)	?	?	?	?	?	(+)	?	?	(+)	?	?	?	?
Frog adults	FA	?	(+)	?	?	?	?	?	(+)	?	?	(+)	?	?	?	?
Eggs of riffle-breeding frogs	RBF E	?	(–)	?	(+)	(–)	?	(+)	(–)	?	+	(–)	?	+	?	?
Tadpoles of riffle-breeding frogs	RBF T	?	(–)	?	(+)	(–)	?	(+)	(–)	?	+	(–)	?	+	?	?
Adults of riffle-breeding frogs	RBF A	?	(–)	?	(+)	(–)	?	(+)	(–)	?	+	(–)	?	+	?	?
Eggs of fast water preferred fishes	FWPF E	(–)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Fast water preferred fishes	FWPF	(–)	–	–	–	–	–	–	–	–	–	–	–	–	–	–
Omnivores	Omn	(–)	?	–	–	(–)	–	–	–	–	–	–	–	–	–	–
Slow water preferred fishes	SWPF	(–)	?	–	(–)	(–)	–	–	(–)	(–)	–	–	–	–	–	–
Carnivores	Car	?	?	(–)	(–)	(–)	(–)	(–)	(–)	(–)	–	(–)	–	–	–	–
Herbivores	Her	+	?	+	(+)	+	+	+	+	(+)	+	+	+	+	+	+
Detritus	Det	–	0	–	0	–	–	–	–	0	–	–	–	–	–	–
Riparian habitat	RH	–	0	–	0	–	–	–	–	0	–	–	–	–	–	–
Subsurface habitat	SSH	0	0	–	–	0	–	–	–	–	–	–	–	–	–	–
Macrophytes	Mac	(+)	?	(+)	+	(+)	+	+	(+)	+	+	+	+	+	+	+
Algae	Alg	(+)	?	?	–	(+)	?	(–)	?	–	–	?	–	–	(–)	–

The cumulative impact scenarios (C1 to C15) are determined by combinations of no-change (0), increase (+) or decrease (–) in hydrologic response variables (see Table 14). Qualitative model predictions show the predicted response of the signed digraph variable. Predictions that are completely determined are shown without parentheses. Predictions that are ambiguous but with a high probability (0.80 or greater) of sign determinacy are shown with parentheses. Predictions with a low probability (less than 0.80) of sign determinacy are denoted by a question mark. Zero denotes completely determined predictions of no change.
Data: Bioregional Assessment Programme (Dataset 1)

2.7.3.3.2 Temporal scope, hydrological response variable and receptor impact variables

The temporal scope for the intermittent streams is the same as that described for the perennial streams. For surface water and groundwater variables the reference assessment interval is defined as the 30 years preceding 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 (i.e. 2013 to 2102).

Following advice from participants during (and after) the qualitative modelling workshop, and guided by the availability of experts for the receptor impact modelling workshop, and the receptor impact variable selection criteria, the receptor impact models were originally designed to focus on the relationship between subsurface habitat and zero-flow days, and riffle-breeding frogs and low flow. However, due to the reservations surrounding the definition of 'low flow', and its sensitivity to stream channel geometry (which varies across the landscape class), the experts at the receptor impact modelling workshops again elected to change the low-flow hydrological response variable to zero-flow days (Table 16).

At the receptor impact modelling workshop, hyporheic invertebrate taxa richness was selected by the experts as a suitable indicator of subsurface habitat quality, hence the receptor impact model for intermittent streams focused on the following relationships:

1. 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; Hancock, 2004), to changes in ZQD (subsequently referred to in this Section as 'zero-flow days) and ZME
2. Mean probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in a 100-m transect, to changes in ZQD and ZME.

Table 16 Summary of the hydrological response variables used in the receptor impact models, together with the signed digraph variables that they correspond to, for intermittent streams in the Hunter 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.	ZFD
ZME	The maximum length of spells (in days per year) with zero flow averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.	ZFD

2.7.3.3.3 Receptor impact models

2.7.3.3.3.1 Hyporheic invertebrate taxa richness

The richness of hyporheic invertebrate taxa has been proposed as an indicator of health in intermittent rivers, similarly to macroinvertebrate richness in permanent rivers (Leigh et al., 2013). The advantage of the hyporheic zone for monitoring the condition of temporary rivers is that hyporheic invertebrates within temporary rivers can be sampled from beneath both dry and wet channels, and across multiple seasons. Aquatic invertebrates often persist beneath surface channels in moist or dry sediments, even during long dry phases, and are sensitive to groundwater quality (Malard et al., 1996).

Elicitation scenarios

Table 17 summarises the elicitation matrix for the mean richness of hyporheic invertebrate taxa. The first six design points – design point identifiers 1 to 6 – address the predicted variability in ZQD and ZME across the landscape class in the reference interval, capturing the lowest and highest predicted values together with one intermediate value. These design points provide for an estimate of the uncertainty in mean hyporheic invertebrate taxa richness across the landscape class in the reference year 2012 (Yref).

Design points 8 to 19 represent scenarios that span the uncertainty in the predicted values of ZQD and ZME 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 17 Elicitation design matrix for the receptor impact model of mean hyporheic invertebrate taxa richness in intermittent streams for the Hunter subregion

Design point identifier	ZME	ZQD	Yref	Year
6	149	323	na	2012
5	48.5	323	na	2012
4	7.78	323	na	2012
3	48.5	142	na	2012
2	0.635	142	na	2012
1	0.0	0.0	na	2012
11	0.0	0.0	1	2042
12	180	350	3	2042
10	23.3	350	3	2042
9	49.0	160	3	2042
15	49.0	350	1	2042
8	0.780	160	3	2042
14	0.780	160	1	2102
19	0.0	0.0	3	2102

Design points for Yref in the future (short- and long-assessment periods) are calculated during the receptor impact modelling elicitation workshop using elicited values for the receptor impact variable in the reference period. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling. ZQD = zero-flow days (averaged over 30 years), ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period, na = applicable
Data: Bioregional Assessment Programme (Dataset 1)

Receptor impact model

The fitted model for mean hyporheic invertebrate taxa richness takes the form

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_{h_1} x_{h_1} + \beta_{h_2} x_{h_2} \qquad (3)$$

here the terms x_0, x_f, x_l are as before and x_{h_1} is the integer value of ZQD and x_{h_2} is the integer value of ZME. 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 17, whilst Table 18 summarises the same information for all five model coefficients.

The model indicates that the experts’ elicited information strongly supports the assertion that ZQD and ZME have a negative effect on the mean richness of hyporheic invertebrate taxa despite the experts being quite uncertain about its average value. The model suggests that it can vary substantially across the landscape class from <10 to almost 20 per sampling unit under conditions of constant flow (ZQD = 0), holding all other covariates at their mid-values. As the number of zero-flow days increase, however, experts were of the opinion that density would drop to values from 5 to 8 under very intermittent flow conditions (ZQD > 320 days) (Figure 17).

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 17), and the relatively symmetric negative 10th and positive 90th percentiles for the long and future coefficients in Table 18. 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 has also eliminated the possibility that the mean richness of hyporheic invertebrate taxa in the reference years has an influence on its density in the future years. This is indicated by the fact that the coefficient β_r has not been included in the best-fitting model (Table 18). This suggestion is consistent with the assertion that there is likely to be very little lag in the response of short-lived species to changes in the hydrological response variables.

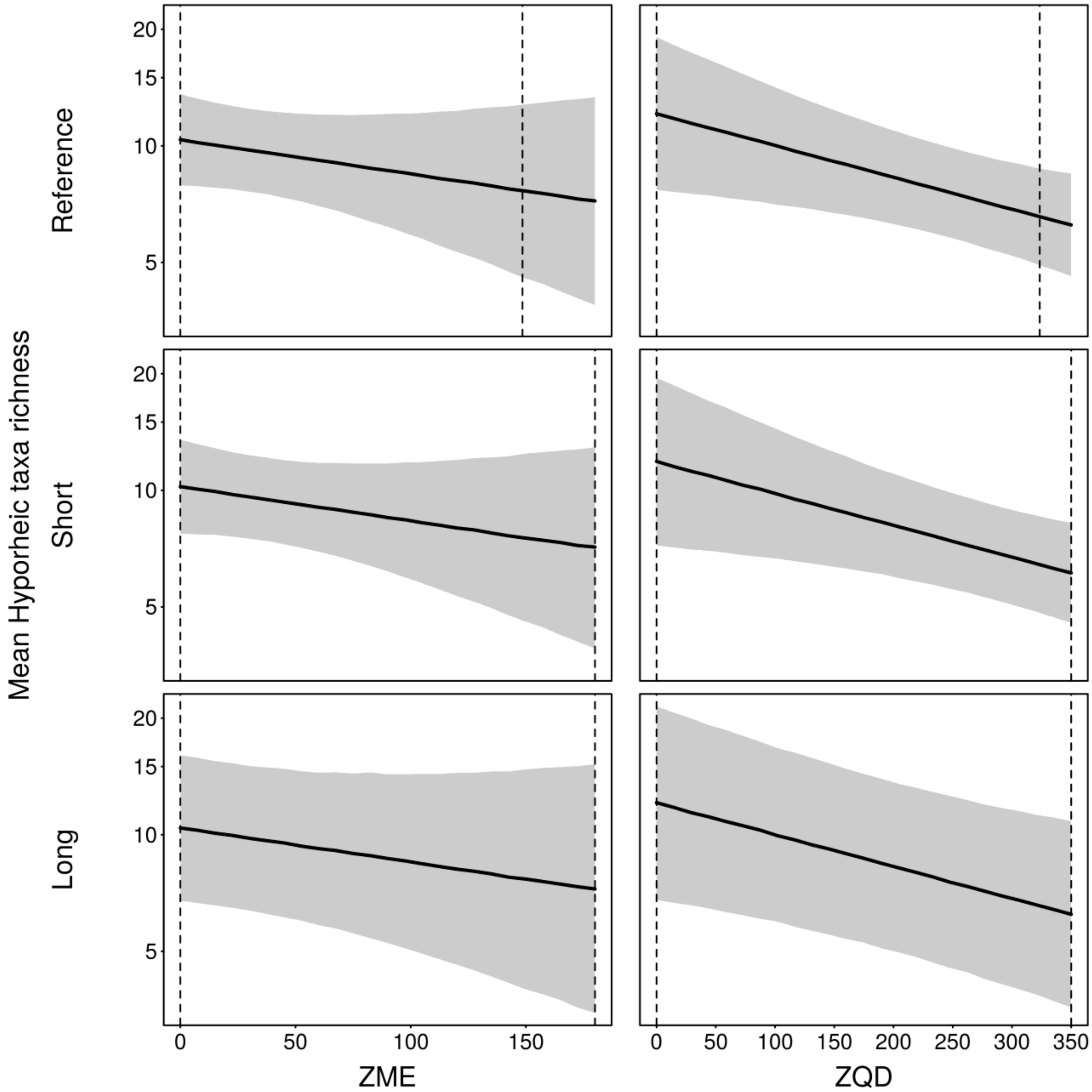

Figure 17 (Top row) Predicted mean (black line) and 80% central credible interval (grey polygon) of mean hyporheic invertebrate taxa richness under reference hydrological conditions in intermittent streams in the Hunter subregion; (middle and bottom rows) predicted future effects (mean = black line, 80% central credible interval = grey polygon)

In middle and bottom rows, all other hydrological response variables are held constant at the midpoint 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), ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period
Data: Bioregional Assessment Programme (Dataset 1)

Table 18 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for mean hyporheic invertebrate taxa richness in intermittent streams for the Hunter subregion

	Mean	q10	q90
(Intercept)	2.64	2.29	3
future1	0.0112	–0.33	0.352
long1	0.0193	–0.496	0.534
ZME	–0.00203	–0.0058	0.00174
ZQD	–0.00189	–0.00335	–0.000431

Future is a binary variable scored 1 if the analysis case is in a short- or long-assessment year. Long is a binary variable scored 1 if the analysis case is in the long assessment year. ZQD = zero-flow days (averaged over 30 years), ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period
Data: Bioregional Assessment Programme (Dataset 1)

2.7.3.3.3.2 Presence of riffle-breeding frogs

The density and diversity of frogs in streams responds to local, ground-level stream and vegetation variables (Parris and McCarthy, 1999). Many frogs that breed in permanent water bodies are excluded from temporary ones because their larval stage is longer than the persistence of water in these habitats. Therefore, the mix of frog species found in different streams can be partially explained by the different periods of water availability needed by each species in order to breed successfully (Brisbane City Council, 2010).

Elicitation scenarios

Table 19 summarises the elicitation matrix for the presence of the riffle-breeding frog in the intermittent streams of the Hunter subregion. The first six design points – design point identifiers 1 to 6 – address the predicted variability (across the intermittent streams in the landscape class during the reference interval) in ZQD and ZME. The design points 6, 1 and 2 capture the combination of the extremes of each hydrological response variable, whilst design points 3, 5 and 4 represent intermediate points in each hydrological response variable axis.

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. The high and low values for Yref were again calculated during the receptor impact modelling workshop.

Table 19 Elicitation design matrix for the receptor impact model of the mean probability of presence of the riffle-breeding frog in intermittent streams for the Hunter subregion

Design point identifier	ZME	ZQD	Yref	Year
6	149	323	na	2012
5	48.5	323	na	2012
4	8.0	323	na	2012
3	48.5	141	na	2012
2	0.630	141	na	2012
1	0.0	0.0	na	2012
11	0.0	10.0	0.087	2042
12	180	350	0.170	2042
10	23.3	350	0.170	2042
9	49.0	160	0.170	2042
5	49.0	350	0.087	2042
8	0.78	160	0.170	2042
14	0.780	160	0.087	2102
19	0.0	10.0	0.170	2102

Design points for Yref in the future (short- and long-assessment periods) are calculated during the receptor impact modelling elicitation workshop using elicited values for the receptor impact variable in the reference period. All other design points (with identifiers) are either default values or values determined by groundwater and surface water modelling. ZQD = zero-flow days (averaged over 30 years), ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period, na = not applicable
Data: Bioregional Assessment Programme (Dataset 1)

Receptor impact model

The fitted model for the probability of presence of the riffle-breeding frog takes the form

$$\begin{aligned}\eta = h(y) = \; & \beta_0 x_0 + \beta_f x_f + \beta_l x_l \\ & + \beta_{h_1} x_{h_1} + \beta_{h_2} x_{h_1}^2 + \beta_{h_3} x_{h_3} + \beta_{i_1} x_{h_2} x_f \end{aligned} \tag{4}$$

where the terms x_0, x_f, x_l are as before, x_{h_1} is the integer value of ZQD, x_{h_3} is the integer value of ZME and h_2 Identifies the coefficient for the quadratic term $x_{h_1}^2$ 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 18, whilst Table 20 summarises the same information for all seven model coefficients.

As per the perennial streams model, the hydrological response variable in the intermittent streams model varies during the reference interval and the future interval. The model indicates that the experts' elicited information strongly supports the assertion that ZQD has a negative effect on the probability of presence of the riffle-breeding frog. The model suggests that the probability of presence can vary across the landscape class from less than 0.2 to 0.8 under conditions of constant flow (ZQD = 0), holding all other covariates at their mid-values. As the number of zero-flow days increase, however, experts were of the opinion that the probability of presence would drop quite dramatically, with the model suggesting some chance of probability of presence of near zero under very intermittent flow conditions (ZQD > 350 days) (Figure 18).

There is evidence in the elicited data that the influence of ZQD on the probability of presence of riffle-breeding frogs may be different in the future assessment years. This is indicated by the positive coefficient of the interaction term β_{i_1}(future1: ZQD, Table 20) and difference in the partial regression plots between the reference year (top) and future years (middle and bottom) (Figure 18).

The increase in the probability of presence of frogs when zero-flow days are less than 100 appears to be due to the influence of the (highly) uncertain probability of presence when zero flow days are less than 160. The experts' responses to the elicitation scenarios appears to indicate that when zero flow days are less than 160, other habitat factors are important in determining the probability of frog presence, hence the value of Yref has a strong influence on the expert's response to the elicitation. As the number of zero flow days increases beyond 160, however, the experts were strongly of the opinion that the increasingly dry conditions will over-ride all other factors and the probability of frogs being present will drop rapidly irrespective of the value of Yref. The automatic model selection procedure included a quadratic coefficient for zero flow days (Table 20) in response to the experts' elicitations which together with the other variables leads to an increase in frogs at relatively wet conditions due to the value of Yref in the elicitation scenarios (19).

A similar effects occurs in the Perennial streams model (Section 2.7.3.2.3.1) reflected there by a quadratic coefficient for zero flow days but also a positive coefficient for Yref in the best selected model (Table 11). In the intermittent streams model the absence of a Yref coefficient in the best fitted model may be an artefact of the automatic model selection procedure and could be due to a very small difference in the likelihood of the alternative model structure.

The second hydrological variable (ZME) also has a negative effect on the probability of presence of riffle-breeding frogs, although this effect appears to be ecologically less important than the effect of ZQD, as indicated by the near-horizontal partial regression plots.

The best-fitting model in this case suggests that the remaining parameters (intercept and long1) have a limited influence on the probability of presence of the riffle-breeding frog (confidence interval spanning zero, Table 20).

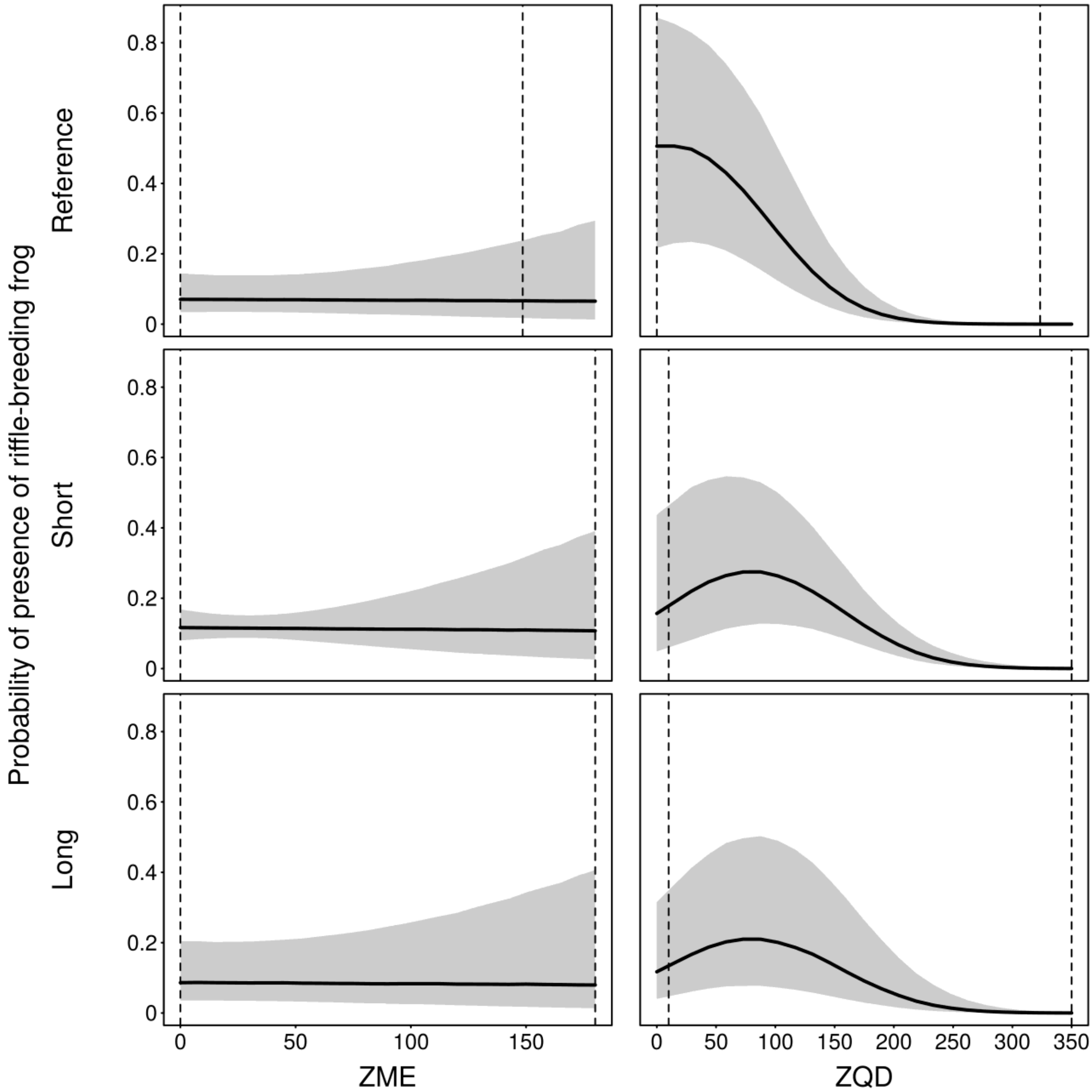

Figure 18 (Top row) Predicted mean (black line) and 80% central credible interval (grey polygon) of mean probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in a 100-m transect in intermittent streams for the Hunter subregion under reference hydrological conditions; (middle and bottom rows) predicted future effects (mean = black line, 80% central credible interval = grey polygon)

In middle and bottom rows, all other hydrological response variables are held constant at the midpoint 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), ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period
Data: Bioregional Assessment Programme (Dataset 1)

Table 20 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for probability of presence of the riffle-breeding frog in intermittent streams for the Hunter subregion

	Mean	q10	q90
(Intercept)	–0.316	–1.11	0.48
future1	–1.42	–2.62	–0.213
long1	–0.31	–1.19	0.571
ZME	–0.000457	–0.01	0.0091
ZQD	0.00195	–0.00789	0.0118
I(ZQD^2)	–9.99e–05	–0.000135	–6.46e–05
future1:ZQD	0.0141	0.00556	0.0226

Future is a binary variable scored 1 if the analysis case is in a short- or long-assessment year. Long is a binary variable scored 1 if the analysis case is in the long assessment year. ZQD = zero-flow days (averaged over 30 years), ZME = the maximum length of spells (in days per year) with zero flow averaged over a 30-year period, I(ZQD^2) = zero-flow days quadratic term, future1:ZQD = linear interaction between future 1 and zero-flow days

Data: Bioregional Assessment Programme (Dataset 1)

2.7.3.4 Ephemeral streams

Ephemeral stream reaches were defined as lacking surface flow for the majority of the year, with a minimum threshold defined as having flow for fewer than 35 days per year and pools holding water for less than 60 days per year. Workshop discussions determined that ephemeral stream systems were adequately described by the model for perennial streams, but with the removal of variables for riffle-breeding frogs and fishes that prefer riffle habitats (Figure 19). A key species group of concern for these systems are frogs of the genus *Pseudophryne*, which make use of pool habitats adjacent to seepages in moist forest habitats. For example, the red-crowned toadlet (*Pseudophryne australis*) is found near permanently moist soaks or along or near head-water streambeds adjacent to first or second order ephemeral drainage lines commonly called ‘feeder creeks’ which drain the ridges, benches, cliffs and talus slopes (Thumm, 1997). These watercourses are often dry or reduced to ponded areas for much of the year and only sustain flow for short periods.

Surface water models generally do not include ephemeral streams in their networks. They are unlikely to be monitored as they are not reliable water sources, have small catchment areas which are often not well represented through interpolated meteorological data surfaces and are difficult to represent using standard recession curve functions. Very few ephemeral streams are represented in the river modelling for the BA for the Hunter subregion. Given their lack of connection to groundwater, and the highly variable nature of ephemeral streamflow, the ecosystems of this landscape class were also considered less vulnerable to changes in catchment runoff from coal resource development, except perhaps where disruptions to surface drainage from mining affect the majority of the contributing area to the stream. As this can only occur very close to the mine site, it was considered a local-scale impact. While impacts on the habitat of ephemeral streams from changes in hydrology due to additional coal resource development cannot be completely ruled out, they were considered unlikely and low priority for a BA, and a quantitative model was not progressed.

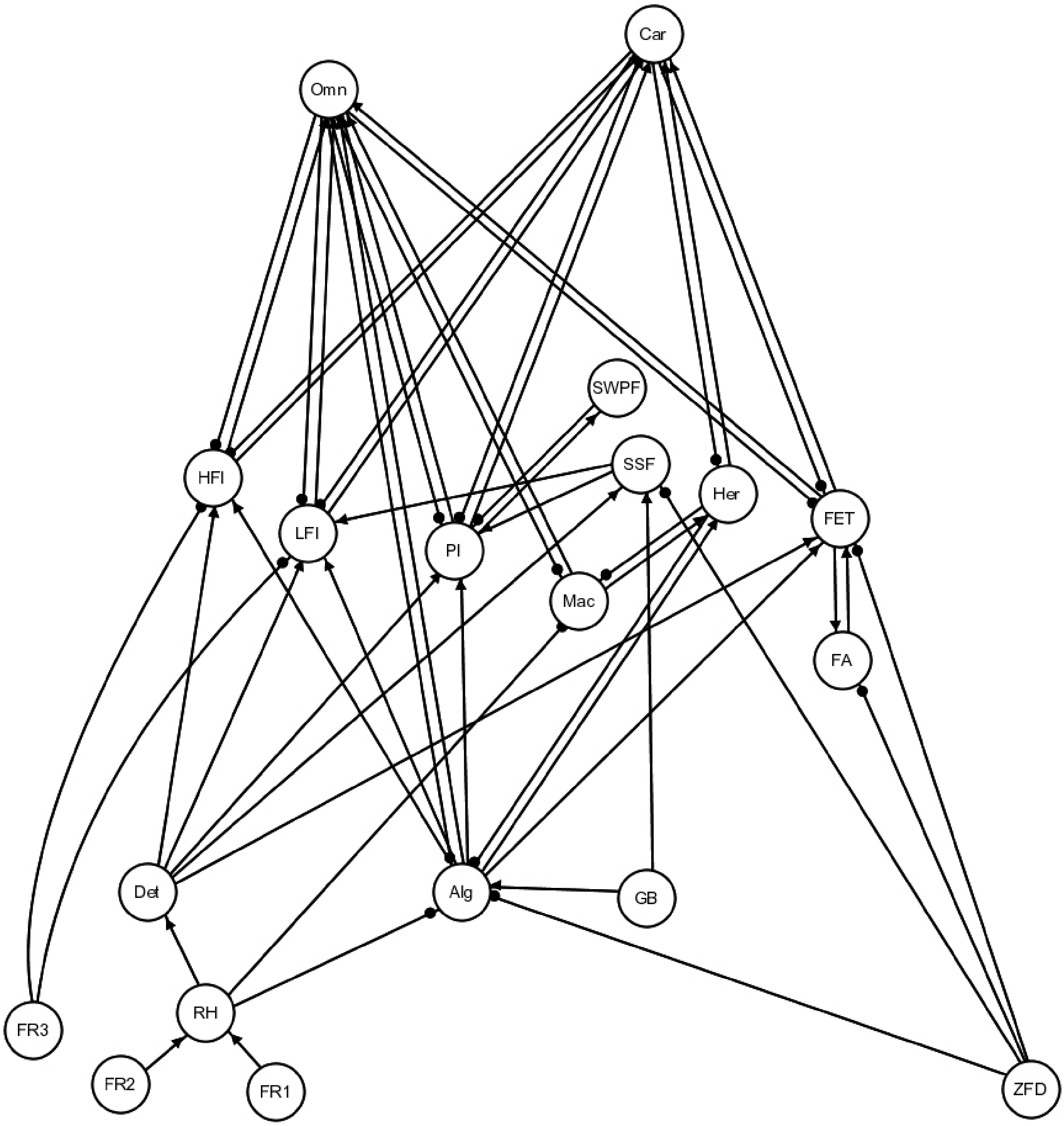

Figure 19 Signed digraph of ephemeral stream communities of the Hunter Valley

Algae (Alg), carnivores (Car), detritus (Det), frog adults (FA), frog eggs and tadpoles (FET), gravel bar (GB), herbivores (Her), high-flow invertebrates (HFI), low-flow invertebrates (LFI), macrophytes (Mac), omnivores (Omn), pool invertebrates (PI), riparian habitat (RH), subsurface fauna (SSF), slow water preferred fishes (SWPF). The hydrological response variables FR1, FR2, FR3 and ZFD are as previously defined.

Data: Bioregional Assessment Programme (Dataset 1)

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2.7.4 'Groundwater-dependent ecosystem' landscape group

Summary

Eight of the nine groundwater-dependent ecosystem (GDE) landscape classes in the Hunter subregion occur within the zone of potential hydrological change. For five of these landscape classes, four qualitative models were developed: 'Forested wetland', 'Wet and dry sclerophyll forest', 'Rainforest', and 'Freshwater wetlands'.

The qualitative mathematical model for the 'Forested wetland' landscape class was based upon the biological processes and environmental factors that regulate competition of casuarina with other tree species, shrubs and herbs. The model recognises the possibility for coal resource development to impact the groundwater regimes that support these forest communities. Groundwater level, overbench flow and overbank flow were identified as critical hydrological determinants of the condition of the forested wetlands ecosystem. Qualitative analysis of the signed digraph model generally indicates a negative predicted response of casuarina trees, seeds and seedlings to each of the cumulative impact scenarios, with a corresponding decline in shade, habitat structure, bank stability and orchids and fungi. Most of the other variables have a zero or ambiguous response prediction.

Relationships identified in the qualitative modelling workshop were formalised into a forested wetlands receptor impact model that predicts the response of annual mean projected foliage cover of woody riparian vegetation (predominately *Eucalyptus tereticornis, Casuarina cunninghamiana* and *E. camaldulensis*) in a 0.25-ha transect extending from the channel to the top of the bank (including floodplain overbank), to changes in the timing and magnitude of drawdown and the occurrence of overbench and overbank flows. The model reflects the experts' view that:

- initial foliage cover in the reference period has a positive effect on future foliage cover
- groundwater extraction has a negative effect on average projected foliage cover
- increased frequency of overbench flows has a positive effect on projected foliage cover
- increased frequency of overbank flows has a positive effect on projected foliage.

The qualitative mathematical model for 'Wet sclerophyll forest' and 'Dry sclerophyll forest' landscape classes is based on the model structure for forested wetlands. Unlike casuarina trees, the sclerophyll forests were not expected to have a requirement for two-to-three-yearly permanent inundation. The qualitative modelling workshop identified one variable, groundwater, as the key hydrological factor governing the quality of the wet and dry sclerophyll forest ecosystem. Qualitative analysis of the signed digraph model generally indicates a negative predicted response for trees, seedlings and shrubs to groundwater depletion, with a corresponding decline in shade, habitat structure, nectar, nectar consumers, predators, sap- and leaf-eating insects, gliders and koalas. Insects were predicted to increase as a consequence of a release from predation pressure, while no change was predicted for saline soils and herbs.

Relationships identified in the qualitative modelling workshop were formalised into a receptor impact model that described the response of annual mean projected foliage cover of sclerophyll forest (predominately *Angophora costata, Corymbia gummifera, Eucalyptus capitellata, Banksia spinulosa*) in a 0.25-ha plot to changes in the timing and magnitude of groundwater. The model reflects the experts' opinion that:

- initial foliage cover in the reference period has a positive effect on future foliage cover
- groundwater extraction has a negative effect on average projected foliage cover.

A model for rainforest communities was developed based on a modified version of the model for wet and dry sclerophyll forests. In this system, epiphytic vegetation in the form of vine thickets are an important component of habitat structure, and trees, shrubs and herbaceous vegetation provide a key resource to consumers of fleshy fruits. Owing to the typical location of these rainforests in sheltered gullies and slopes in hilly-to-steep terrain, experts thought it likely that this vegetation would probably use local groundwater (e.g. perched watertables, springs) opportunistically, and this groundwater would not be connected to regional watertables. Thus, no cumulative impact scenarios were developed for qualitative analyses of the model system, and no quantitative models were developed for the 'Rainforest' landscape class.

The 'Freshwater wetland' landscape class was described as a complex of marsh (littoral) and pond (open water) habitats, where the relative area of each habitat type was determined by the average level and degree of fluctuation in the water surface. Given that the best available information is that these wetlands are likely to be dependent on local, perched groundwater systems no cumulative impact scenarios were developed for qualitative analyses of the model system, and no quantitative models were developed for this landscape class.

2.7.4.1 Description

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 Hunter subregion, as in much of Australia, there is considerable uncertainty as to the nature of groundwater dependency for much terrestrial vegetation.

The water requirements of GDEs are poorly understood and there is large uncertainty as to the frequency, timing, life stage and duration of their groundwater use (Andersen et al., 2016). 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 in nature and did not quantify the groundwater requirements of the vegetation. Specific studies of GDEs within the Hunter 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., 2016). Modelled depths to groundwater (Summerell and Mitchell, 2011) for the subregion are generally shallow (within 16 m of the ground surface). However, there is likely to be uncertainty in the mapping owing to the sparse network of monitoring bores over much of the subregion.

The hydroclimatic environment of the Hunter subregion is subtropical in the eastern part, and bordering on temperate in the western part of the subregion. Average annual rainfall ranges from 600 to 1440 mm/year, with higher values associated with higher elevations and coastal areas. Precipitation is summer-dominated when potential evaporation is also highest (see companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). Hence, the region is classified as being water limited in as much as potential evaporation (1250 to 1950 mm/year) exceeds rainfall in most months of the year. In areas that experience a rainfall deficit, vegetation may be dependent to varying extents on groundwater within the Hunter subregion.

The geomorphology and hydrogeology of the Hunter subregion is described in companion product 1.1 (McVicar et al., 2015) and only a brief summary is presented here as context. The hydrogeological systems in the Hunter subregion are associated with Permian-Triassic sedimentary rock aquifers, alluvial aquifers along major rivers and creeks and aeolian sands aquifers in the coastal zone of the subregion. The Hunter Valley represents a regional groundwater discharge zone and a dividing streamline for groundwater flow. The main regional surface water and groundwater fluxes largely follow the subregion topography from the upland towards the river channels with overall discharge towards the Tasman Sea. From a surface water perspective, the Hunter subregion is primarily composed of the Hunter river basin (87.5% of the subregion) and the Macquarie and Tuggerah basin (10.7% of the subregion) (see companion product 1.1 for the Hunter subregion (McVicar et al., 2015)).

The subregion has three main hydrogeological units (see companion product 1.1 for the Hunter subregion (McVicar et al., 2015)) relevant to sustaining GDE structure and function, which provide a useful conceptual framework for examining landscape classes that are dependent on groundwater:

- alluvial aquifers along major rivers and creek lines
- fractured rock aquifers of the Hunter subregion
- coastal aquifers in the coastal area.

2.7.4.1.1 Alluvial aquifers

Alluvial aquifers form in sediments such as gravel, sand, silt and/or clay deposited by physical processes in river channels or on floodplains (Figure 20). These unconsolidated sedimentary aquifers may be layered and/or discontinuous due to the presence of deposits of low permeability silt and clay within the alluvia (Queensland Government, 2013a). Alluvial aquifers are generally shallower than sedimentary and fractured rock aquifers and water levels often fluctuate due to varying recharge and pumping rates (Geoscience Australia, 2016). Alluvia may be underlain by impermeable layers, which separate the unconfined sedimentary aquifer from other groundwater aquifers. Alluvia may support a range of ecosystems (Queensland Government, 2013a). Palustrine (e.g. swamps) and lacustrine (e.g. lakes) wetlands and riverine (e.g. streams and rivers) water bodies on alluvial deposits may depend on the surface expression of groundwater, while terrestrial vegetation may depend on subsurface groundwater that is typically accessed through the capillary zone above the watertable. Unconsolidated sedimentary aquifers in alluvial deposits may also support ecosystems within the aquifer itself, such as stygofauna (Hose et al., 2015).

The alluvial aquifer of the Hunter subregion is considered a regional discharge zone for the aquifers within the region (EPA, 2013), implying an interaction from the groundwater to surface water system through the alluvial aquifer. The connection between the alluvial aquifer and underlying fractured rocks is considered bi-directional (EPA, 2013). Groundwater discharge contributes to baseflow throughout the subregion, but is more persistent in the main Hunter alluvial systems than in the elevated areas, where there is a permanent connection to groundwater. The main recharge mechanisms for the alluvial aquifer are: river leakage to the alluvium (particularly during flooding), direct rainfall recharge and upward flow from Permian fractured rocks (see companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). River leakage is generally considered to be the largest recharge component, and in various modelling studies it has been fitted as up to four times greater than diffuse rainfall recharge (Worley Parsons, 2009; Heritage Computing, 2012).

GDE landscape classes, which are based on vegetation forms from Keith (2004) that are likely to be associated with alluvial aquifers include forested wetlands, and some freshwater wetlands, rainforests and semi-arid wetlands.

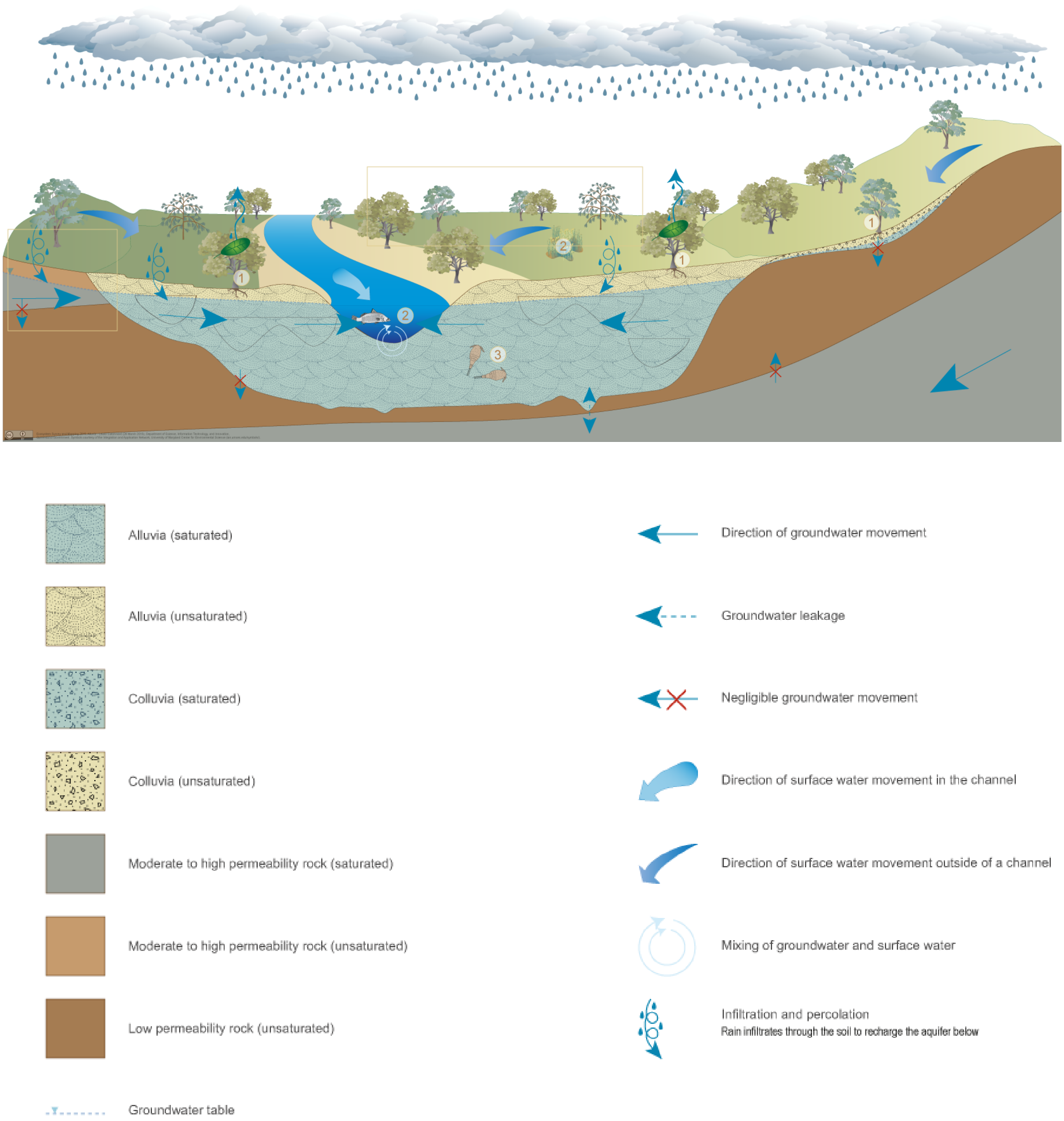

Figure 20 Conceptual model of the major groundwater processes in alluvia along major rivers and creeks in lower catchments

Numbers refer to types of groundwater-dependent ecosystems (GDEs) as follows: 1 = terrestrial GDEs, 2 = surface expression GDEs, 3 = subterranean GDEs.
Source: Queensland Government (2013a)
Data: Queensland Department of Science, Information Technology and Innovation (Dataset 1)

2.7.4.1.2 Fractured rock

In fractured rock aquifers (Figure 21), groundwater is stored in the fractures, joints, bedding planes and cavities of the rock mass (Geoscience Australia, 2016) and transmitted through fractures within the otherwise low permeability rock (Queensland Government, 2015). Fractured rock aquifers may discharge groundwater into channels, particularly in the lower parts of the landscape. Groundwater diffuse recharge from Permian-Triassic rocks in the Hunter subregion is estimated at less than 2% of annual rainfall, with high values associated with areas of the enhanced regolith permeability.

GDE landscape classes most likely to be associated with fractured rock aquifers include some rainforests, wet and dry sclerophyll forests, grassy woodlands and semi-arid woodlands.

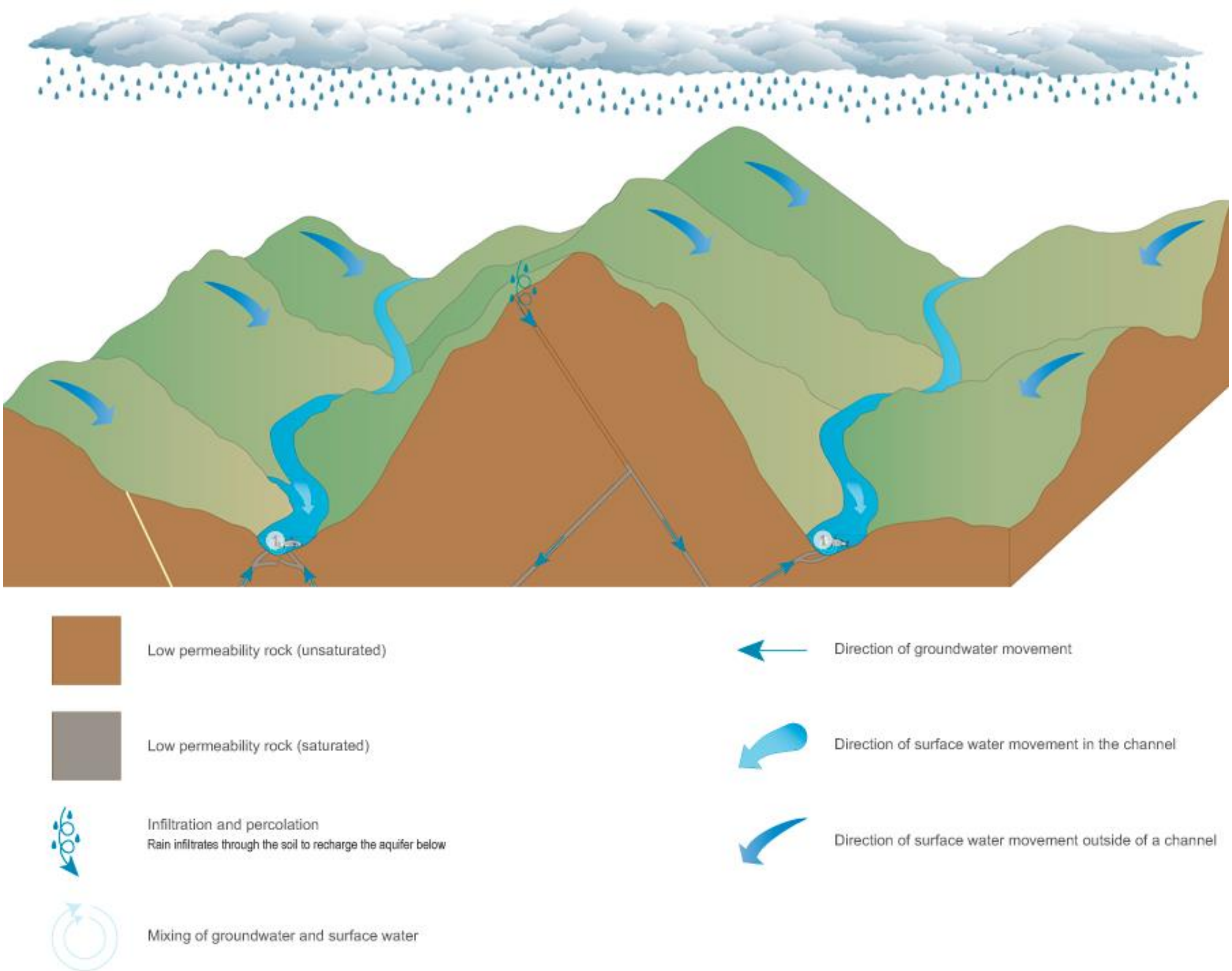

Figure 21 Conceptual model of the major groundwater processes in fractured rock systems

The number '1' indicates a surface expression groundwater-dependent ecosystem (GDE).
Source: Queensland Government (2015)
Data: Queensland Department of Science, Information Technology and Innovation (Dataset 1)

2.7.4.1.3 Coastal aquifers

Coastal sands typically support a single, unconsolidated sedimentary aquifer, in which groundwater forms a freshwater lens in the intergranular voids of the coastal sand mass (Figure 22). Perched aquifers may also occur over low permeability layers within the sand mass (Queensland Government, 2013b). Palustrine (e.g. swamps) and lacustrine (e.g. lakes) wetlands and riverine (e.g. streams and rivers) water bodies on coastal sand masses may depend on the surface expression of groundwater from these unconsolidated sedimentary aquifers, while terrestrial vegetation may depend on subsurface groundwater that is typically accessed through the capillary zone above the watertable. Unconsolidated sedimentary aquifers may also support subterranean ecosystems within the aquifer itself, indicated by the presence of stygofauna.

In the Hunter subregion, dunal and/or coastal (of aeolian origin) sands form a highly permeable unconfined aquifer and rainfall rapidly infiltrates through the unsaturated zone to recharge the saturated zone (companion product 1.1 for the Hunter subregion (McVicar et al., 2015)). An example of this is the Tomago Sandbeds, which experiences amongst the highest diffuse recharge rates in the region. Transmissivity has been estimated at between 400 m/day and more than 600 m/day (Crosbie, 2003) with a specific yield of about 0.2. The groundwater level is very responsive to rainfall events, with groundwater level rises over a metre observed on an event basis (Crosbie, 2003).

GDE landscape classes most likely to be associated with coastal aquifers include some freshwater wetlands, forested wetlands, heathlands and rainforests. Estuarine and near-shore marine ecosystems located adjacent to coastal sand masses can also depend on the discharge of groundwater from these unconsolidated sedimentary aquifers; note that the 'Coastal lakes and estuaries' landscape group is covered in Section 2.7.5.

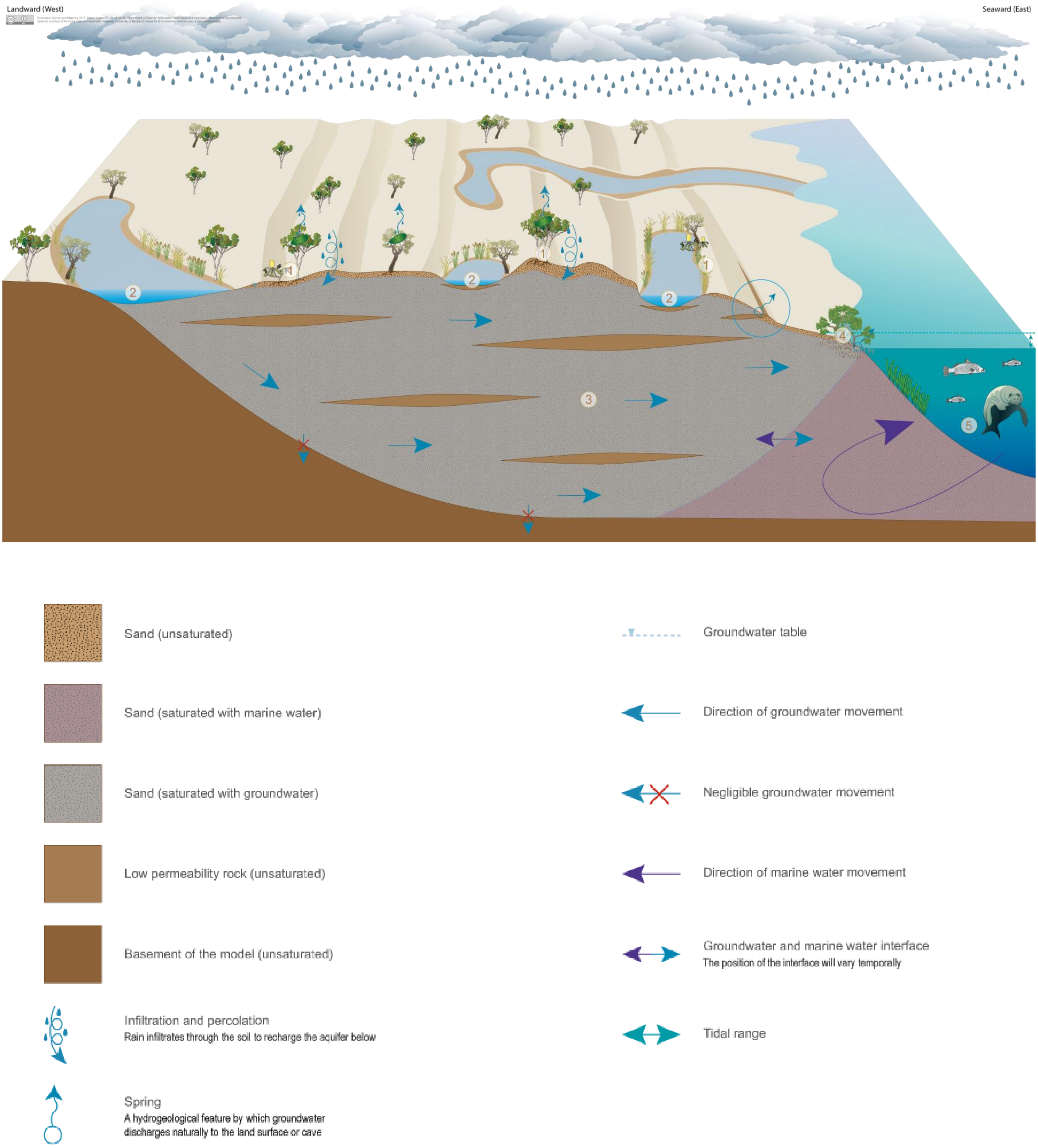

Figure 22 Conceptual model of the major groundwater processes on coastal areas

Numbers refer to types of groundwater-dependent ecosystems (GDEs) as follows: 1 = terrestrial GDEs, 2 = surface expression GDEs, 3 = subterranean GDEs, 4 = surface expression GDEs (estuarine systems), 5 = surface expression GDEs (near-shore marine systems).
Source: Queensland Government (2013b)
Data: Queensland Department of Science, Information Technology and Innovation (Dataset 1)

2.7.4.1.4 Potentially impacted landscape classes

Eight of the nine GDE landscape classes occur within the zone of potential hydrological change (Table 4 in Section 2.7.2). Qualitative models were developed for forested wetlands, wet and dry sclerophyll forests, freshwater wetlands and rainforests, and quantitative models were developed for forested wetlands and wet and dry sclerophyll forests. The qualitative models are described in the following sections. Models were not developed for the small areas of the 'Heathland' (0.2 km^2), 'Grassy woodland (0.2 km^2) and 'Semi-arid woodland' (<0.1 km^2) landscape classes within the zone (see Section 2.7.2.3).

2.7.4.2 Forested wetlands

In the Hunter subregion zone of potential hydrological change, the 57.7 km^2 of the 'Forested wetland' landscape class consists of 'Coastal floodplain wetlands' (3.8 km^2), 'Coastal swamp forests' (25.2 km^2), 'Eastern riverine forests' (18.2 km^2) and 'Coast and tableland riverine forests' (10.6 km^2). The riverine forests are located in the central and western uplands of the Hunter subregion while the coastal swamp forests and floodplain wetlands are located near the coast in the south-east of the subregion. The qualitative model applies to the whole 'Forested wetland' landscape class while the quantitative model applies to the riverine forests only.

2.7.4.2.1 Qualitative mathematical model

A qualitative model was developed to describe the ecological community associated with the 'Forested wetland' landscape class (Figure 23). The following description of the class is adapted from the NSW Office of Environment and Heritage 'Forested wetlands' webpage (OEH, 2017a). Forested wetlands are restricted to fertile soils along riverine corridors and floodplains, mostly at low altitude. They are dominated by sclerophyllous trees (including several *Eucalyptus* and *Melaleuca* species as well as *Casuarina* species) but are distinguished from sclerophyll forests by the presence of hydrophytes in the understorey, which are adapted to periodic inundation by floodwaters. Floodwaters are also an important factor in the nutrient cycle of forested wetlands. Invertebrates are numerous, with insects dominating forest floors while streams and standing water have an abundance of crustaceans, aquatic insects and other invertebrates. Many species have both aquatic and terrestrial life stages. A complex food web exists in forested wetlands; submerged debris is a substrate for algae, microbes and filter-feeders, which in turn are food for larger animals. Many fauna species are also reliant on trees for feeding, nesting, shelter, and hunting.

The qualitative model was based upon the biological processes and environmental factors that regulate competition of *Casuarina* with other tree species, shrubs and herbs, and draws upon the extensive knowledge of the ecology and water requirements of river sheoak (*Casuarina cunninghamiana*) and other wetland tree species (e.g. Chalmers et al., 2009; Erskine et al., 2013; Morris and Collopy, 1999; Woolfrey and Ladd, 2001). The suspected allelopathic properties of leaf litter from *Casuarina* trees generally (Hozayn et al., 2015) is thought to suppress the germination of other species of vegetation. The competitive advantage that *Casuarina* has in suppressing understory vegetation is regulated by the level of disturbance (Dis) to, or removal of, the leaf-litter layer through such processes as wind, fire and floods. Casuarina seeds (CS) are a principal food resource for the glossy black-cockatoo (*Calyptorhynchus lathami*) (GBC), and the root structure of mature trees are key in providing stream bank stability (SBS) (Erskine et al., 2013; Erskine et al., 2012). Within forested wetlands, tree canopies provide shade and forest structure that contribute to habitat suitability for the Australian water dragon (*Intellagama lesueurii*) (AWD), as well as species of frogs and skinks (F&S). Nectar (Nec) provided by flowering trees (Tre), shrubs (Shr) and herbs (Her) is a key resource for numerous species of nectar consumers (NC) (e.g. bats, birds, bees, beetles), which in turn support populations of predators (Pre) such as quolls, snakes, owls and raptors. All vegetation components of this system support various species of sap- and leaf-eating insects (S&LEI), and the shrubs and herbaceous vegetation are a key resource for wombat (Wom) populations, which are also dependent on particular aspects of the stream and floodplain morphology for the construction of burrows.

Land clearing and grazing (LC&G) were identified as drivers of hydrological changes that could lead to the development of saline soils (SS), which generally suppress the growth of trees and shrubs. This process is not within the scope of the bioregional assessment (BA) modelling, but was identified in the qualitative model as a factor influencing the recruitment and condition of tree and shrub species in this landscape class. In the model, these nodes are not affected by hydrological changes from coal resource development.

Three water regimes were described as being important to specific life history stages of forested wetland vegetation and the production of nectar. While these were denoted by groundwater regime (GWR) in the workshop, the specific water requirements are met through the interaction of groundwater and streamflow in and upon the floodplain alluvium.

1. GWR1 pertains to the ecohydrology of tree seedlings (Casuarina (CSI) and non-Casuarina (SI)), which cannot survive permanent inundation or saturation (from overbench and overbank flows or elevated watertables), or permanent drying. Seedling survival also requires that the rate of the seasonal lowering of groundwater does not outpace the growth rate of seedling roots. This regime was described as being relevant to seedling year-class success over a two-to-three-year time window (Roberts and Marston, 2011).
2. GWR2 is a water regime that provides sufficient groundwater stores during the flowering period of wetland forest vegetation.
3. GWR3 is similar to GWR1, but pertains to the canopy of mature tree and shrub species. The requirement is that the soil is not permanently saturated or permanently dry, especially during the season of major growth, and that the maximum depth to which groundwater falls in a season does not exceed the maximum root depth of dominant tree species.

The dependence of terrestrial vegetation on groundwater is difficult to predict or even quantify (Eamus et al., 2006); riparian and near-riparian vegetation may have an absolute dependency on groundwater (obligate phreatophyte), whereas vegetation growing above deeper groundwater, especially if shallow-rooted, may make only occasional use of groundwater (facultative phreatophyte). In stream reaches where the hydraulic gradient is from the stream to the adjoining floodplains (i.e. a 'streamflow in losing reach'; SFLR), streamflow replenishes the alluvial groundwater store and thus is important in the ecohydrology of the 'Forested wetland' landscape class.

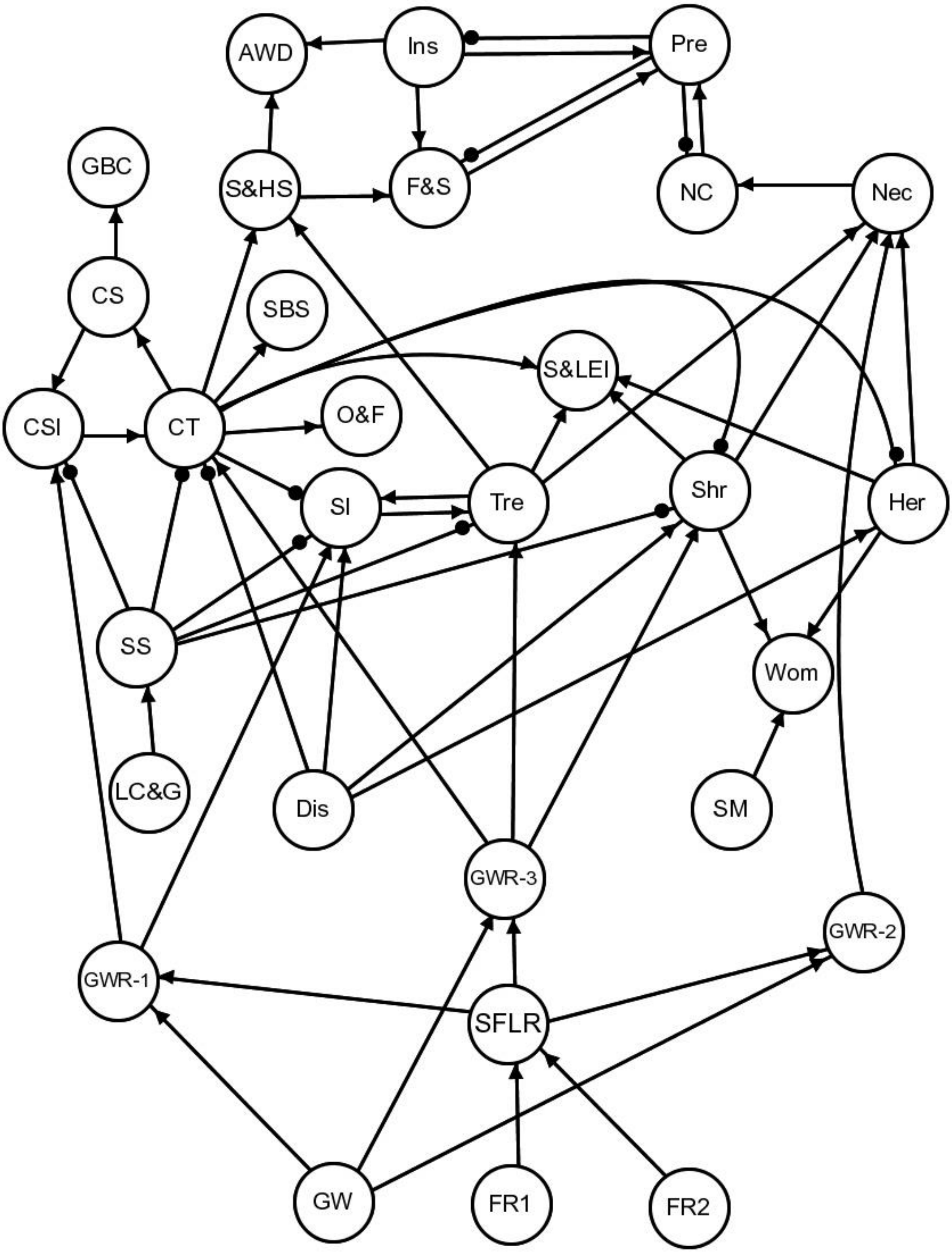

Figure 23 Signed digraph of forested wetland communities of the Hunter Valley

Australian water dragon (*Intellagama lesueurii*) (AWD), casuarina seeds (CS), casuarina seedlings (CSI), casuarina trees (CT), disturbance (Dis), frogs and skinks (F&S), glossy black-cockatoo (*Calyptorhynchus lathami*) (GBC), groundwater regime 1 (for seedling ecohydrology) (GWR-1), groundwater regime 2 (for nectar production) (GWR-2), groundwater regime 3 (for tree and shrub canopy cover) (GWR-3), herbs (Her), insects (Ins), land clearing and grazing (LC&G), nectar consumers (NC), nectar (Nec), orchids and fungi (O&F), predators (Pre), shade and habitat structure (S&HS), sap- and leaf-eating insects (S&LEI), stream bank stability (SBS), streamflow in losing reach (SFLR), shrubs (Shr), seedling (SI), stream morphology (SM), saline soils (SS), tree (Tre), wombats (Wom). Hydrological variables added subsequent to the qualitative modelling workshop are flow regimes 1 and 2 (FR1, FR2) and groundwater level (GW).
Data: Bioregional Assessment Programme (Dataset 2)

The hydrological variables that maintain and support the forested wetlands ecosystem were identified subsequent to the qualitative modelling workshop. Based on experience gained during the Gloucester subregion assessment, and comments received by experts following the Hunter qualitative modelling workshop, groundwater levels (GW), overbench flow (flow regime 1, FR1) and overbank flow (flow regime 2, FR2) were identified as the critical hydrological determinants of the condition of the forested wetlands ecosystem. In the qualitative models for this landscape class, a diminishment in overbench flows (FR1) and overbank flows (FR2) were both projected to have a negative effect on the replenishment of streamflow for each groundwater regime (via SFLR). A decrease in groundwater levels was also described as having a negative impact on the three groundwater regimes. Based on combinations of these potential impacts, three cumulative impact scenarios were developed for qualitative analyses of response predictions (Table 21).

Table 21 Summary of the (cumulative) impact scenarios (CISs) for forested wetlands in the Hunter subregion

CIS	FR1	FR2	GW
C1	0	0	+
C2	–	–	0
C3	–	–	+

Pressure scenarios are determined by combinations of no change (0), increase (+) or decrease (–) in hydrological response variables. Scenario C1 shows the expected impacts under the coal resource development pathway (CRDP).
FR1 = flow regime 1 (overbench flow), FR2 = flow regime 2 (overbank flow), GW = groundwater level
Data: Bioregional Assessment Programme (Dataset 2)

Qualitative analysis of the signed digraph model (Figure 23 and Table 22) generally indicates a negative predicted response of casuarina trees, seeds and seedlings (CT, CS and CSI, respectively) to each of the cumulative impact scenarios, with a corresponding decline in shade and habitat structure (S&HS), stream bank stability (SBS) and orchids and fungi (O&F). While most of the other variables have a zero or ambiguous response prediction, the predicted decline in casuarina trees would result in competitive release that benefits shrubs (Shr) and herbaceous vegetation (Her), with flow-on benefits to wombats (Wom), nectar (Nec) and nectar consumers (NC).

Table 22 Predicted response of the signed digraph variables of forested wetlands to (cumulative) changes in hydrological responses variables

Signed digraph variable (full name)	Signed digraph variable (shortened form)	C1	C2	C3
Casuarina trees	CT	–	–	–
Casuarina seeds	CS	–	–	–
Casuarina seedlings	CSl	–	–	–
Glossy black-cockatoo	GBC	–	–	–
Shade and habitat structure	S&HS	(–)	(–)	(–)
Stream bank stability	SBS	–	–	–
Orchids and fungi	O&F	–	–	–
Saline soils	SS	0	0	0
Land clearing and grazing	LC&G	0	0	0
Tree	Tre	?	?	?
Seedling	Sl	?	?	?
Disturbance	Dis	0	0	0
Shrubs	Shr	?	?	(+)
Australian water dragon	AWD	?	?	(–)
Herbs	Her	+	+	+
Frogs and skinks	F&S	?	?	(–)
Insects	Ins	?	?	?
Nectar	Nec	?	?	?
Sap- and leaf-eating insects	S&LEI	?	?	?
Wombats	Wom	(+)	(+)	(+)
Nectar consumers	NC	?	?	(+)
Predators	Pre	?	?	?
Stream morphology	SM	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 a completely determined prediction of no change.
Data: Bioregional Assessment Programme (Dataset 2)

2.7.4.2.2 Temporal scope, hydrological response variables and receptor impact variables

The temporal scope for the forested wetlands is the same as that described for the riverine models described in Section 2.7.3. For surface water and groundwater variables the reference assessment interval is defined as the 30 years preceding 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.

For forested wetlands, the qualitative modelling workshop identified three ecologically important water regimes that were thought to: (i) be instrumental in maintaining and shaping the components, functions and processes provided by the landscape class ecosystem and, (ii) have the potential to change due to coal resource development. Most of the ecological components and processes represented in the qualitative model are potential receptor impact variables and are predicted to vary as the hydrological factors vary either individually or in combination (Table 22). The exceptions are saline soils (SS), land clearing and grazing (LC&G), disturbance (Dis) and stream morphology (SM), which in the model are completely determined predictions of no change.

Following advice from participants during (and after) the qualitative modelling workshop, and guided by the availability of experts for the receptor impact modelling workshop, and the receptor impact variable selection criteria (Section 2.7.1.2.3), the receptor impact models were designed to focus on the relationship between trees (Tre) and changes to flow regimes 1 and 2 and groundwater.

The key hydrological components of the model, identified during the Hunter subregion qualitative modelling workshop, were subsequently reinterpreted in terms of hydrological response variables that could be derived from the modelled groundwater and streamflow time series (Table 23). The precise definitions of the receptor impact variables, typically a species or group of species represented by a qualitative model node, were determined by the experts during the receptor impact modelling workshop.

Using the 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 a forested wetland receptor impact model that describes the response of:

- mean annual projected foliage cover of woody riparian vegetation (predominately *Eucalyptus tereticornis, Casuarina cunninghamiana* and *E. camaldulensis*) in a 0.25-ha transect extending from the channel to the top of the bank (including floodplain overbank), to changes in dmaxRef, tmaxRef, EventsR0.3 and EventsR3.0 (Table 23).

Table 23 Summary of the hydrological response variables used in the receptor impact models, together with the signed digraph variables that they correspond to, for the 'Forested wetland' landscape class in the Hunter 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
Yrs2tmaxRef	The difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102)	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 maximum 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 maximum change due to additional coal resource development.	FR2

2.7.4.2.3 Receptor impact model

2.7.4.2.3.1 Projected foliage cover of woody riparian vegetation

Elicitation scenarios

Table 24 summarises the elicitation design matrix for the projected foliage cover of woody riparian vegetation in the 'Forested wetland' landscape class. The first six design points – design point identifiers 1, 2, 4, 5, 6 and 7 – address the predicted variability (across the perennial streams in the landscape class during the reference interval) in the overbench (EventsR0.3) and overbank (EventsR3.0) flows, defined as events with a return interval of 3.3 events and 0.33 events per year, respectively. The design points 1, 5 and 7 capture the combination of the extremes of each hydrological response variable, whilst design points 2, 4 and 6 capture intermediate points in each hydrological response variable axis.

The first six design points provide for an estimate of the uncertainty in mean projected foliage 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 (2012) assessment years.

Table 24 Elicitation design matrix for the receptor impact model of mean projected foliage cover in the riparian-dependent community in the 'Forested wetland' landscape class for the Hunter subregion

Design point identifiers	EventsR0.3	EventsR3.0	dmaxRef	tmaxRef	Yref	Year
5	3.3	0.330	0.0	na	na	2012
6	3.3	0.330	0.0	na	na	2012
4	3.3	0.330	0.0	na	na	2012
7	3.3	0.330	0.0	na	na	2012
1	3.3	0.330	0.0	na	na	2012
2	3.3	0.330	0.0	na	na	2012
44	2.9	1.100	5.8	2041	0.07	2042
55	1.1	0.033	0.2	2102	0.07	2042
9	9.4	1.100	0.2	1980	0.07	2042
25	1.1	1.100	34.0	1980	0.07	2042
78	9.4	0.320	34.0	2102	0.07	2042
21	9.4	0.033	34.0	1980	0.07	2042
148	1.1	0.320	5.8	2102	0.22	2042
155	2.9	0.033	34.0	2102	0.22	2042
82	1.1	0.033	0.2	1980	0.22	2042
111	9.4	0.033	0.2	2041	0.22	2042
306	9.4	1.100	0.2	2102	0.22	2102
167	2.9	0.320	0.2	1980	0.07	2102
208	1.1	0.033	34.0	2041	0.07	2102
270	9.4	1.100	34.0	1980	0.22	2102
277	1.1	1.100	0.2	2041	0.22	2102
228	9.4	0.033	5.8	2102	0.07	2102
241	1.1	1.100	34.0	2102	0.07	2102

Receptor impact model (RIM) elicitation design matrix for percentage of projected foliage. Design points for Yref in the future (short- and long-assessment periods) are calculated during the RIM 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. Hydrological response variables are as defined in Table 23.
na = not applicable
Data: Bioregional Assessment Programme (Dataset 2)

Design point identifiers 9 through to 306 (as listed in Table 24) 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.

Receptor impact model

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) (Hosack et al., 2018)). The fitted model takes the form

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \sum_{j=1}^{4} \beta_{h_j} x_{h_j} \quad (5)$$

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 when the design case is in the reference year), and $x_{h_j}, j = 1 \ldots 4$ 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 the quadratic value of, and in interactions between, the hydrological response variables but in this instance the simple linear model above was identified as the most parsimonious representation of the experts’ responses.

The model estimation procedure adopts a Bayesian approach. The model coefficients $(\beta_0, \beta_f, \beta_l, \beta_r, \beta_{h_j})$ are assumed to follow a multivariate normal distribution. The Bayesian estimation procedure quantifies how compatible different values of the parameters of this distribution are with the data (the elicited expert opinion) under the model. Table 25 summarises information for all eight model coefficients, whilst Figure 24 summarises the (marginal) mean and 80% central credible intervals of the four hydrological response variable coefficients in partial regression plots.

Table 25 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for projected foliage cover

	Mean	q10	q90
(Intercept)	–2.23	–3.45	–1.02
Yref	1.09	0.817	1.37
future1	2.09	0.772	3.41
long1	–0.364	–0.768	0.0397
EventsR0.3	0.0405	0.00202	0.079
EventsR3.0	0.472	0.105	0.839
dmaxRef	–0.0144	–0.0248	–0.00401
Yrs2tmaxRef	–0.00244	–0.00562	0.000749

Yref is value of receptor impact variable in the reference assessment year; it has no value if the design case is in the reference assessment year. Future is a binary variable scored 1 if the design case is in a short- or long-assessment year. Long is a binary variable scored 1 if the design case is in the long assessment year. EventsR0.3, EventsR3.0 and dmaxRef are defined in Table 23. Yrs2tmaxRef is the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102).
Data: Bioregional Assessment Programme (Dataset 2)

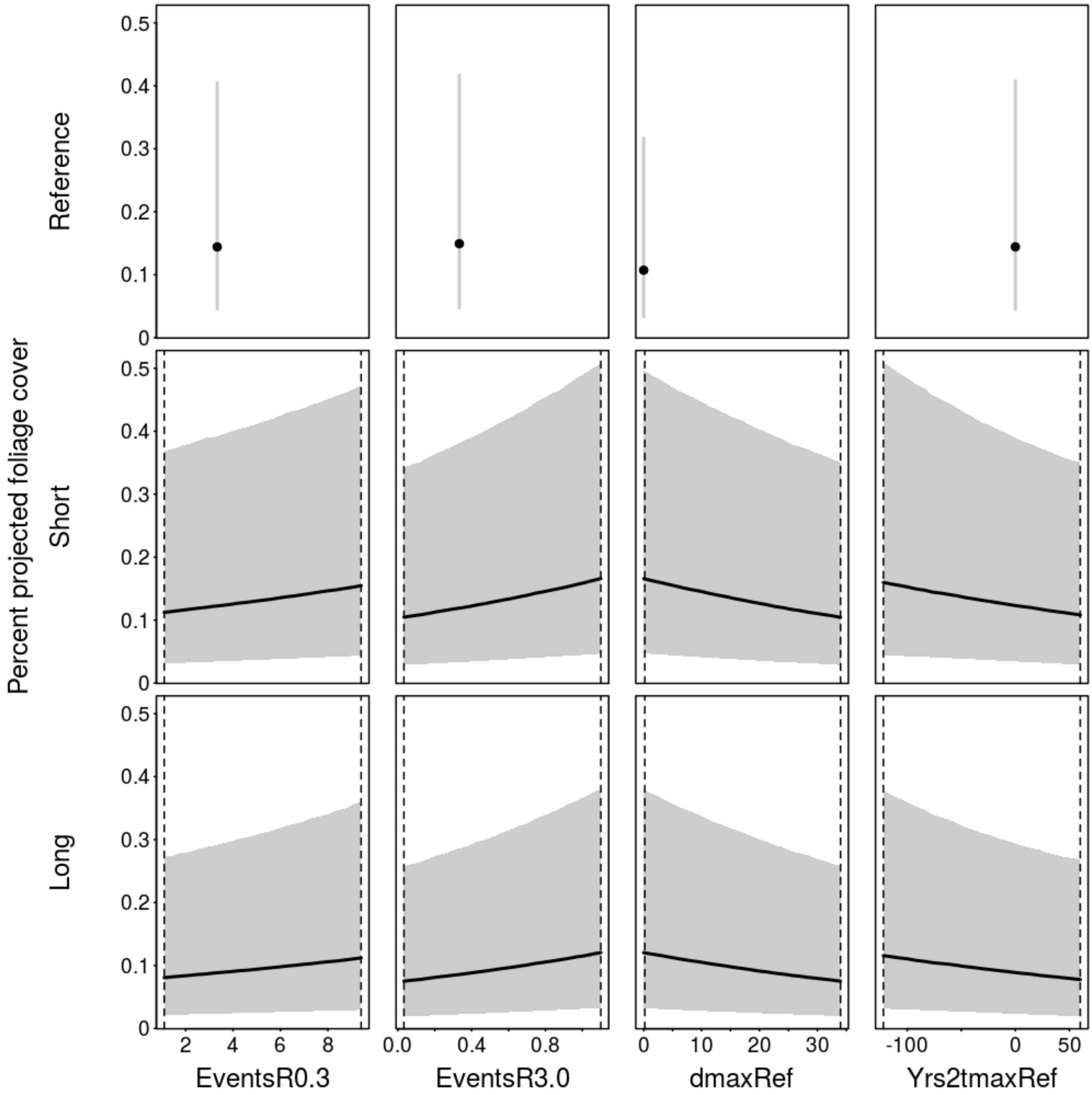

Figure 24 (Top row) Predicted mean (black dot) and 80% central credible interval (grey line) of projected foliage cover under reference hydrological conditions; (middle and bottom rows) predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on mean projected foliage cover for the Hunter subregion

In the middle and bottom rows, all other hydrological response variables are held constant at the midpoint of their elicitation range (during risk estimation all hydrological response variables vary simultaneously). Dashed vertical lines show the hydrological response variable range used in the elicitation. EventsR0.3, EventsR3.0 and dmaxRef are defined in Table 23. Yrs2tmaxRef is the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102). The numbers on the y-axis range from 0 to 1 as the receptor impact model was constructed using the proportion for the statistical modelling. They should be interpreted as a percent foliage cover ranging from 0 to 100%.
Data: Bioregional Assessment Programme (Dataset 2)

The model reflects the experts' opinion that the projected foliage cover in the reference year (Yref) has a positive effect on average projected foliage cover in the future. That is, for the same changes in hydrology, a site with a high foliage cover in 2012 is likely to have a higher foliage cover in the future than a site with a low foliage cover in 2012. This reflects the lag in the response of canopy cover to changes in hydrological response variables that would be expected of mature trees with long life spans.

The model reflects the experts' opinion that groundwater drawdown (as indicated by dmaxRef) has a negative effect on average projected foliage cover. In other words, projected foliage 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 projected foliage cover will drop from about 10% to about 6.5% for a decrease in groundwater levels of 35 m relative to the reference level in 2012. There is, however, considerable uncertainty in these predictions, with an 80% chance that the foliage cover will lie somewhere between approximately 47% and 5% in the short-assessment period, and somewhere between roughly 52% and 5% in the long-assessment period, with a 35-m drop in groundwater level.

The mean negative coefficient associated with the covariate Yrs2tmaxRef suggests that projected foliage cover is higher in the assessment year if the assessment year occurs after the time of maximum drawdown (Yrs2tmaxRef<0 in Figure 24). One interpretation is that the more time that has elapsed since tmaxRef, the greater the groundwater recovery and, in turn, the greater the projected foliage cover in the assessment year. Again, there is considerable uncertainty around the predicted effect on percent projected foliage cover, reflecting uncertainty around the magnitude of and rate at which groundwater levels decline due to pumping and the trees' ability to adjust to these changes. This is reflected in the large credible intervals in Figure 24.

The model represents the frequency of overbench flows as having a positive relationship with projected foliage cover – an 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 9 over the future period, causes an increase in average projected foliage cover of about 4%. The uncertainty in the projected foliage cover in the short- and long-assessment years is driven by the relative large uncertainty in the intercept, Yref and future coefficients (indicated by the relatively large 80% credible interval, Table 24). There is relatively small variation in expert's belief about the positive effect of over bench flows (indicated by the relatively small 80% credible interval, Table 24).

The model also suggests that the frequency of overbank flows will have a positive effect on average projected foliage cover – the predicted slight increase in the average frequency of overbench flood events, from 0.3 (by definition) in the 30 years preceding the reference year, to a maximum average value of 1.2 over the future period, causes the average percentage projected foliage cover to increase by about 7%. Again the uncertainty in the projected foliage cover in the future assessment periods is driven by uncertainty in the intercept, reference year and future terms, not by large uncertainty in the effect of overbank flows.

Finally, the model suggests that we can expect differences in projected foliage cover in the future compared to the reference period, and even between short-term and long-term assessment. While 'future' is associated with a positive coefficient, 'long' is estimated to have a negative effect on projected foliage cover. This indicates that greater effects are expected in the short-term period than in the long-term period, as can be observed in Figure 24.

2.7.4.3 Wet and dry sclerophyll forests

Experts at the Hunter qualitative modelling workshop determined that, given the state of knowledge, wet and dry sclerophyll forests were sufficiently similar in their ecological interactions between the main components and the environment (including groundwater needs) that they could be dealt with in a single model. There were 18.8 km^2 of combined wet and dry sclerophyll forests within the zone of potential hydrological change in the Hunter subregion. Landscape class descriptions are given in Table 5 of companion product 2.3 for the Hunter subregion (Dawes et al., 2018). Wet sclerophyll forests are dominated by trees of the Myrtaceae family, particularly of the genera *Eucalyptus, Angophora, Corymbia, Syncarpia* and *Lophostemon*. Dominant tree species tend to have smaller, hard leaves and be adapted to varying extents to the occurrence of wild fires. Wet sclerophyll forests are restricted to areas of higher rainfall and moderate fertility and often include a dense understorey of soft-leaved rainforest shrubs and small trees in moister situations (shrubby subformation). In drier situations these forests may have an open, grassy understorey (grassy subformation) with a sparse, sclerophyllous shrub layer. Dry sclerophyll forests are open forests that include a wide range of structural and floristic types. In general they occur on poorer substrates and relatively drier situations than the wet sclerophyll forests. On moderately poor soils these forests may develop a dense, grassy understorey with a more open shrub layer (shrub/grass subformation) while on the poorest substrates (sands and sandstones) a dense, sclerophyllous shrub layer dominates. Fire often plays an important role in the ecology of these forests.

Within the zone of potential hydrological change in the Hunter subregion, dry sclerophyll forests are overwhelmingly dominated by the Keith (2004) vegetation class 'Sydney coastal dry sclerophyll forests' (11.9 km^2), which are 10- to 25-m tall dry open eucalypt forests with a prominent and diverse sclerophyll shrub understorey and open groundcover of sclerophyll sedges. They occur in areas receiving 1000 mm to over 1300 mm mean annual rainfall, at elevations below 700 m, on quartzose sandstone ridges, slopes and gullies with infertile sandy loams. Common overstorey species are *Angophora costata* (Sydney red gum) and *Corymbia gummifera* (red bloodwood) (OEH, 2017b).

Within the zone of potential hydrological change in the Hunter subregion, wet sclerophyll forests are overwhelmingly dominated by the Keith (2004) vegetation class 'North coast wet sclerophyll forests' (4.3 km^2), which 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 in the canopy (OEH, 2017c).

2.7.4.3.1 Qualitative mathematical model

The wet and dry sclerophyll forests signed digraph in Figure 25 is a modified version of the forested wetlands signed digraph. This model lacks life-stage variables for *Casuarina* spp. and related model variables (i.e. glossy black-cockatoo (GBC), orchids and fungi (O&F), disturbance of leaf litter (Dis)) and components that require a connection with stream or riparian areas (i.e. bank stability (SBS), stream morphology (SM) and wombats (Wom)). Added to this model were variables for populations of koalas (Koa), which use the tree canopy (Tre) for habitat and food resources, and gliders (Gli), which feed on nectar (Nec) and insects (Ins). The same three groundwater regimes identified in the forested wetlands qualitative model were described as being applicable to this system, but the requirement for no permanent inundation (GWR1) over a two-to-three-year period was not relevant to seedlings of non-casuarina tree species because these landscape classes are rarely associated with floodplains and commonly associated with ranges, foothills, ridges, slopes and gullies.

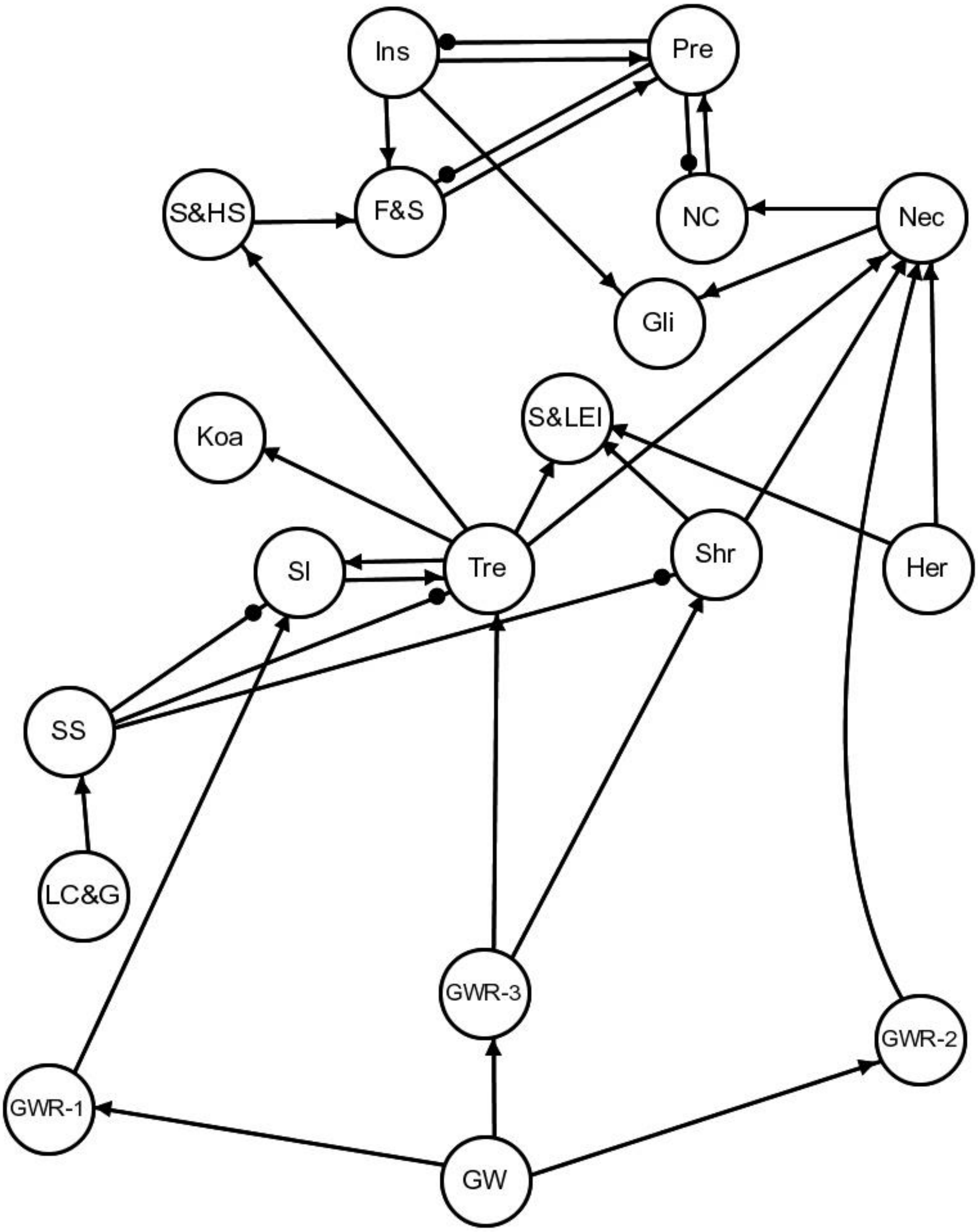

Figure 25 Signed digraph of wet and dry sclerophyll forests

Frogs and skinks (F&S), gliders (Gli), groundwater regime 1 (for seedling ecohydrology) (GWR-1), ground-water regime 2 (for nectar production) (GWR-2), groundwater regime 3 (for tree and shrub canopy cover) (GWR-3), herbs (Her), insects (Ins), koala (Koa), land clearing and grazing (LC&G), nectar consumers (NC), nectar (Nec), predators (Pre), shade and habitat structure (S&HS), sap- and leaf-eating insects (S&LEI), shrubs (Shr), seedling (Sl), saline soils (SS), tree (Tre). Hydrological variable added subsequent to the qualitative modelling workshop is groundwater (GW).
Data: Bioregional Assessment Programme (Dataset 2)

In the qualitative models for this landscape class, a decrease in groundwater levels was described as having a negative impact on each of the three groundwater regimes, and a single cumulative impact scenario was developed for qualitative analyses of response predictions. Qualitative analysis of the signed digraph model (Figure 25 and Table 26) generally indicates a negative predicted response for trees (Tre), seedlings (Sl) and shrubs (Shr) to the cumulative impact scenario, with a corresponding decline in shade and habitat structure (S&HS), nectar (Nec), nectar consumers (NC), predators (Pre), sap- and leaf-eating insects (S&LEI), gliders (Gli) and koalas (Koa). Insects (Ins) were predicted to increase as a consequence of a release from predation pressure, while no change was predicted for saline soils (SS) and herbs (Her).

Table 26 Predicted response of the signed digraph variables of wet and dry sclerophyll forests to (cumulative) changes in hydrological responses variables

Signed digraph variable (full name)	Signed digraph variable (shortened form)	C1
Shade and habitat structure	S&HS	–
Saline soils	SS	0
Land clearing and grazing	LC&G	0
Trees	Tre	–
Seedling	Sl	–
Shrubs	Shr	–
Herbs	Her	0
Frogs and skinks	F&S	?
Insects	Ins	+
Nectar	Nec	–
Sap- and leaf-eating insects	S&LEI	–
Nectar consumers	NC	(–)
Predators	Pre	–
Gliders	Gli	(–)
Koala	Koa	–

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 a completely determined prediction of no change.
Data: Bioregional Assessment Programme (Dataset 2)

2.7.4.3.2 Temporal scope, hydrological response variables and receptor impact variables

The temporal scope for the wet and dry sclerophyll forests is the same as that described for the other landscape classes of the Hunter subregion. For surface water and groundwater variables the reference assessment interval is defined as the 30 years preceding 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.

For wet and dry sclerophyll forests, the qualitative modelling workshop identified one variable – groundwater– as the key hydrological factor governing the quality of the wet and dry sclerophyll forests ecosystem.

As before, this hydrological variable was interpreted as two hydrological response variables that can be modelled (Table 27), and the receptor impact variable formally defined during the receptor impact modelling workshop. As a result, the relationships identified in the qualitative modelling workshop were formalised into a receptor impact model that described the response of:

- annual mean projected foliage cover of sclerophyll forest (predominately *Angophora costata*, *Corymbia gummifera*, *Eucalyptus capitellata*, *Banksia spinulosa*) in a 0.25-ha plot to changes in dmaxRef and tmaxRef.

Table 27 Summary of the hydrological response variables used in the receptor impact models, together with the signed digraph variables that they correspond to, for the wet and dry sclerophyll forests landscape classes in the Hunter 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

2.7.4.3.3 Receptor impact models

2.7.4.3.3.1 Projected foliage cover of trees

Elicitation scenarios

Table 28 summarises the elicitation design matrix for the projected foliage cover of trees in the 'Wet sclerophyll forest' and Dry sclerophyll forest' landscape classes. The first design point – design point identifier Ref – set the variability in projected foliage cover under the reference conditions (no drawdown).

The remaining design points represent hydrological scenarios that span the uncertainty in the values of the hydrological response variables in the relevant time period of hydrological history associated with the short (2042) and long (2012) assessment years.

Design point identifiers 2 through to 32 (as listed in Table 28) represent combinations of the two hydrological response variables (dmaxRef, tmaxRef), together with high and low values of Yref. The high and low values for Yref were calculated during the receptor impact modelling workshop following the experts' response to the first design point, and then automatically included within the design for the elicitations at the subsequent design points.

Table 28 Elicitation design matrix for the receptor impact model of mean projected foliage cover in the casuarina tree community in the wet and dry sclerophyll forests landscape classes for the Hunter subregion

Design point identifiers	dmaxRef	tmaxRef	Yref	Year
Ref	0.0	na	na	2012
18	45.0	2102	0.4	2042
13	0.2	2041	0.4	2042
2	6.8	1980	0.2	2042
6	45.0	2041	0.2	2042
25	0.2	2102	0.2	2102
32	6.8	2041	0.4	2102
30	45.0	1980	0.4	2102
19	0.2	1980	0.2	2102

Design points for Yref in the future (short- and long-assessment periods) are calculated during the receptor impact model 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. Hydrological response variables dmaxRef and tmaxRef are defined in Table 27.
na = not applicable
Data: Bioregional Assessment Programme (Dataset 2)

Receptor impact model

The model fitted to the elicited values of mean percentage foliage cover for the wet and dry sclerophyll forests landscape classes takes the form

$$\eta = h(y) = \beta_0 x_0 + \beta_f x_f + \beta_l x_l + \beta_r x_r + \sum_{j=1}^{2} \beta_{h_j} x_{h_j} \quad (6)$$

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 $x_{h_j}, j = 1 \ldots 2$ are the (continuous or integer) values of the two hydrological response variables (dmaxRef, tmaxRef). Each term has a fitted coefficient β. Note that the modelling framework provides for more complex models, including the quadratic value of, and in interactions between, the hydrological response variables but in this instance the simple linear model above was identified as the most parsimonious representation of the experts' responses.

The (marginal) mean and 80% central credible intervals of the two hydrological response variable coefficients are summarised in partial regression plots in Figure 26, whilst Table 29 summarises the same information for all six model coefficients.

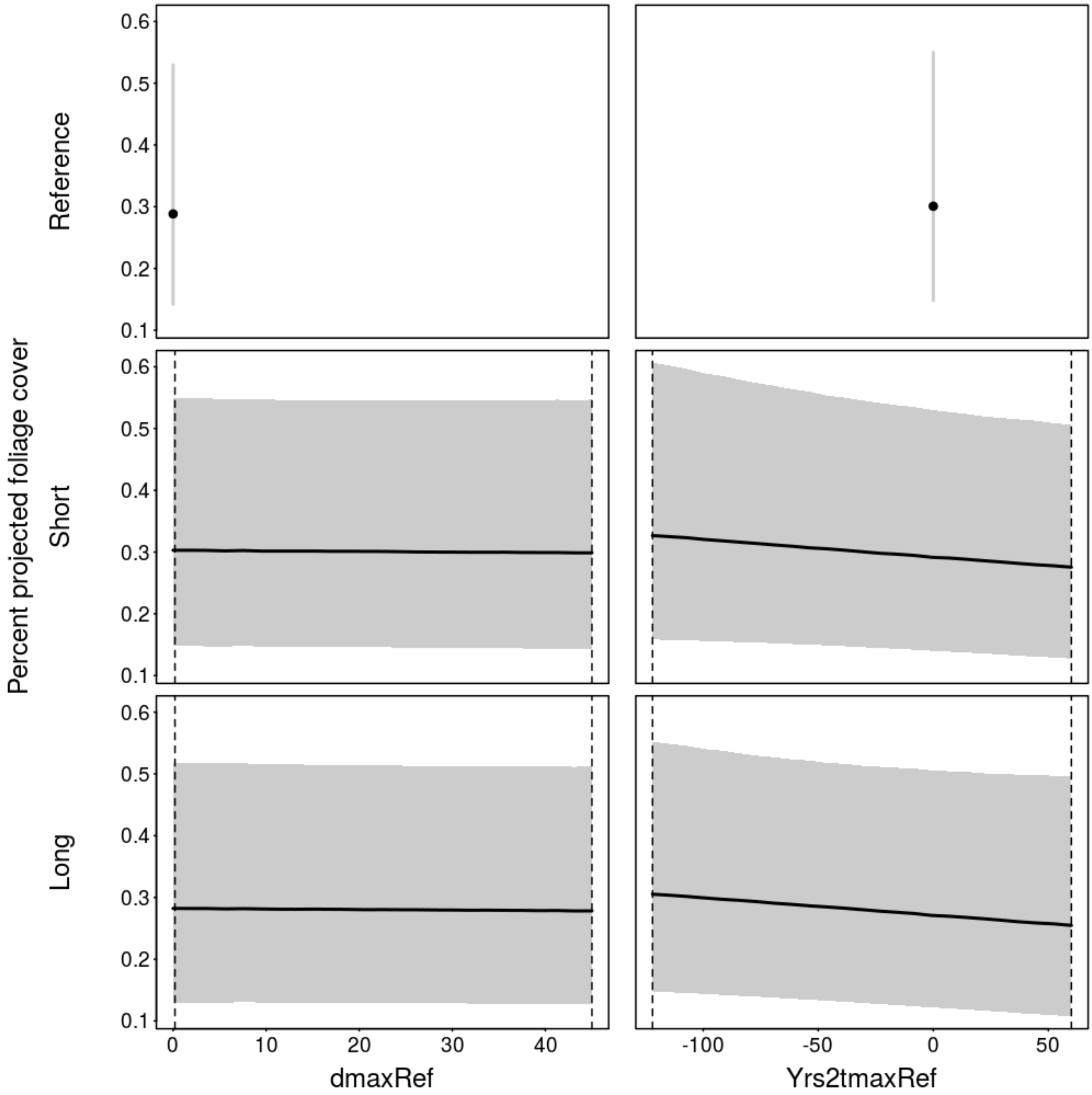

Figure 26 (Top row) Predicted mean (black dot) and 80% central credible interval (grey area) of projected foliage cover under reference hydrological conditions; (middle and bottom rows) predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on mean projected foliage cover for the Hunter subregion

In the middle and bottom rows, all other hydrological response variables are held constant at the midpoint of their elicitation range (during risk estimation all hydrological response variables vary simultaneously). Dashed vertical lines show the hydrological response variable range used in the elicitation. dmaxRef is defined in Table 27. Yrs2tmaxRef is the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102). The numbers on the y-axis range from 0 to 1 as the receptor impact model was constructed using the proportion for the statistical modelling. They should be interpreted as a percent foliage cover ranging from 0 to 100%.
Data: Bioregional Assessment Programme (Dataset 2)

Table 29 Mean, 10th and 90th percentile of the coefficients of the receptor impact model for projected foliage cover

	Mean	q10	q90
(Intercept)	–1.07	–1.86	–0.282
Yref	1.01	0.732	1.29
future1	1.08	0.253	1.91
long1	–0.0999	–0.375	0.175
dmaxRef	–0.000415	-0.00474	0.00391
Yrs2tmaxRef	–0.00129	-0.0037	0.00112

Yref is value of receptor impact variable in the reference assessment year; it has no value if the design case is in the reference assessment year. Future is a binary variable scored 1 if the design case is in a short- or long-assessment year. Long is a binary variable scored 1 if the design case is in the long assessment year. dmaxRef is defined in Table 27. Yrs2tmaxRef is the difference between tmaxRef and the assessment year that is relevant for the prediction (2012, 2042 or 2102).
Data: Bioregional Assessment Programme (Dataset 2)

The model reflects the experts' opinion that the projected foliage cover in the reference year (Yref) has a positive effect on projected foliage cover in the future. That is, for the same changes in hydrology, a site with a high foliage cover on average in 2012 is likely to have a higher foliage cover on average in the future than a site with a low foliage cover in 2012. This reflects the lag in the response of canopy cover to changes in hydrological response variables that would be expected of mature trees with long life spans.

The model also reflects the experts' opinion that groundwater drawdown (as indicated by dmaxRef) has a negative effect on average projected foliage cover. In other words, projected foliage 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 projected foliage cover will drop from about 32% to about 28% if the groundwater levels decrease by 40 m relative to the reference level in 2012. There is, however, considerable uncertainty in these predictions, with an 80% chance that the canopy cover will lie somewhere between approximately 55% and 15% on the short-assessment period, and somewhere between roughly 52% and 13% in the long-assessment period, with a 40-m drop in groundwater level.

As in the forested wetland model, the mean negative coefficient associated with the covariate Yrs2tmaxRef suggests that projected foliage cover is expected to be higher in the assessment year if the assessment year occurs after the time of maximum drawdown (Yrs2tmaxRef<0 in Figure 26). One interpretation is that the more time that has elapsed since tmaxRef, the greater the groundwater recovery and, in turn, the greater the projected foliage cover in the assessment year. Again, there is considerable uncertainty around the predicted effect on percent projected foliage cover, reflecting uncertainty around the magnitude of and rate at which groundwater levels decline due to pumping and the trees' ability to adjust to these changes. This is reflected in the large credible intervals in Figure 26.

Finally, the model suggests that we can expect differences in projected foliage cover in the future compared to the reference period, and even between short-term and long-term assessment. While 'future' is associated with a positive coefficient, 'long' is estimated to have a negative effect on projected foliage cover. This indicates that greater effects are expected in the short-term period than in the long term, as can be observed in Figure 26.

2.7.4.4 Rainforests

The 23.9 km^2 of the ‘Rainforest’ landscape class in the zone of potential hydrological change in the Hunter subregion are nearly exclusively ‘Northern warm temperate rainforests’, which consist of closed forest up to 30 m tall, generally lacking emergents. The canopy is comprised of 4 to 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 hilly to steep terrain of the coast and escarpment on moderately fertile soils in high rainfall areas, extending above 1000 m elevation, on granites, rhyolites, syenites or sedimentary substrates that yield acid soils with moderate levels of nutrients. It has occasional lianas and epiphytes, an open shrub/sapling stratum and variable fern/herb groundcover amongst copious leaf litter. Mosses, liverworts and lichens may be conspicuous on tree trunks or the forest floor (OEH, 2017d).

2.7.4.4.1 Qualitative mathematical model

A model for rainforest communities (Figure 27) was developed based on a modified version of the model for wet and dry sclerophyll forests (Figure 25). In this system, epiphytic vegetation (EV) in the form of vine thickets are an important component of habitat structure, and trees (Tre), shrubs (Shr) and herbaceous vegetation (Her) provide a key resource to consumers (FC) of fleshy fruits (FF). Omitted from this model are koalas (Koa) and the influence of saline soils (SS) on tree and shrub growth, or associated impacts from land clearing and grazing (LC&G). The influence of groundwater was linked to seedling success, canopy cover and fruit production.

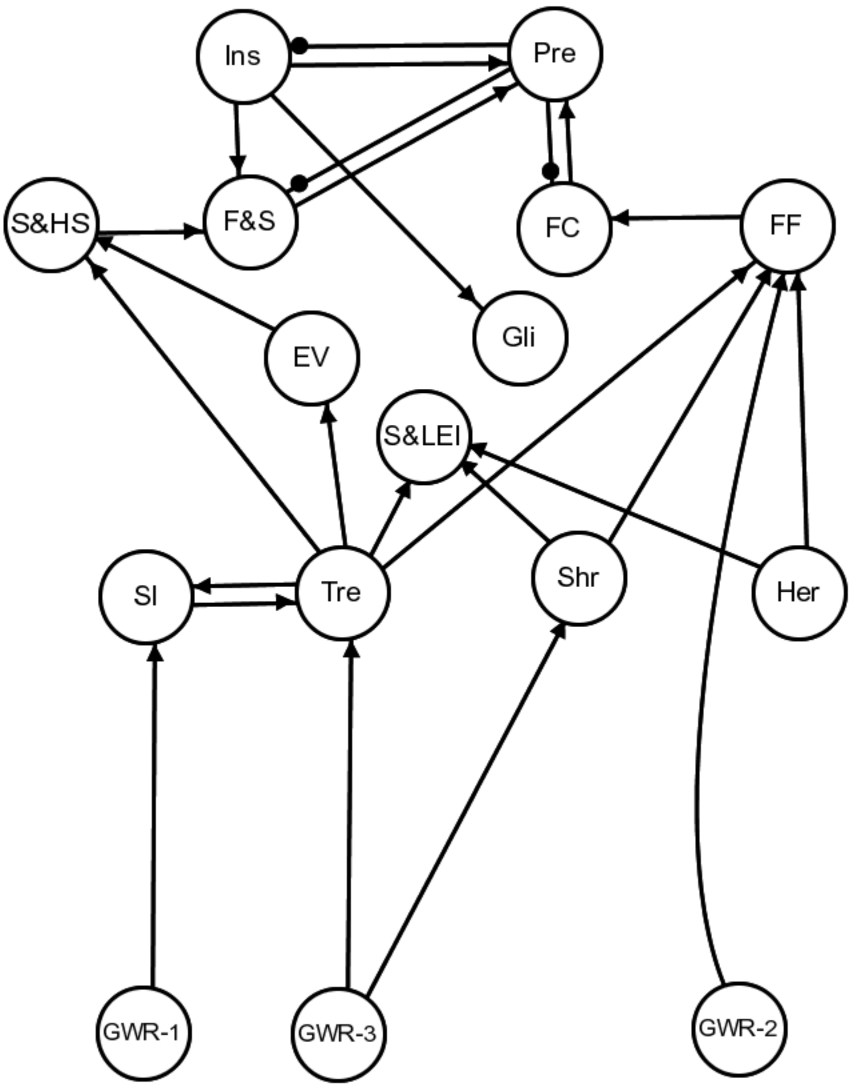

Figure 27 Signed digraph of rainforest communities of the Hunter Valley

Epiphytic vines (EV), frogs and skinks (F&S), fruit consumers (FC), fleshy fruits (FF), gliders (Gli), groundwater regime 1 (for seedling ecohydrology) (GWR-1), groundwater regime 2 (for fruit production) (GWR-2), groundwater regime 3 (for canopy cover) (GWR-3), herbs (Her), insects (Ins), predators (Pre), shade and habitat structure (S&HS), sap- and leaf-eating insects (S&LEI), shrubs (Shr), seedling (Sl), tree (Tre)
Data: Bioregional Assessment Programme (Dataset 2)

Based on the expected location of these rainforests in sheltered gullies and slopes in hilly to steep terrain, experts thought it likely that if this vegetation were using groundwater at all then it would probably use local groundwater (e.g. perched watertables, springs) opportunistically, and this groundwater would not be connected to regional watertables. Thus, no cumulative impact scenarios were developed for qualitative analyses of the model system. However, 10 km^2 of the distribution of 'Northern warm temperate rainforests' overlaps with the alluvium in the Hunter subregion suggesting that, despite their topographic position, these rainforest communities may have some dependence on alluvial groundwater in some circumstances. The rainforest model presented in this section does not reflect this. The dependence of this landscape class on groundwater, where it coincides with alluvium, is a likely knowledge gap. Note that Dawes et al. (2018) considered that 'northern warm temperate rainforests' may depend on both local and regional groundwater (Table 6 in that report). The opinion of the experts at the workshop was that this dependency was more likely to be on local groundwater.

2.7.4.5 Freshwater wetlands

Freshwater wetlands occur on areas where perennial or permanent inundation by water, either still or moving, dominates ecological processes. They occur in a range of environments where local relief and drainage result in open surface water at least part of the time and this often plays a range of vital roles in the functioning of ecosystems. The periodicity and duration of inundation in wetlands often determines, to a large extent, the suite of species present as do the extent and depth of water. The 'Freshwater wetland' landscape class within the zone of potential hydrological change is entirely comprised of Keith's (2004) 'Coastal freshwater lagoons' vegetation class (1.2 km^2).

2.7.4.5.1 Qualitative mathematical model

The 'Freshwater wetland' landscape class was described as a complex of marsh (littoral) and pond (open water) habitats, where the relative area of each habitat type was determined by the average level and degree of fluctuation in the water surface (Figure 28). Where water levels or the relative amount of fluctuation in water levels (WLF) are reduced, then growth of emergent *Typha* (Typ) increases (Deegan et al., 2007), causing an expansion of marsh at the expense of pond areas (PA/MA). Sedge and rush vegetation (S&R) in marsh habitats provides substantial input into the detritus cycle (DC) of the marsh, which is the principal basal resource for production of invertebrates (Inv), and where the decomposition of this organic matter is controlled by the natural fluctuation in water levels (Pabst et al., 2008). Sedge and rush vegetation provide key habitat for invertebrates, but also wetland frogs (WF) and small predators (SPr), including insectivores such as the vulnerable (NSW's *Threatened Species Conservation Act 1995*) white-fronted chat (WFC) and the reed warbler (RW). Larger predators (LPr) such as foxes and eagles, which target populations of small predators, sit at the top of the food chain.

Vegetation in the ponds (open water) include submerged macrophytes (SM), floating macrophytes (FM) and algae (Alg), the growth of which are controlled primarily by the supply of nutrients and light (Boulton et al., 2014). Floating macrophytes can act to shade and suppress the growth of submerged macrophytes, which can also be impacted by herbivorous birds (HB) (Perrow et al., 1997). The growth of algae is controlled by the degree of light penetration (LP) through the water column. Algae is the principal food resource of herbivorous aquatic invertebrates (AI), which in turn sustain populations of turtles (Tur), fish (Fis) and their predators. Terrestrial invertebrates and aerial stages of aquatic invertebrates are prey for birds, such as the white-fronted chat.

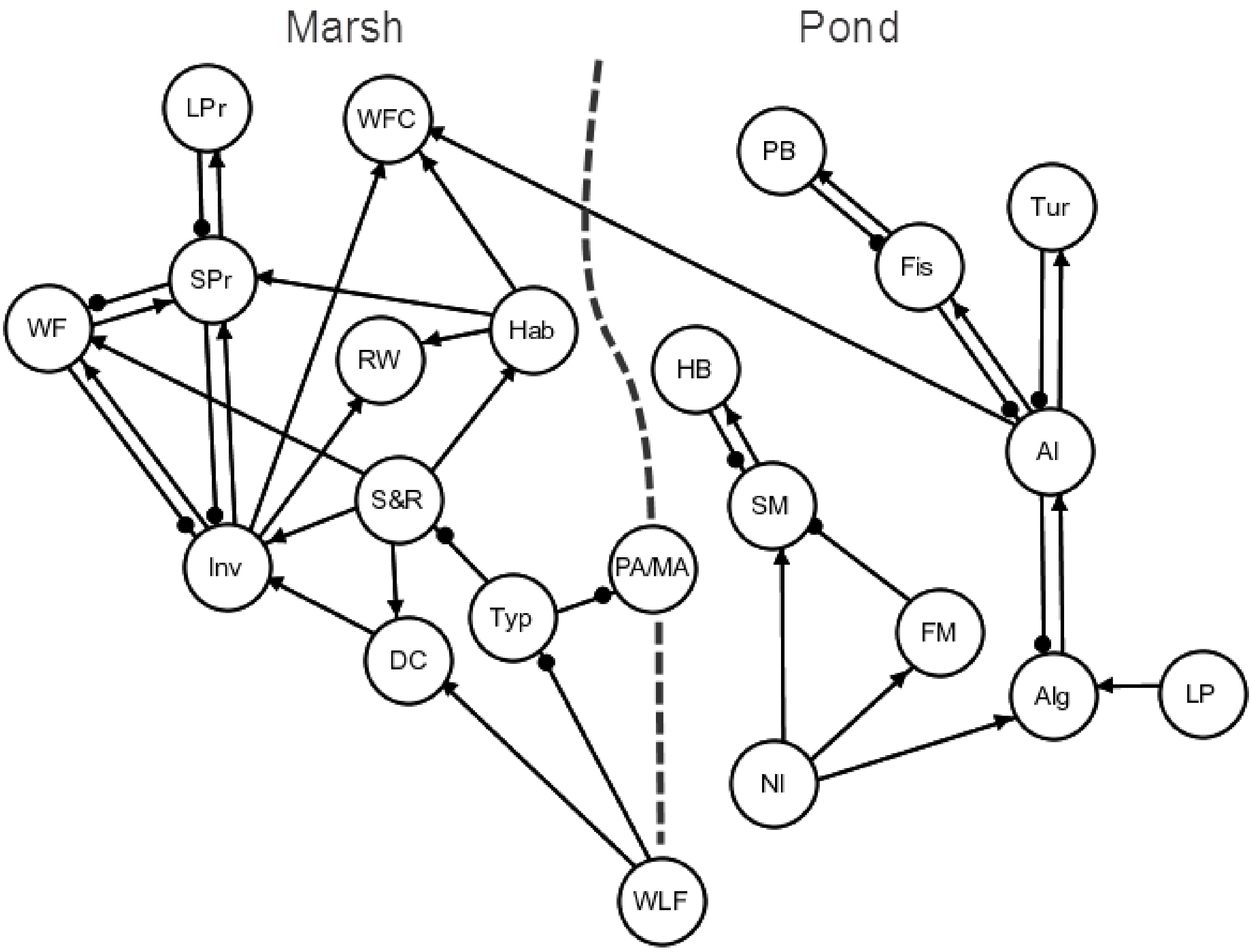

Figure 28 Signed digraph of freshwater wetland communities of the Hunter subregion

Aquatic invertebrates (AI), algae (Alg), detritus cycling (DC), fish (Fis), floating macrophytes (FM), habitat (Hab), herbivorous birds (HB), invertebrates (Inv), light penetration (LP), large predators (LPr), nutrient inflow (NI), pond area versus marsh area (PA/MA), piscivorous birds (PB), reed warblers (RW), sedges and rushes (S&R), submerged macrophytes (SM), small predators (SPr), turtles (Tur), *Typha* (Typ), wetland frogs (WF), white-fronted chat (WFC), water level fluctuation (regime) (WLF)
Data: Bioregional Assessment Programme (Dataset 2)

Given that the best available information is that these wetlands are likely to be dependent on local, perched groundwater systems, no cumulative impact scenarios were developed for qualitative analyses of the model system, and no quantitative models were developed for this landscape class.

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2.7.5 ‘Coastal lakes and estuaries’ landscape group

Summary

Qualitative models were developed for subtidal benthos and intertidal wetlands (‘Seagrass’, ‘Lakes’, ‘Lagoons’ and ‘Saline wetlands’ landscape classes). Together the two models represent the continuum of ecosystems from the shoreline to lake depths of about 2 m, and could be joined via their common seagrass nodes.

The qualitative model for intertidal wetlands includes an interaction between groundwater and saltmarsh, whereby groundwater extraction leads to micro-scale (mm) subsidence. The process is so local in scale that development of a quantitative model to evaluate potential impacts on intertidal wetlands from the additional coal resource development was not considered warranted.

The qualitative model for subtidal benthos indicates that seagrass is sensitive to subsidence resulting from underground mining, due to lowering of the lake bed, hence increasing depth of water above the seagrasses, and hence reduced light penetration. Experts did not consider groundwater drawdown a risk to seagrasses, as lake levels are maintained by seawater level and the degree of groundwater dependence for seagrass could not be determined. Changes in stream inflows to these coastal lake systems were also not expected to impact seagrasses. For these reasons, a quantitative model for subtidal benthos was not developed.

2.7.5.1 Description

The hydrogeological systems in the Hunter subregion are associated with aeolian sand aquifers in the coastal zone of the subregion (companion product 1.1 for the Hunter subregion (McVicar et al., 2015)) as illustrated in Figure 22. As discussed in Section 2.7.4.1.3, coastal sands typically support a single, unconsolidated sedimentary aquifer, in which groundwater forms a freshwater lens in the intergranular voids of the coastal sand mass. Estuarine and near-shore marine ecosystems located adjacent to coastal sand masses may also depend on the discharge of groundwater from these unconsolidated sedimentary aquifers.

The landscape classes within the ‘Coastal lakes and estuaries’ landscape group are based on mapping of coastal lakes and estuaries (NSW Department of Environment Climate Change and Water, Dataset 1), and mapping of saline wetlands (mangroves and saltmarshes) and seagrasses (NSW Department of Primary Industries, Dataset 2). For estuaries and lakes, the assessment team adopted the classification scheme used by the NSW Department of Environment and Heritage (Roper et al., 2011), which classifies estuaries and lakes into ‘Drowned valleys’, ‘Lakes’, ‘Barrier river’, ‘Lagoons’, and ‘Creeks’ based on dilution factors, tidal flushing times and geomorphology. Coastal lake and estuary landscape classes within the zone of potential hydrological change that are most likely to be associated with coastal aquifers are ‘Lakes’, ‘Lagoons’, ‘Saline wetlands’ and ‘Seagrass’. Groundwater-dependent ecosystem (GDE) landscape classes that could be associated with coastal aquifers (e.g. ‘Forested wetland’) are covered in Section 2.7.4. ‘Lakes’, ‘Lagoons’ and ‘Saline wetlands’ landscape classes are represented by the qualitative model for intertidal wetlands (Section 2.7.5.2); the ‘Seagrass’ landscape class is represented in the qualitative model for subtidal benthos (Section 2.7.5.3), but can be linked to the intertidal wetlands model via the seagrass node in the intertidal wetlands model. Thus, the two qualitative models describe a continuum across the land–water interface, reflecting the changes in communities with variations in degree of submergence from partial and intermittent to complete and permanent.

2.7.5.2 Intertidal wetlands

2.7.5.2.1 Qualitative mathematical model

A qualitative model for intertidal wetlands was developed based on the processes that regulate production of organic matter in saltmarsh, seagrass and mangrove habitats, and their importance to fish and migratory bird populations (Figure 29). The seagrass (SG) node in the intertidal wetlands model provides an important link to the seagrasses in the subtidal benthos model (Section 2.7.5.3), reflecting the fact that saltmarsh, seagrass and mangrove occur in broadly the same habitat (coastal lakes and lagoons) but, within which, their distributions are controlled by water level depth and fluctuations.

In the intertidal wetlands model, mangrove forests (M) and saltmarshes (SM) are recognised as providing numerous and similar ecosystem functions (e.g. carbon sequestration, filtration, basal habitat for terrestrial ecosystem), but saltmarshes are likely to be the preferred roosting habitat for migratory wading birds (MWB). Both generally benefit from any net increase in sediment accretion (NSA), although sedimentation may eventually convert saltmarsh into supra-tidal floodplain (Saintilan et al., 2009). A naturally fluctuating tidal cycle (TC), dependent on estuary entrance (EE) conditions, may control the interaction of saltmarshes and mangrove forests (Saintilan et al., 2009). Salinity (Sal) may also act as a regulating variable in the competitive interaction between mangroves and other habitat types, where higher salinity levels favour saltmarsh vegetation at the expense of mangroves, owing to the tolerance of saltmarsh plants to hypersaline conditions (Adam, 1990).

Submerged saltmarsh and mangrove vegetation provide substrate for the growth of microphytobenthos (MPB) communities, and are an important source of nutrient-rich organic matter (OM) to support secondary production (Connolly, 2009). Inputs of detritus from terrestrial vegetation (TV), as well as seagrass (SG), also contribute to the stores of organic matter in the system. These stores provide the basis for production of communities of infauna and epifauna (I&E), which in turn are a critical food resource for numerous fishes (Fis) and migratory wading birds (MWB) (Connolly, 2009; Spencer et al., 2009). The latter seek feeding areas adjacent to suitable roosting habitat and also benefit from open areas with standing pools (OA&PH) as a refuge from predation. The pools in these open areas are a key habitat for production of insects (e.g. mosquitoes; Dale and Breitfuss, 2009), which are a main food resource for populations of insectivorous bats (B). The larvae of many invertebrate species (IL), especially crab larvae, are dependent on saltmarsh and mangrove habitats for both habitat structure and food resources, and in turn are a key resource for many species of fish (Connolly, 2009). The quality of roosting habitat and the open-area habitat can be compromised by replacement of saltmarsh by mangroves (Spencer et al., 2009).

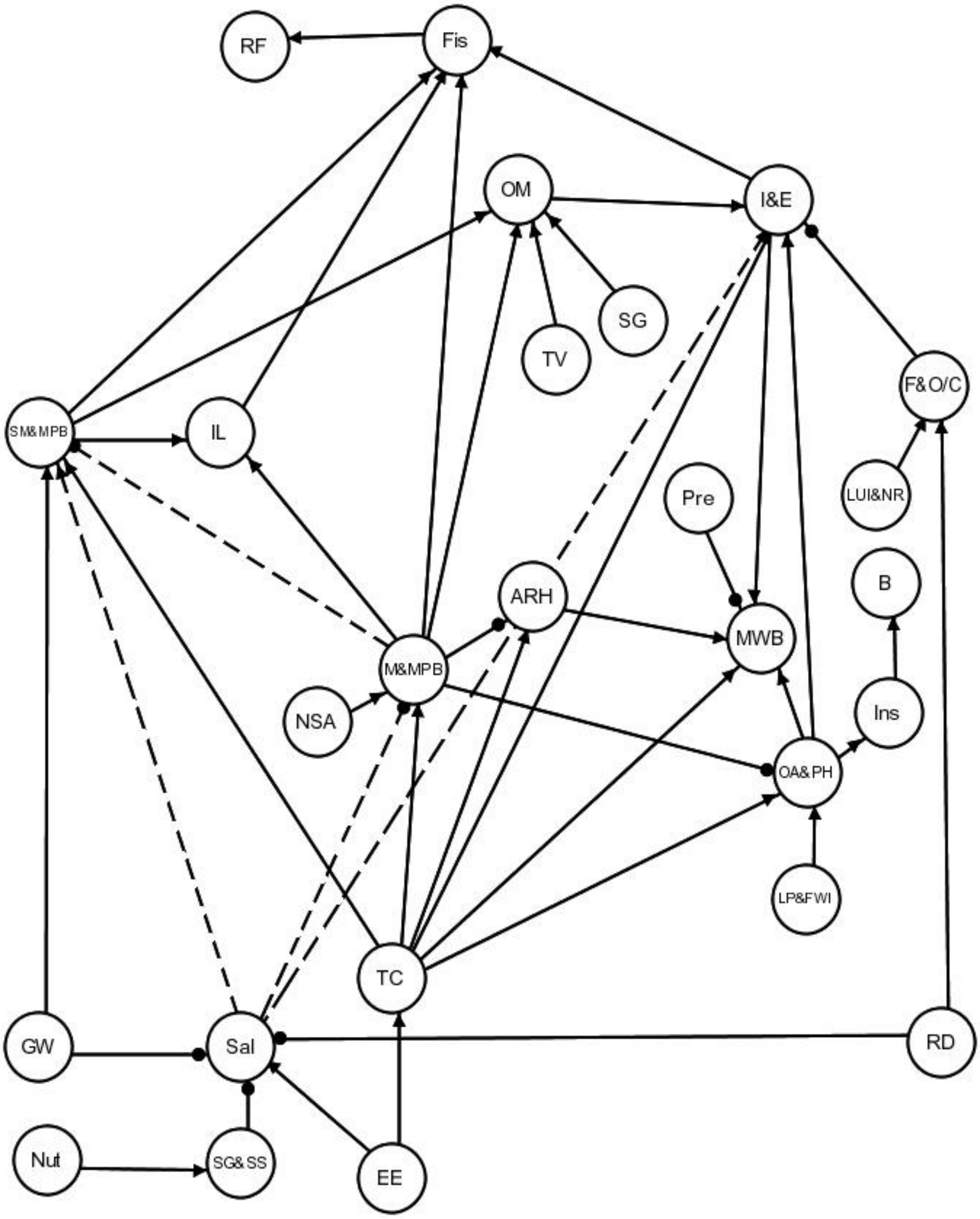

Figure 29 Signed directed graph of intertidal wetland communities of the Hunter Valley

Adjacent roosting habitat (ARH), bats (B), entrance efficiency (EE), fines and organics versus coarse sediment (F&O/C), fishes (Fis), groundwater (GW), infauna and epifauna (I&E), invertebrate larvae (e.g. crab larvae) (IL), insects (Ins), local precipitation and freshwater input (LP&FWI), land use intensity and nutrient runoff (LUI&NR), mangroves and microphytobenthos (M&MPB), migratory wading birds (MWB), net sediment accretion (NSA), nutrients (Nut), open areas and pool habitats (OA&PH), organic matter (OM), predators (Pre), river discharge (RD), recreational fishing (RF), salinity (Sal), seagrass (SG), seagrass and steep shore (SG&SS), saltmarsh and microphytobenthos (SM&MPB), tidal cycle (TC), terrestrial vegetation (TV)
Data: Bioregional Assessment Programme (Dataset 3)

River discharge (RD) can act to increase the fine-to-coarse sediment ratio, which can alter the species composition of benthic macroinvertebrates (Coleman et al., 1978). High inflows of river discharge and groundwater can decrease salinity of intertidal areas, but at a local level, groundwater favours saltmarsh vegetation by maintaining the elevation of the marsh (Rogers and Saintilan, 2008). A local effect of a semi-enclosed water body next to the shore was described as being produced where there was a steep beach profile along a shoreline that was also coupled with dense growth of seagrass beds due to high nutrient levels. In such situations there can be a lack of hydraulic flushing, and local inputs of groundwater can create a long-lasting drop in salinity along the shore, which can impact adjacent saltmarsh and mangrove forest communities.

There were several uncertainties in the model structure (dash-lined links in Figure 29), with the effect of salinity possibly being either positive or negative to infauna and epifauna or to saltmarsh vegetation. The negative effect of salinity on mangroves was also uncertain, and it could also have no effect, or at least be weak enough to have no appreciable effect. The negative effect of mangroves on saltmarsh vegetation was also deemed to be uncertain, and could possibly be too weak to have a significant effect.

The qualitative model for intertidal wetlands includes an interaction between groundwater and saltmarsh. Experts were of the view that groundwater drawdown would result in ‘winners and losers’ in intertidal wetlands. Drawdown would generally favour mangroves, which occupy a lower landscape position than the saltmarsh. Some saltmarsh species could benefit from groundwater drawdown, while others could suffer. Drawdown was thought to be more beneficial than not for infauna and epifauna. Regional groundwater drawdown due to the additional coal resource development is not predicted to extend under Tuggerah Lake, but there is predicted to be a small chance of drawdown under mapped saline wetlands at the Dora Creek inflow to Lake Macquarie, around the Lake Macquarie entrance and on the eastern side of Lake Budgewoi (companion product 2.6.2 for the Hunter subregion (Herron et al., 2018)).

Saltmarsh tolerates less inundation than mangrove, and groundwater extraction can potentially result in subsidence owing to reduced soil volume and more prolonged inundation (Saintilan et al., 2009). However, the subsidence of saltmarsh caused by groundwater removal that has been reported is at the millimetre scale (Rogers and Saintilan, 2008). There is a greater risk from subsidence caused by mining directly under intertidal wetlands, which can submerge saltmarsh and mangroves. It is worth noting, however, that state regulations place restrictions on mining activities (e.g. prohibiting the collapsing of longwall panels) in the near-shore zone of Lake Macquarie and the Tuggerah Lakes to minimise risks to both coastal developments and the intertidal and subtidal communities. In any event, the proposed Wallarah 2 and Mandalong Southern Extension mines are not under the coastal lakes so will not cause subsidence of the lake beds. The Chain Valley extension, which does involve coal extraction from under Lake Macquarie, will not extract within the high-water-mark subsidence barrier, as per current restrictions on mining in these areas.

Development of a quantitative model for the intertidal wetlands was considered low priority and not progressed.

2.7.5.3 Subtidal benthos

2.7.5.3.1 Qualitative mathematical model

A model of subtidal benthic communities focused on the factors and processes regulating the production of seagrass, its associated biota, and the productivity of adjacent soft-sediment habitats (Figure 30). The growth of seagrass (SG) was described as being strongly controlled by available light (Lig), which can be reduced as a function of water depth or turbidity (Tur) (Hemminga and Duarte, 2009a). Seagrass growth can also be suppressed due to high wave energy (WE&D), excessive accretion of sediments (SA) and, in areas adjacent to power plants, discharges of hot water plumes (HWD) (Hemminga and Duarte, 2009c). Where levels of light are relatively high, shallow-water species of seagrass outcompete seagrass of the genus *Halophila* (Hal), but with increased water depth and reduced light penetration, seagrass beds are composed exclusively of *Halophila* spp. (Rasheed et al., 2014). Relatively little living seagrass is directly consumed by grazers, however, swans (Swa) can be an important consumer of seagrass (Choney et al., 2014).

The growth of epiphytes and their associated epifauna (EP&EF) can limit growth of seagrass by directly covering and shading seagrass leaves from light, especially if nutrients are plentiful (Hays, 2005). Their growth can be controlled by epiphytic grazers, which in turn are an important resource for juvenile fishes (Gacia et al., 1999). There is also an invertebrate community (IC) associated with seagrass beds that supports juvenile fishes and populations of syngnathids (Dickinson et al., 2006). Seagrass beds are key to the survival of juvenile fishes due to the refuge they provide from predators (Jelbart et al., 2007).

Seagrass beds contribute to the stores of fines and organic matter (F&OMS). The stores of fines and organic matter are the principal resource of infauna communities, which can play an important, though uncertain, role in regulating the levels of nutrients from sediments (i.e. dashed-line link in Figure 30). Where infauna (Inf) facilitate the release of ammonia they also increase the relative amount of nutrients released from sediments (Herbert, 1999). It was hypothesised that infauna can also act to suppress the release of phosphorus via facilitating its bonding to iron oxides. If this effect is strong, and if phosphorus is a limiting nutrient, then infauna could have a negative influence of nutrient releases from surface sediments. Decomposition of organic matter can also create high levels of sulfides in surface sediments that can suppress the growth of seagrass (Hemminga and Duarte, 2009b).

In addition to the uncertain relationship between infauna and the release of surface nutrients, there was uncertainty as to whether juvenile fish could effectively control populations of grazers over soft sediments, and if epiphytes and epifauna provided a benefit to invertebrate consumers associated with seagrass beds. Soft-sediment habitats between seagrasses are an important and widespread substrate for the growth of microphytobenthos, which are depicted as an important consumer of nutrients from both the water column and from surface sediments, and also an important resource for grazers (Cahoon, 2009) and phytoplankton. These populations of grazers are an important food resource for juvenile fishes, which must venture out of the protection provided by seagrass beds to consume them.

An important physical driver to this system is the entrance efficiency of the estuary (EE), which regulates levels of turbidity (Tur), water column nutrients (WCN), and levels of fines and organic matter stores (F&OMS). River discharge and catchment runoff (RD&CR) contribute to the level of nutrients in the water column, and organic matter exported from intertidal habitats (i.e. saltmarsh vegetation, intertidal seagrass vegetation, mangrove vegetation and associated microphytobenthos) constitutes a major input of organic matter to the subtidal system. The impact of subsidence (Sub) from underground longwall mining is depicted as a local increase in depth (Dep).

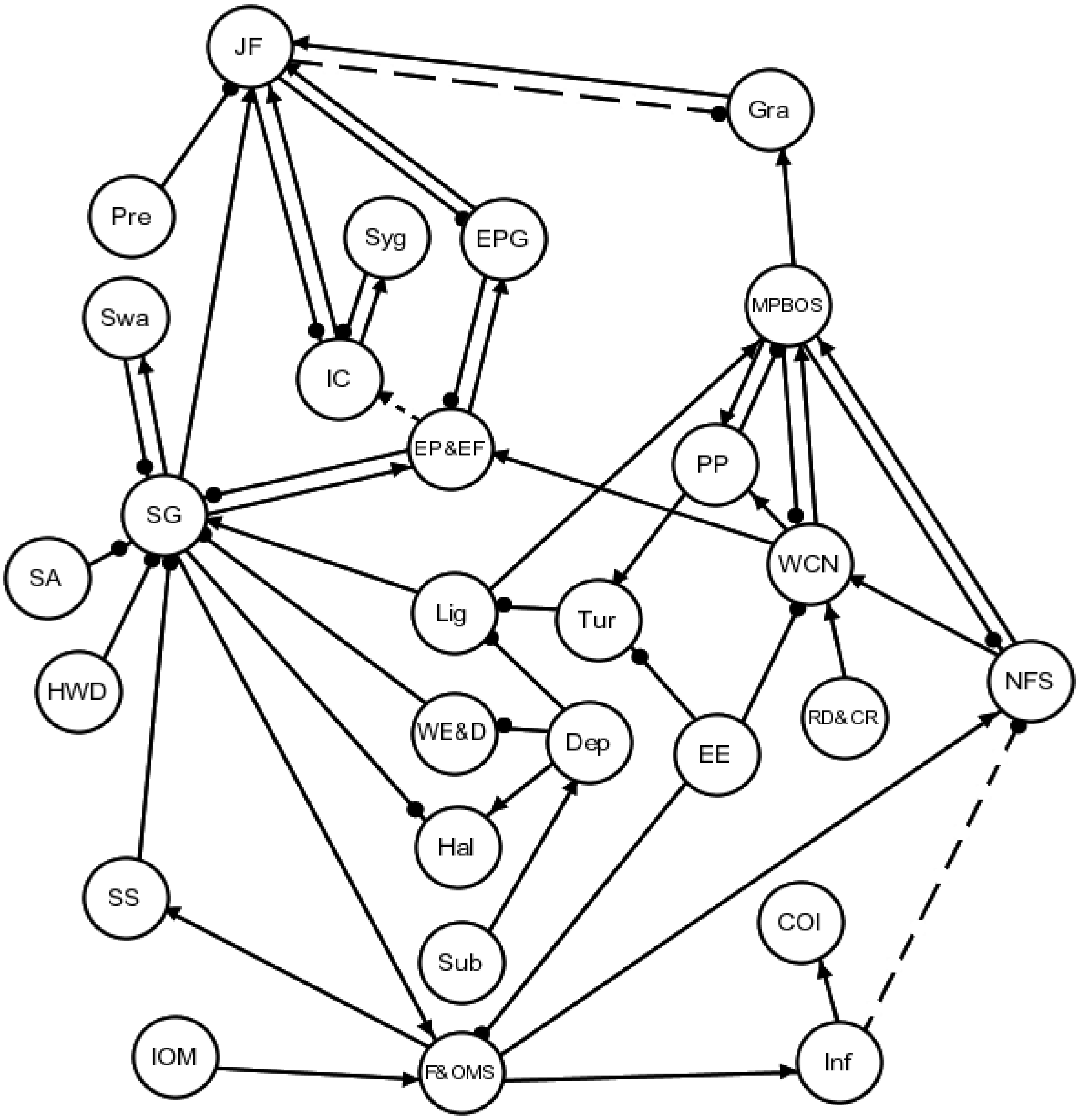

Figure 30 Signed directed graph of subtidal benthic communities of the Hunter Valley

Consumers of infauna (COI), depth (Dep), entrance efficiency (EE), epiphytic grazers (EPG), epiphytes and epifauna (EP&EF), fines and organic matter stores (F&OMS), grazers (Gra), *Halophila* (Hal), hot water discharge (HWD), invertebrate community (IC), infauna (Inf), intertidal organic matter (IOM), juvenile fishes (JF), light (Lig), microphytobenthos on sediments (MPBOS), nutrients from sediments (NFS), phytoplankton (PP), predators (Pre), river discharge and catchment runoff (RD&CR), sediment accretion (SA), seagrass (SG), sediment sulfate (SS), subsidence (Sub), swans (Swa), sygnathids (Syg), turbidity (Tur), water column nutrients (WCN), wave energy and disturbance (WE&D)
Data: Bioregional Assessment Programme (Dataset 3)

The qualitative model for subtidal benthos shows that seagrass can be sensitive to subsidence resulting from underground mining, as increasing the depth of water above the seagrasses (through base-level lowering) results in reduced light penetration. Modelling subsidence was not within the scope of the bioregional assessments and has not been predicted. As previously noted, the Wallarah 2 and Mandalong Southern Extension mines are not under coastal lakes and will not cause subsidence under the coastal lakes; and the Chain Valley extension, which will be under a part of Lake Macquarie, does not involve extraction within the high-water-mark subsidence barrier.

A quantitative model of the subtidal benthos was not progressed because their degree of groundwater dependence could not be determined and hydrological changes from underground mining were not considered a risk to this ecosystem.

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2.7.6 Limitations and gaps

Summary

Limitations of the bioregional assessment (BA) for the Hunter subregion receptor impact models and the knowledge gaps that prevented qualitative models for some potentially impacted landscape classes being developed into quantitative models are summarised.

2.7.6.1 Prediction of receptor impact variables

Figure 3 in Section 2.7.1.2 summarises the receptor impact modelling workflow, starting from the identification of the landscape classes that occur within the zone of potential hydrological change for the Hunter subregion 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 the 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 (companion product 3-4 for the Hunter subregion (Herron et al., 2018)), where the hydrological response variables are propagated through the receptor impact models to produce a range or distribution of the predicted receptor impact variable response at different time points and for the two futures considered in BAs. 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.

2.7.6.2 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 Hunter subregion reflect the subjectivity and bias inherent in the knowledge base of the assembled experts – for example, 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 the timing, magnitude, or level of surface water and groundwater. 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 the impact and risk analysis for the Hunter subregion (companion product 3-4 (Herron 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.

No specific limitations were identified in the receptor impact models for perennial streams and intermittent streams. The riffle-breeding frog, Hydropsychidae larvae and hyporheic invertebrate taxa receptor impact variables for the perennial streams and intermittent streams were selected as indicators of instream ecosystems that are sensitive to changes in hydrology and can represent the response of other components of the ecosystem to changes in hydrology, and components that depend on those components. The extent to which they are suitable indicators of ecosystem response for all instream ecosystems across the Hunter subregion is not known. The interpretation of results of the receptor impact models presented in companion product 3-4 for the Hunter subregion (Herron et al., 2018) is couched in terms of risk to instream habitat, rather than risks to the receptor impact variables themselves.

Ephemeral streams were assumed to not be connected to groundwater, hence unlikely to be impacted by drawdown of the regional watertable and changes in baseflow. While there is potential for additional coal resource development to affect catchment runoff to ephemeral streams, the changes were considered unlikely to impact communities, which are assumed to be highly adapted to variable runoff or opportunistic users of creek flows when they occur.

No specific limitations were identified in relation to the wet and dry sclerophyll forests receptor impact model. The density of foliage cover was generally considered a good indicator of water availability.

The forested wetland receptor impact model was specifically developed for riparian vegetation along unregulated rivers in the Hunter river basin and is not considered suitable for evaluating the impact of hydrological changes due to additional coal resource development on the regulated Hunter River, nor for the ‘Coastal swamp forests’ and ‘Coastal floodplain wetlands’ vegetation classes found in the Macquarie-Tuggerah lakes basin. The receptor impact modelling results for the forested wetlands presented in Section 3.4 of companion product 3-4 for the Hunter subregion (Herron et al., 2018) represent less than 50% of the mapped extent of forested wetlands identified as intersecting the zone of potential hydrological change.

The rainforest qualitative model assumes rainforests occur in sheltered gullies and slopes in hilly-to-steep terrain of the coast and escarpment of the Macquarie-Tuggerah lakes hinterland. About 10 km^2 of the mapped rainforest groundwater-dependent ecosystems (GDEs) in the zone of potential hydrological change occur on the alluvium of larger perennial rivers, for which the rainforest qualitative model is not considered appropriate. The potential for adverse impacts to these riparian rainforests along the Wyong River and Jilliby Jilliby Creek has not been assessed as part of this BA. Given they occupy a similar landscape position to forested wetlands, the forested wetland receptor impact model might be appropriate for a first pass assessment of potential impacts from the proposed underground mines in this area. This idea was not tested with the invited experts and the ecological water requirements of these rainforests is a knowledge gap of this assessment.

Experts at the receptor impact modelling workshop lacked the expertise to develop a quantitative model for the 'Freshwater wetlands' landscape class. Uncertainty about the connectivity of freshwater wetlands to regional groundwater was also identified during the qualitative modelling workshop. The available literature suggests they are probably rain-fed, local aquifers, with poor connection to deeper groundwater. Better groundwater information is needed for each of the subregion's freshwater wetlands to assess potential impacts from hydrological changes due to additional coal resource development.

Experts were uncertain about the potential impacts of changes in salinity and groundwater drawdowns on saline wetlands (including saltmarsh and mangroves), represented in the qualitative model for inter-tidal wetlands. This stemmed, in part, from uncertainty about the connection of Hunter subregion saline wetlands to regional groundwater. Seagrasses, represented in both the intertidal wetlands and subtidal benthos qualitative models, were considered particularly sensitive to changes in light attenuation, which could result from base-level lowering caused by mine subsidence below seagrass beds, but not from underground mines away from the lakes. Experts generally considered there was little threat from changes in surface water inflows and groundwater drawdown.

A summary of the assumptions and limitations of the qualitative and receptor impact models that emerged during the expert elicitation workshops is provided in Table 30. Knowledge gaps and research opportunities are identified for some models. A more comprehensive listing of the gaps and opportunities that have emerged during the BA for the Hunter subregion is provided in Section 3.7 of companion product 3-4 for the Hunter subregion (Herron et al., 2018).

Table 30 Assumptions and limitations of qualitative (QM) and receptor impact models (RIM) developed for Hunter subregion landscape classes that intersect the zone of potential hydrological change

Landscape class	Model	Assumptions/limitations	Gap/opportunity
Forested wetland	RIM	Experts restricted the receptor impact model to Eastern Riverine forests on unregulated rivers, coastal swamp forests and riverine forests on regulated river were excluded.	Hydrological changes in regulated rivers; development of a receptor impact model to quantify changes in 'Coastal swamp forests' and 'Coastal floodplain wetlands' vegetation classes
Freshwater wetland	QM	Experts were uncertain about connections with groundwater; literature indicates they are most likely local, perched systems fed by rainfall. Experts at the receptor impact modelling workshop did not have expertise to quantify changes.	Characterise connection of subregion freshwater wetlands with regional groundwater
Rainforest	QM	Experts assumed limited dependency on groundwater (opportunistic); this misses riparian rainforests in Wyong River catchment.	Characterise water dependency of riparian rainforest
Wet and dry sclerophyll forests	RIM	No specific issues emerged	Nothing specifically identified
Perennial stream	RIM	Number of zero-flow days part of definition of perennial -> changes that lead to >30–40 no-flow days per year mean that the perennial model is no longer the appropriate model – intermittent or ephemeral model will be relevant	Nothing specifically identified
Intermittent stream	RIM	Number of zero-flow days part of definition of perennial -> changes that lead to a high proportion of no-flow days per year mean that the ephemeral stream model might be more relevant	Nothing specifically identified
Ephemeral stream	QM	No connection to groundwater; local surface water impact only	Local characterisation of groundwater connection (flow regime modelled)
Saline wetlands	QM	Uncertainty about effect of changes in salinity on salt marsh and mangroves; uncertainty about drawdown impact on salt marsh	Characterise connection of subregion saline wetlands with regional groundwater
Seagrasses	QM	Vulnerable to subsidence; changes in groundwater and inflows to lakes/lagoons deemed a low source of risk	Nothing specifically identified

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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.

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

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

baseline coal resource development: a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012 bioregion: a geographic land area within which coal seam gas (CSG) and/or coal mining developments are taking place, or could take place, and for which bioregional assessments (BAs) are conducted

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

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

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

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

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

conceptual model: abstraction or simplification of reality

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

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

consequence: synonym of impact

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

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

dataset: a collection of data in files, in databases or delivered by services that comprise a related set of information. Datasets may be spatial (e.g. a shape file or geodatabase or a Web Feature Service) or aspatial (e.g. an Access database, a list of people or a model configuration file).

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).

ephemeral stream: a stream that flows only briefly during and following a period of rainfall, and has no baseflow component

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.

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

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

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

groundwater system: see water system

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

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

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

Hunter subregion: Along the coast, the Hunter subregion extends north from the northern edge of Broken Bay on the New South Wales Central Coast to just north of Newcastle. The subregion is bordered in the west and north–west by the Great Dividing Range and in the north by the towns of Scone and Muswellbrook. The Hunter River is the major river in the subregion, rising in the Barrington Tops and Liverpool Ranges and draining south-west to Lake Glenbawn before heading east where it enters the Tasman Sea at Newcastle. The subregion also includes smaller catchments along the central coast, including the Macquarie and Tuggerah lakes catchments.

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

impact: a change resulting from prior events, at any stage in a chain of events or a causal pathway. An impact might be equivalent to an effect (change in the quality and/or quantity of surface water or groundwater), or it might be a change resulting from those effects (for example, ecological changes that result from hydrological changes).

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

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

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

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

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

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

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 (2013 to 2102).

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 streamflow below the 10th percentile threshold.

material: pertinent or relevant

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

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

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

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.

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

preliminary assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. The PAE is estimated at the beginning of a bioregional assessment, and is updated to the 'assessment extent' on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

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'.

quantile: a set of values of a variate that divide the range of a probability distribution into contiguous intervals with equal probabilities (e.g. 20 intervals with probability 0.05, or 100 intervals with probability 0.01). Within bioregional assessments, probability distributions are approximated using a number of runs or realisations.

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

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.

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

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)

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

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

tmax: year of maximum change

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

transmissivity: A parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow).

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

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

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

very unlikely: less than 5% chance

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

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

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

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

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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