Australian Government

BIOREGIONAL ASSESSMENTS

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

Impacts and risks

Submethodology M10 from the Bioregional Assessment Technical Programme

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.

Department of the Environment and Energy

The Australian Government Department of the Environment and Energy is strengthening the regulation of coal seam gas and large coal mining development by ensuring that future decisions are informed by substantially improved science and independent expert advice about the potential water-related impacts of those developments. For more information, visit https://www.environment.gov.au/water/coal-and-coal-seam-gas/office-of-water-science.

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ISBN-PDF 978-1-925315-72-1

Citation

Henderson BL, Barry S, Hayes KR, Hosack G, Holland K, Herron N, Mount R, Schmidt RK, Dambacher J, Ickowicz A, Lewis S, Post DA and Mitchell PJ (2018) Impacts and risks. Submethodology M10 from the Bioregional Assessment Technical Programme. Department of the Environment and Energy, Bureau of Meteorology, CSIRO and Geoscience Australia, Australia. http://data.bioregionalassessments.gov.au/submethodology/M10.

Authorship is listed in relative order of contribution.

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Wards River, NSW, 10 December, 2013

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Australian Government
Department of the Environment and Energy
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CSIRO

v20180601

Executive summary

A bioregional assessment is a regional cumulative analysis that assesses potential impacts of current and future coal resource development on water resources and water-dependent assets. It compares two futures, a *baseline* future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012, and a *coal resource development pathway* (CRDP) future that includes not only the baseline coal resource developments but also the *additional coal resource development*, all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012.

The *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) states that the impact and risk analysis is the central purpose of BAs. While the BA methodology provides a high-level overview of the components and conceptual workflow, it is not detailed enough to clearly guide project teams performing a BA. This submethodology uses the concepts in the BA methodology, and provides the overall scientific logic that runs through all components and companion submethodologies, culminating in the impact and risk analysis for a bioregion or subregion.

The impact and risk analysis must meet the objectives of the BA methodology, while addressing the complexity of the bioregions and assets, and respecting good practice in risk assessment. A series of design choices that meet these requirements ensures that BAs are credible and timely and thus can constructively inform public debate and decision making. The major design choices are:

- a dedicated hazard analysis
- a quantitative analysis of impacts and risks
- a focus on the predictive uncertainty
- hydrological predictions for any location in the landscape
- decomposition of the predictions into conditionally independent components
- a landscape classification
- two assessment time points
- use of expert opinion where empirical data is not available
- qualitative mathematical modelling to estimate direct and indirect impacts and choose key variables
- automation of the analysis.

Given the most likely coal resource development in a region, a systematic hazard analysis provides a basis for describing the nature and severity of potential risks by identifying the potential causal pathways that may lead to changes in surface water and groundwater. Coupled with the conceptual understanding of the regional geology and hydrogeology, these pathways are embedded in regional hydrological models that make predictions at specific locations. Uncertainty is propagated through hydrological models by basing predictions upon plausible distributions of model parameters rather than fixed values. The large number and diversity of ecological assets is addressed by classifying ecosystems into landscape classes that, while still subject to predictive uncertainty, are expected to respond similarly to changes in groundwater and/or surface water. For those landscape classes that may experience hydrological change, qualitative mathematical modelling is used to produce signed digraphs that summarise the key interactions between ecosystem components and their dependence on hydrology for a landscape class. The qualitative mathematical modelling captures direct and indirect effects that may occur following changes to the hydrology as a result of coal resource development. Qualitative mathematical modelling also underpins the choice of important hydrological response variable predictions, to come from the hydrological models, and the receptor impact variables that are used as ecological indicators for that landscape class. Receptor impact models for a landscape class are functions that translate potential change in meaningful hydrological response variables into predicted changes in a receptor impact variable. They are constructed on the basis of structured expert opinion and incorporate both uncertainty in the input hydrology and uncertainty in the functional relationship as characterised by the elicited responses from experts.

Predicted distributions of the maximum hydrological change at particular locations across the simulation period (2013 to 2102), for hydrological response variables at particular locations in the short term (2013 to 2042) and long term (2073 to 2102), and for receptor impact variables at particular locations at the end of the short term (2042) and at the end of the long term (2102) underpin the assessment of impact and risk. Predictions at specific locations may be summarised and aggregated for assessing impacts and risks for individual water-dependent assets. The predicted distributions are a result of the probabilistic treatment of uncertainty through a modelling chain that considers the ecosystem modelling as conditionally independent of the hydrological modelling, and enables the quantitative assessment of impact and risk.

There are a very large number of multi-dimensional and multi-scaled datasets that are used in the impact and risk analysis for each BA. These include model outputs, and ecological, economic and sociocultural data from a wide range of sources. The data are organised into impact and risk analysis databases to enable efficient management. The purpose of the databases is to produce result datasets that integrate the available modelling and other evidence across the assessment extent of the BA.

The impact and risk analysis is reported and communicated through product 3-4 (impact and risk analysis). In addition, more details are available on the BA Explorer (www.bioregionalassessments.gov.au/explorer), including three types of profiles:

- a characterisation of the *hydrological impact*, including the summary of changes in the hydrological response variables, the identification of one or more zones of potential hydrological change, and a discussion of changes that are in scope but that are not modelled quantitatively
- a *landscape class profile*, which rules out landscape classes that are outside the zone of potential hydrological change. For landscape classes within the zone, the profile assesses the hydrological changes (through hydrological response variables) and the ecological changes (through receptor impact variables) that individual landscape classes may experience. Note

that receptor impact models may be developed for a prioritised subset of landscape classes within the zone, with the landscape class priority governed by factors such as the spatial extent, legislative significance and the availability of external scientific expertise for the qualitative mathematical modelling or expert elicitation

- an *asset profile*, which summarises potential hydrological changes for groundwater and surface water economic assets and rules out ecological assets that are outside the zone of potential hydrological change. For ecological assets within the zone of potential hydrological change, the changes individual assets may experience are summarised by different hydrological response variables (for hydrological changes) and receptor impact variables (for ecological changes in the constituent landscape classes).

A BA is an analysis at a particular point in time. It seeks to help governments, industry and the community make better-informed regulatory, water management and planning decisions. The impact and risk analysis flags where future efforts of regulators and proponents should be directed, and where further attention is not necessary for the CRDP considered.

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Contributors to the Technical Programme

The following individuals have contributed to the Technical Programme, the part of the Bioregional Assessment Programme that undertakes bioregional assessments.

Role or team	Contributor(s)
Assistant Secretary	Department of the Environment and Energy: Matthew Whitfort
Programme Director	Department of the Environment and Energy: John Higgins, Anthony Swirepik
Technical Programme Director	Bureau of Meteorology: Julie Burke
Projects Director	CSIRO: David Post
Principal Science Advisor	Department of the Environment and Energy: Peter Baker
Science Directors	CSIRO: Brent Henderson Geoscience Australia: Steven Lewis
Integration	Bureau of Meteorology: Richard Mount (Integration Leader) CSIRO: Becky Schmidt
Programme management	Bureau of Meteorology: Louise Minty CSIRO: Paul Bertsch, Warwick McDonald Geoscience Australia: Stuart Minchin
Project Leaders	CSIRO: Alexander Herr, Kate Holland, Tim McVicar, David Rassam Geoscience Australia: Tim Evans Bureau of Meteorology: Natasha Herron
Assets and receptors	Bureau of Meteorology: Richard Mount (Discipline Leader) Department of the Environment and Energy: Glenn Johnstone, Wasantha Perera, Jin Wang
Bioregional Assessment Information Platform	Bureau of Meteorology: Lakshmi Devanathan (Team Leader), Derek Chen, Trevor Christie-Taylor, Melita Dahl, Angus MacAulay, Christine Price, Paul Sheahan, Kellie Stuart CSIRO: Peter Fitch, Ashley Sommer Geoscience Australia: Neal Evans
Communications	Bureau of Meteorology: Jessica York CSIRO: Clare Brandon Department of the Environment and Energy: John Higgins, Miriam McMillan, Milica Milanja Geoscience Australia: Aliesha Lavers
Coordination	Bureau of Meteorology: Brendan Moran, Eliane Prideaux, Sarah van Rooyen CSIRO: Ruth Palmer Department of the Environment and Energy: Anisa Coric, Lucy Elliott, James Hill, Andrew Stacey, David Thomas, Emily Turner
Ecology	CSIRO: Anthony O'Grady (Discipline Leader), Caroline Bruce, Tanya Doody, Brendan Ebner, Craig MacFarlane, Patrick Mitchell, Justine Murray, Chris Pavey, Jodie Pritchard, Nat Raisbeck-Brown, Ashley Sparrow

Role or team	Contributor(s)
Geology	CSIRO: Deepak Adhikary, Emanuelle Frery, Mike Gresham, Jane Hodgkinson, Zhejun Pan, Matthias Raiber, Regina Sander, Paul Wilkes Geoscience Australia: Steven Lewis (Discipline Leader)
Geographic information systems	CSIRO: Jody Bruce, Debbie Crawford, Dennis Gonzalez, Mike Gresham, Steve Marvanek, Arthur Read Geoscience Australia: Adrian Dehelean
Groundwater modelling	CSIRO: Russell Crosbie (Discipline Leader), Tao Cui, Warrick Dawes, Lei Gao, Sreekanth Janardhanan, Luk Peeters, Praveen Kumar Rachakonda, Wolfgang Schmid, Saeed Torkzaban, Chris Turnadge, Andy Wilkins, Binzhong Zhou
Hydrogeology	Geoscience Australia: Tim Ransley (Discipline Leader), Chris Harris-Pascal, Jessica Northey, Emily Slatter
Information management	Bureau of Meteorology: Brendan Moran (Team Leader), Christine Panton CSIRO: Qifeng Bai, Simon Cox, Phil Davies, Geoff Hodgson, Brad Lane, Ben Leighton, David Lemon, Trevor Pickett, Shane Seaton, Ramneek Singh, Matt Stenson Geoscience Australia: Matti Peljo
Information model and impact analysis	Bureau of Meteorology: Carl Sudholz (Project Manager), Mark Dyall, Michael Lacey, Brett Madsen, Eliane Prideaux Geoscience Australia: Trevor Tracey-Patte
Products	CSIRO: Becky Schmidt (Products Manager), Maryam Ahmad, Helen Beringen, Clare Brandon, Heinz Buettikofer, Sonja Chandler, Siobhan Duffy, Karin Hosking, Allison Johnston, Maryanne McKay, Linda Merrin, Sally Tetreault-Campbell, Catherine Ticehurst Geoscience Australia: Penny Kilgour
Risk and uncertainty	CSIRO: Simon Barry (Discipline Leader), Jeffrey Dambacher, Rob Dunne, Jess Ford, Keith Hayes, Geoff Hosack, Adrien Ickowicz, Warren Jin, Dan Pagendam
Surface water hydrology	CSIRO: Neil Viney and Yongqiang Zhang (Discipline Leaders), Santosh Aryal, Mat Gilfedder, Fazlul Karim, Lingtao Li, Dave McJannet, Jorge Luis Peña-Arancibia, Tom Van Niel, Jai Vaze, Bill Wang, Ang Yang

Acknowledgements

This technical product was reviewed by several groups:

- Discipline Leaders: Anthony O'Grady (ecology), Russell Crosbie (groundwater modelling)
- 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.

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.

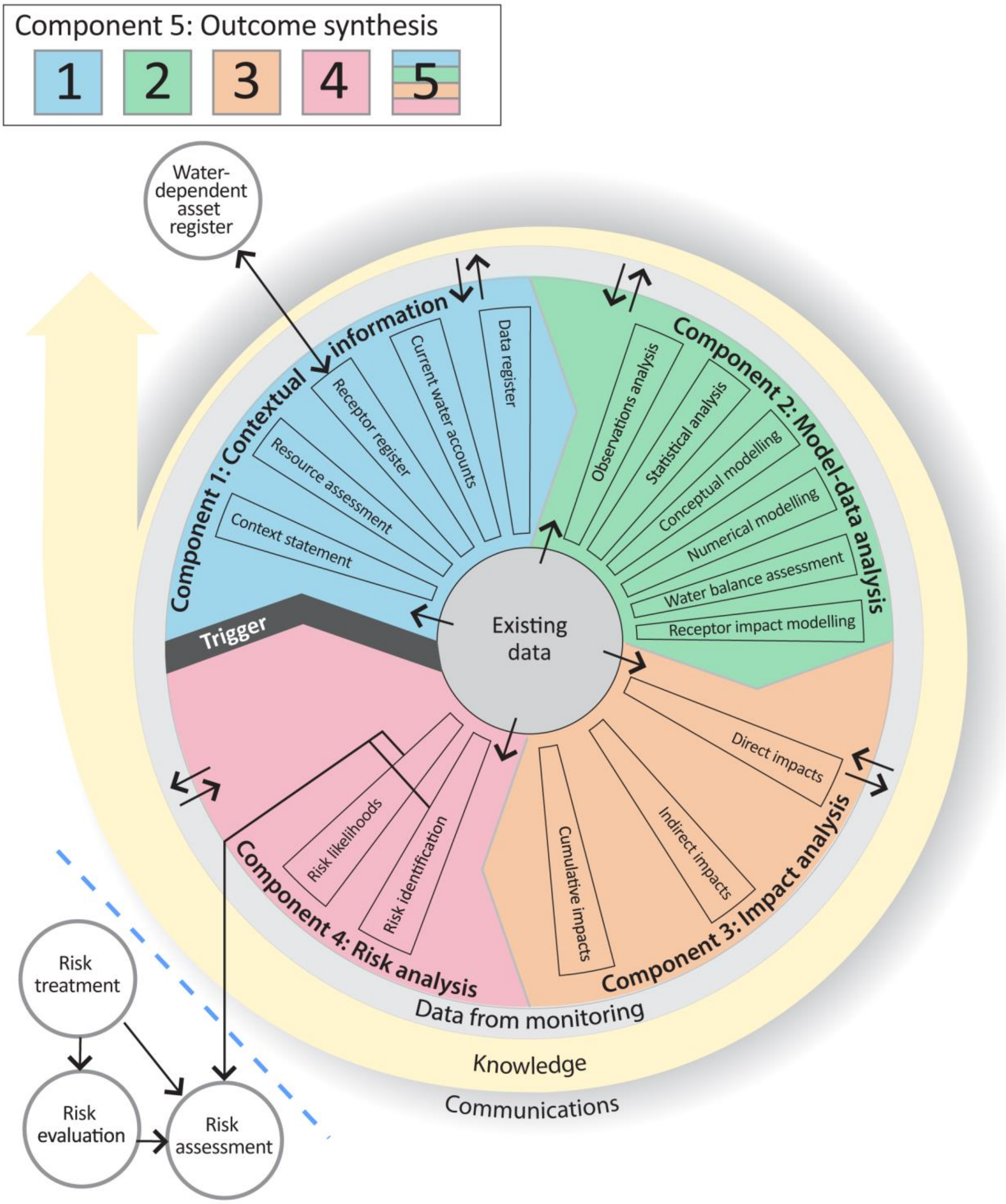

Figure 1 Schematic diagram of the bioregional assessment methodology

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 to 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) to, in the first instance, 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.

About this submethodology

The following notes are relevant only for this submethodology.

- All reasonable efforts were made to provide all material under a Creative Commons Attribution 3.0 Australia Licence.
- All maps created as part of the BAs for inclusion in this document used the Albers equal area with a central meridian of 140.0° East for the Lake Eyre Basin bioregion and its subregions, and 151.0° East for all other bioregions and subregions. The two standard parallels for all bioregions and subregions are –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 submethodology. 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 created date. Where a created date is not available, the publication date or last updated date is used.

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

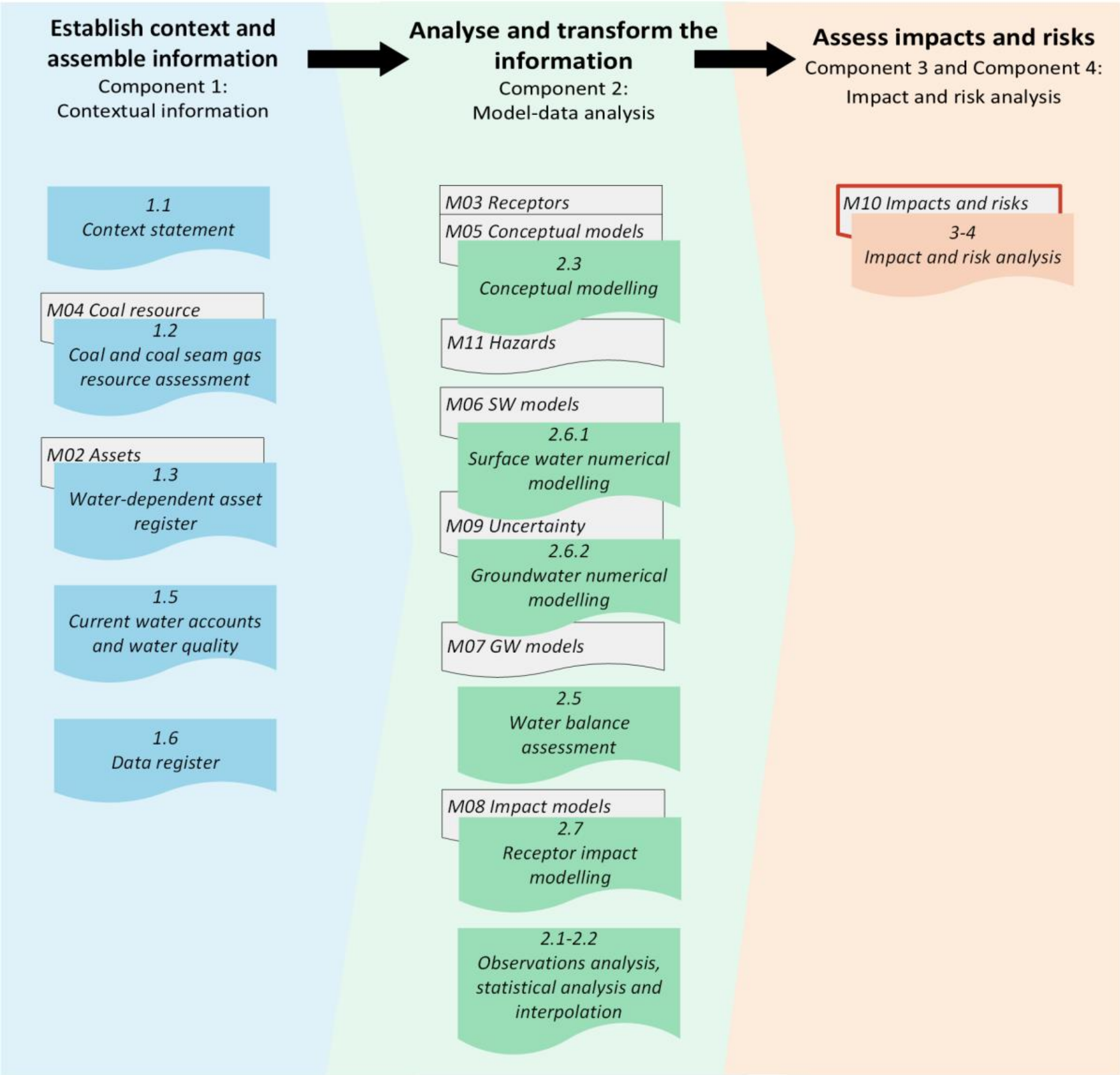

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

In each component (Figure 1) of a bioregional assessment (BA), 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 submethodology. The BA methodology (Barrett et al., 2013) specifies the overall approach.

Technical products

The outputs of the BAs include a suite of technical products presenting information about the ecology, hydrology, hydrogeology and geology of a subregion or 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 BA methodology specifies the information to be included in technical products. 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.

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.

Table 2 Technical products delivered by the Bioregional Assessment Programme

For each subregion or bioregion in a bioregional assessment (BA), technical products are delivered online at http://www.bioregionalassessments.gov.au. Other products – such as datasets, metadata, data visualisation and factsheets – are also 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 products 2.6.1 (surface water modelling) and 2.6.2 (groundwater 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[a]
Component 1: Contextual information for the subregion or bioregion	1.1	Context statement	2.5.1.1, 3.2
	1.2	Coal and coal seam gas resource assessment	2.5.1.2, 3.3
	1.3	Description of the water-dependent asset register	2.5.1.3, 3.4
	1.5	Current water accounts and water quality	2.5.1.5
	1.6	Data register	2.5.1.6
Component 2: Model-data analysis for the subregion or bioregion	2.1-2.2	Observations analysis, statistical analysis and interpolation	2.5.2.1, 2.5.2.2
	2.3	Conceptual modelling	2.5.2.3, 4.3
	2.5	Water balance assessment	2.5.2.4
	2.6.1	Surface water numerical modelling	4.4
	2.6.2	Groundwater numerical modelling	4.4
	2.7	Receptor impact modelling	2.5.2.6, 4.5
Component 3 and Component 4: Impact and risk analysis for the subregion or bioregion	3-4	Impact and risk analysis	5.2.1, 2.5.4, 5.3
Component 5: Outcome synthesis for the bioregion	5	Outcome synthesis	2.5.5

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

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Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 1 June 2018, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 1 June 2018, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

1 Introduction

1.1 Background

The *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) describes a multidisciplinary scientific approach to assess the potential impacts of coal resource development on water resources and water-dependent assets. Figure 3 is a simple diagram of the four components in the BA methodology.

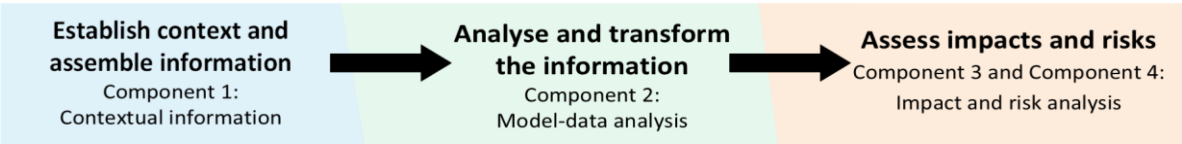

Figure 3 The components in a bioregional assessment

In Component 1: Contextual information, the context for the BA is established and the relevant information is assembled. This includes defining the extent of the subregion or bioregion, then compiling information about its ecology, hydrology, hydrogeology and geology, as well as water-dependent assets, coal resources and coal resource development. In Component 2: Model-data analysis, the information is analysed and transformed, by developing and using the conceptual model of causal pathways, geological models and hydrological models, in preparation for Component 3: Impact analysis and Component 4: Risk analysis.

The BA methodology is designed to include as much relevant information as possible and to retain variables in the assessment until they are ruled out of contention. Further, estimates of the certainty, or confidence, of the decisions are to be provided where possible, to assist the user to evaluate the strength of the evidence.

1.2 Role of this submethodology in a bioregional assessment

The BA process is complex, as shown in Figure 4 which includes all the supporting submethodologies, workshops and technical products. Readers should consider this submethodology in the context of the complete suite of methodologies from the Bioregional Assessment Programme (see Table 1), particularly the BA methodology (Barrett et al., 2013), which remains the foundation reference that describes, at a high level, how BAs should be undertaken.

An impact and risk analysis is the key output of the BAs. The BA methodology (Barrett et al., 2013) states:

> The central purpose of BAs is to analyse the impacts and risks associated with changes to water-dependent assets that arise in response to current and future pathways of CSG and coal mining development.

While the BA methodology gives a high-level overview of the components and conceptual workflow, it is not detailed enough to clearly guide assessment teams performing a BA. This is consistent with the intent of the BA methodology, which is analogous to an architect's design sketches. These sketches lay out the look and feel of the building and provide a guiding vision of the completed project. But to build it the architect needs to develop working drawings that explicitly show the detail of the construction that the tradespeople can use to actually construct the building. This submethodology performs the same role for BAs. Using the concepts in the BA methodology, it provides the overall scientific logic that runs through all components and the companion submethodologies, and culminates in the impact and risk analysis for a bioregion or subregion. Some details of the analysis are included here – mainly sufficient details so that users can efficiently generate high-quality impact and risk analyses for BA purposes – but otherwise this submethodology cross-references other submethodologies for details (e.g. to undertake hydrological modelling or receptor impact modelling).

The impact and risk submethodology for BA was developed and refined over time. It reflects learnings from the logistical and scientific challenges that arose in the application and evolution of the methodology. This submethodology describes the final process used to generate the assessments for the different regions, and also provides the reasoning behind the particular design choices that were made.

This submethodology includes the following:

- Chapter 2 explains the objectives and constraints of a BA, and key design choices made to meet objectives within the constraints.
- Chapter 3 describes the high-level logic and workflow that incorporates these design choices and culminates in the impact and risk analysis.
- Chapter 4 describes the process for the impact and risk analysis: predicting hydrological and ecological changes at locations across the landscape (assessment units) and then aggregating and summarising predictions for landscape classes and water-dependent assets.
- Chapter 5 guides how the impacts and risks are communicated and reported, through product 3-4 (impact and risk analysis) and other BA outputs.
- Chapter 6 discusses how the BA may be built on, focusing on the rule-out process, the identification of knowledge gaps, the availability of assessment data and information, and the requirements for designing monitoring that validates the impact and risk analysis.
- Appendix A discusses how the information generated from a BA is managed and used in the automated assessment of impacts and risks and how the requirement for transparency is addressed.

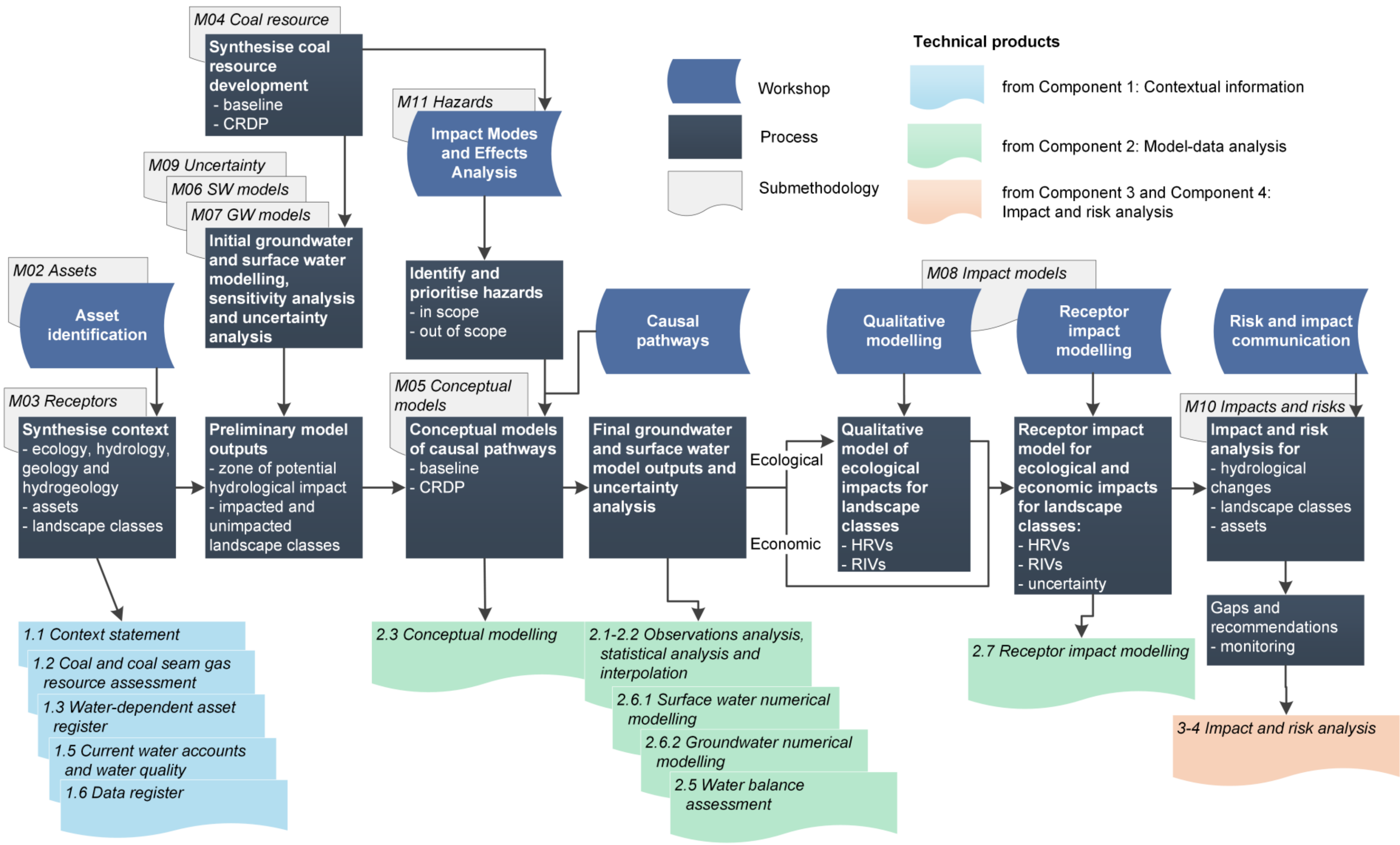

Figure 4 A bioregional assessment from end to end, showing the relationship between the workflow, technical products, submethodologies and workshops

CRDP = coal resource development pathway, HRVs = hydrological response variables, RIVs = receptor impact variables

2 Design choices for the impact and risk analysis

2.1 Objectives

The BA methodology (Barrett et al., 2013) defines a bioregional assessment (BA) as a regional cumulative analysis that assesses potential impacts of coal resource development on water resources and water-dependent assets by comparing results for two possible futures. The *baseline* future includes all coal resource developments that commenced commercial production prior to December 2012. The *coal resource development pathway* (CRDP) future includes not only the baseline coal resource developments but also the *additional coal resource development*, new developments, or expansions of baseline operations that are expected to commence production after 2012. The primary focus of a BA is on the potential impacts on water resources and water-dependent assets that are attributable to this additional coal resource development.

In the Bioregional Assessment Programme (the Programme), the term ‘coal resource development’ specifically includes coal mining (both open-cut and underground) as well as coal seam gas (CSG) extraction. However, other forms of coal-related development activity, such as underground coal gasification and in situ microbial enhancement of coal-hosted gas resources, are not within the scope of the assessment.

A risk analysis requires the consideration of consequences of impacts as well as the likelihood of them occurring. In BAs, the consequences are reported for water resources and water-dependent assets that have been identified by the local communities and natural resource management agencies as having ecological, economic or sociocultural value. The overarching objective of the impact and risk analysis is to determine how the specified coal resource development may impact these water resources and water-dependent assets over both space and time given the existing understanding and uncertainty in the biophysical systems and coal resource development operations. BAs present the predicted biophysical consequences of coal resource development in terms of changes to hydrology and ecological variables. BAs do not assess the ecological or socioeconomic significance of these changes because this requires value judgments and non-scientific information that is outside the scope of BA.

At the heart of the impact and risk analysis is a conceptual chain of causation, where activities in the coal resource development within the biophysical context of the bioregion or subregion lead to hydrological changes (represented by *hydrological response variables*, such as groundwater drawdown), which in turn results in changes in the environment and ecology (represented by *receptor impact variables*, such as vegetation condition). Figure 5 illustrates this chain of causation and the conditional relationship between variables considered in the impact and risk analysis. The fundamental comparison between the two futures enables prediction of hydrological and ecological changes that are attributed to the additional coal resource development (∆D in Figure 5).

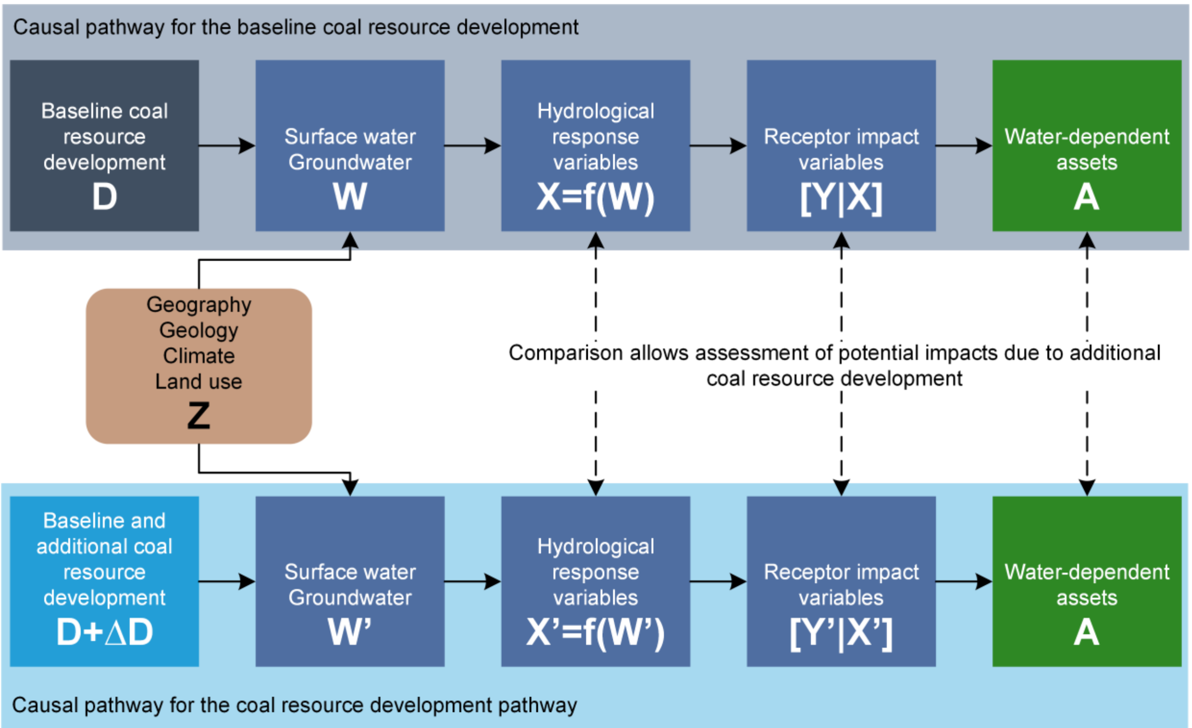

Figure 5 The difference in results under the baseline coal resource development (baseline) and coal resource development pathway (CRDP) provides the potential impacts due to additional coal resource development

2.2 Design constraints

Three classes of constraints influenced the design of this methodology. Those imposed by:

- the BA methodology
- the complexity of the bioregions and assets
- good practice in risk assessment.

2.2.1 Constraints imposed by the bioregional assessment methodology

The objectives of the BA methodology (Barrett et al., 2013) are very challenging, and to date have not been achieved elsewhere. Among the specific constraints, the BA methodology:

- specifies that the analysis needs to assess direct, indirect and cumulative impacts, which is still a developing area in risk analysis
- requires assessing water-related impacts of coal resource development on assets. Impacts vary in space and time, so achieving this requires the ability to predict impacts spatially and temporally
- focuses on impacts related to water quantity and availability. Potential water quality impacts are limited to salinity, with other water quality impacts beyond the scope
- is explicit about assessing impacts for two futures: baseline and CRDP, which includes likely additional coal resource development.

- does not consider the value of assets beyond accepting that the community values the assets that they identified. The methodology predicts consequences (i.e. biophysical impacts such as hydrological or ecological changes), but does not address the significance of the predicted consequences.

2.2.2 Constraints imposed by complexity of the bioregions

The bioregions or subregions are often large and cover broad geographic extents, and the human and ecological systems are complex and diverse. Specific constraints include:

- The landscape is heterogeneous and may depend on various subsurface features. It is necessary to consider individual elements of a landscape within the broader system context and interactions to simplify and ensure the analysis is tractable.
- The scale, intensity and spatial extent of impacts will vary through time but high-resolution ecological and hydrological predictions are not currently feasible. Results at specific locations can be predicted for only a few time points.
- A large number of water-dependent assets were identified, and it is not possible to manually assess each asset individually within time frames that are useful for decision makers.
- Some of the hydrological changes that may occur after development may not have been observed before in an area, and there is therefore no empirical data to base inferences on.
- The complexity of the bioregion or subregion needs to be addressed within the operational constraints of the Programme. If a region can be ruled out from impact, halting further analysis ensures that resources can be concentrated on the most important areas.
- Ecological systems are complex and demonstration of causation is challenging so the unambiguous identification of direct, indirect and cumulative impacts is difficult.

2.2.3 Constraints imposed to achieve good practice in risk assessment

Good practice in risk assessments (Burgman, 2005; Suter, 2006) needs to be achieved so that the results are of high scientific quality, and are useful for managing risks. Specific constraints include that the impact and risk analysis needs to:

- be repeatable and falsifiable, and make predictions that can be validated over time through observation
- be complete in its coverage of the breadth of potential impacts on and risks to water resources and water-dependent assets within the scope of BA
- effectively integrate across available models and information, but also allow updates if models and information change or improve
- reliably represent and communicate the uncertainties embedded in the impact and risk analysis, and equally importantly identify where confidence in results is high.

2.3 Design choices

The design constraints described in the previous section define requirements for the impact and risk methodology: it must meet the objectives of the BA methodology while also being practical and respecting good practice. Making design choices that meet these requirements ensures that BAs are credible and timely and thus can constructively inform public debate and decision making.

The major design choices are:

- a dedicated hazard analysis
- a quantitative analysis of impacts and risks
- assessment of regional-scale cumulative impacts
- a focus on predictive uncertainty
- hydrological predictions for any location in the landscape
- decomposition of the predictions into conditionally independent components
- a landscape classification
- two assessment time points
- use of expert opinion where empirical data are limited
- qualitative mathematical modelling to estimate direct and indirect impacts and choose key variables
- automation of the analysis.

2.3.1 A dedicated hazard analysis

A hazard can be defined as a situation that in particular circumstances could lead to harm (The Royal Society, 1983) or alternatively considered as a substance's or activity's propensity for risk. Hazards are sometimes perceived to be solely a function of a substance's intrinsic properties but, as emphasised in the definition above, they are more usefully conceptualised as a function of both the intrinsic properties of a substance and circumstance.

For example, co-produced water from CSG production may not ordinarily be considered hazardous, but if it is used carelessly to irrigate land it may cause detrimental changes to the soil chemistry and negatively impact agricultural production. Thus a substance's intrinsically hazardous properties can often only be realised under a very specific set of circumstances. A hazard analysis should properly acknowledge both the intrinsic properties and the circumstances required in order for harm to be realised. The measure of the likelihood of these circumstances and the magnitude of the subsequent harm is a measure of risk. Put another way, a hazard becomes a risk only when there is a non-negligible probability of a manifestation of the hazard (Beer and Ziolkowski, 1995).

Hazard analysis is a structured process designed to identify the substances and circumstances surrounding an activity that cause harm; such an analysis provides a mechanism to rank potential hazards against a variety of criteria, but most usually the likelihood and severity of this harm. In this manner a hazard analysis prioritises tasks and resources within an assessment and provides the logical basis to support the breadth and detail of the analysis presented in the products. For example, a hazard that has low likelihood of occurring and little consequence may be reported as such (in the interests of transparency), but accorded fewer resources for the analysis compared to hazards with higher consequence and likelihood.

A carefully structured hazard analysis is a key component of a BA and needs to be completed to enable this essential ruling out, given the wide scope of potential risk endpoints. Significant commonality across bioregions and subregions means that results are widely applicable. Further information about how to undertake a BA-specific hazard analysis is found in Section 3.2.2 of this submethodology and in the companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016). Hazard analyses undertaken for individual subregions are available as datasets from product 2.3 (conceptual model of causal pathways).

2.3.2 A quantitative analysis of impacts and risks

There are many different definitions and formulations of risk, with notable differences between application domains. It is common to distinguish the likelihood from the consequence. The AS/NZS ISO 31000:2009 standard on risk management (mandated by the BA methodology) departs from this and considers risk as ‘the effect of uncertainty on objectives’ and seeks to describe what could happen given the uncertainty in external and internal factors and influences, and how the objectives may be affected. Within BAs the objective is the community’s desire to protect the water-dependent assets that they value. The specific objectives related to individual assets are, however, unknown and require careful consideration of a number of non-scientific matters and value judgments. Therefore the risk evaluation and imposition of risk management strategies that typically occur as part of a broader regulatory process are beyond the scope of BAs; these are roles of proponents and government regulators.

There are many different ways to calculate risk, with qualitative, semi-quantitative and fully quantitative approaches. Within BAs a quantitative or probabilistic approach to risk is adopted. The hazard analysis identifies those risks, and the assessment seeks to understand those risks by assessing the impact (or consequence), the likelihood of that impact, and the uncertainty associated with the likelihood (represented by probabilities, see Section 3.2.4).

In BAs, qualitative descriptors are defined quantitatively. For example, where a high/medium/low scale is used to communicate the results of an assessment, the quantitative cut-offs between the classes are explicit. This protects against different interpretations of these terms by different audiences, and allows for coherent calculation of the uncertainty in the risk predictions (Section 2.3.3.; Lindley, 2006)

Concepts and quantities used are well defined and, where appropriate, measurable, at least conceptually. As an example, abstract concepts such as ‘ecosystem health’ have not been used if they are not defined explicitly in terms of measurable quantities such as, for example, number of species, or biomass. This restriction helps protect against linguistic uncertainty and the ensuing misunderstandings this creates because of the ambiguity of natural language, and means that predictions can be tested against data in the future.

2.3.3 Assessment of regional-scale cumulative impacts

BAs focus on the cumulative impacts of coal resource developments at a regional scale, rather than specifically on individual mines or CSG operations. Coal resource developments in a bioregion or subregion typically comprise a suite of developments, which are distributed across a bioregion or subregion at variable distances from each other and have variable, but often overlapping periods of operation. Thus there is potential for the impacts to accumulate to varying degrees in both space and time.

Regional-scale models allow the assessment to address some of the complexity challenges in a bioregion or subregion, and are used to predict the cumulative hydrological changes and potential impacts of those developments on ecosystems and water-dependent assets from multiple developments over time. The area of potential impact may often be more extensive and extend greater distances downstream of developments than what is predicted from site-scale, single mine models. In some cases the spatial or temporal alignment of certain coal resource developments can allow for attribution of potential effects to individual developments, but that occurs because of that alignment rather than by design.

Results of a BA impact and risk analysis do not replace the need for the detailed site- or project-specific investigations that are currently required under existing state and Commonwealth legislation. The hydrological and ecological systems modelling undertaken for a BA is appropriate for assessing the potential impacts on and risks to water resources and water-dependent assets at the ‘whole-of-basin’ scale, whereas the modelling undertaken by a proponent for an individual coal resource development, as part of an environmental impact assessment, occurs at a much finer scale and makes use of local information to more accurately represent the local situation. Therefore, results from detailed specific coal resource development studies are expected to differ from those from a BA. BA results should not be used to invalidate existing site-specific modelling or impact assessments.

2.3.4 A focus on predictive uncertainty

Probability is used to represent uncertainties in BAs. These probabilities are interpreted as representing an individual’s (for example, an expert’s or analyst’s) degree of belief in an uncertain event given their current knowledge base (Lindley, 2006). This choice naturally accommodates expert opinion, which is an important part of the analysis and ensures that uncertainties are propagated coherently (i.e. in accordance with the standard laws of probability).

The BA methodology (Barrett et al., 2013) defines key aspects of the scope of the analysis and imposes constraints on the uncertainty analysis by specifying that some components of the problem are to be considered constant or fixed at the time an individual expresses their degree of belief about an uncertain event. Nonetheless, the scope of BA poses a considerable challenge, and for processes and activities that are in scope, a choice needs to be made about whether to acknowledge uncertainty or to choose a particular possibility and fix this in the analysis. Practically, this requires the risk analysis to specify which parts of a problem are considered to be uncertain and which parts must be conditioned on (i.e. taken as fixed).

Four examples illustrate the application of these choices:

- BAs do not assess the effects of uncertainty in the CRDP. It is not known exactly what developments will occur and when they will occur as this depends on regulation, market conditions and other socioeconomic or political factors. The assessment is based on a single most likely pathway for coal mining and CSG development in the bioregion or subregion (companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014)). Multiple development pathways are not generated or evaluated in the BAs due to the increased level of uncertainty in the analysis that this would create.
- Uncertainty in the impacts caused by risks that are currently managed under existing industry standards or regulatory processes, such as the failure of a tailings dam or incomplete well casings, are not considered. Although these types of failure may have socioeconomic or ecological consequences, they are addressed through industry standards or site-based risk management and are not therefore considered as part of the assessment or the uncertainty analysis.
- The impacts due to coal resource development will depend on the climate over the assessment period. For example, a reduction in groundwater, or a discharge of produced water, would have a different impact depending on whether there was a sustained drought or a period of above average rainfall. A pragmatic choice has been made to fix the climate within BAs to a single 'mid-range' future climate time series (companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016)). The BA methodology restricts the scope to impacts due only to coal resource development. The level of agricultural, industrial and urban development is specified as fixed at the baseline extent. The effect of changes in (for example) agricultural practice, and the uncertainty that this creates, has not been incorporated into the assessment because the focus of BA is on the difference between two coal resource development futures.
- BAs focus solely on water-related impacts, and specifically those related to water quantity and availability. Potential water quality hazards are identified through the comprehensive hazard analyses, but the analysis, as determined by the BA scope, is limited to salinity and is only addressed qualitatively.

For those parts of the problem that are considered uncertain, there is central focus on characterising the range of potential hydrological outcomes (i.e. changes to surface water or groundwater) and, where appropriate, the range of potential outcomes in ecologically relevant receptor impact variables, by considering parameter uncertainty as fully as possible in all predictions. For example, groundwater models are run many thousands of times using a wide range of plausible input parameters for many of the critical hydraulic properties, such as the hydraulic conductivity and storage coefficients of all modelled hydrogeological layers. This differs from the traditional deterministic approach used more routinely for surface water and groundwater modelling and is driven by the risk analysis focus of BAs. The quantitative representation of the predictive uncertainty through probability distributions allows BAs to consider the likelihood of impacts or effects of a specified magnitude and underpins the impact and risk analysis. Numerical models are created to represent a simplified conceptual understanding of the system. Where there are sources of uncertainty that those models are unable to incorporate quantitatively their effects, particularly on predictions, are considered qualitatively.

2.3.5 Hydrological predictions for any location in the landscape

The chain of causation depicted in Figure 5 shows that an assessment of the potential impacts and risks to a water-dependent asset requires prediction of the hydrological change for that asset. In order to represent any hydrological or ecological change that asset may experience, it is necessary to make predictions for the full extent of that asset. The extent of assets is large, and therefore effective predictions need to be made at any location in the bioregion or subregion.

There are, of course, practical limits and constraints to this. Hydrological models have their own resolutions, whether that be the node-link model resolutions of surface water models or the possibly variable sizes of grid cells in groundwater models as described in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) and companion submethodology M07 for groundwater modelling (Crosbie et al., 2016). However, to reliably assess potential impacts, outputs from those hydrological models need to be interpolated to locations that are relevant to water-dependent assets.

The locations where predictions are required are divided into square grids of *assessment units*. The size of the grid cell used is flexible but in practical implementation ranges between 500 x 500 m in the Gloucester subregion and 1500 x 1500 m in the Maranoa-Balonne-Condamine subregion, with most subregions at 1000 x 1000 m resolution. The choice of resolution is primarily driven by the groundwater model resolution. Impacts on and risks to particular assets or landscapes classes may be assessed by aggregating predictions across the assessment units that pertain to that asset or landscape class. The assessment units are tagged with other information, such as details of the landscape class and relevant hydrological response variables and receptor impact variables.

The assessment unit supersedes the use of receptors as points in the landscape where predictions are required and water-related impacts assessed (as originally specified in the BA methodology and companion submethodology M03 (as listed in Table 1) for assigning receptors to water-dependent assets (O'Grady et al., 2016). Conceptually, assessment units contain an infinite number of receptors and hence can be used as a multi-purpose spatial device to map any number of potential impacts for a range of receptors identified within water-dependent assets and/or landscape classes.

2.3.6 Decomposition of the predictions into conditionally independent components

Figure 5 outlines the logical basis of the analysis. Conditional on coal resource development, hydrological predictions are made with associated uncertainty. Conditional on a given hydrological change (and the scope and analysis restrictions described in Section 2.3.3), a receptor impact model predicts the possible ecological outcomes. Thus, uncertain ecological or economic impacts can be estimated from uncertain hydrological impacts.

Decomposing the workflow and associated predictions into components ensures that the assessment is, where possible, modular. Changes or updates to one component should not necessarily trigger changes to all other components. This means that future updates or iterations to a BA do not have to revisit each component of work to the same level and intensity as done during the initial BA. For example, if the CRDP was to change, adjustments to some components of work may be needed (e.g. incorporating new coal resource developments in the groundwater model) but may not affect many other components (e.g. the water-dependent asset register). If an improved surface water model becomes available, the modelled hydrological changes could be updated as part of the assessment workflow in a future BA. Although there is effort and expertise required in any update, the modular nature of the assessment means that effort is relatively much reduced.

2.3.7 Landscape classification

A bioregion or subregion is a complex landscape with a wide range of integrated human and ecological systems. Because of this complexity a direct analysis of each and every point in the landscape across the bioregions and subregions is not currently possible. Abstraction and a systems-level classification help manage the challenges of the dimensionality of the task.

In each bioregion and subregion, a set of landscape classes is defined that are similar in their physical, biological and hydrological characteristics (refer to companion submethodology M05 (as listed in Table 1) for developing a conceptual model of causal pathways (Henderson et al., 2016) for additional information on landscape classes). This reduces the complexity of the analysis task in each bioregion or subregion and is appropriate for a regional-scale assessment. Landscape classes provide a structure that helps the analysis to focus on the key processes, functions and interactions that determine how ecological systems respond to changes in hydrological variables.

The Assessment team chooses the method for landscape classification, but wherever possible they build on existing, well-accepted classifications such as the Australian National Aquatic Ecosystem (ANAE). Substantial previous time and effort has gone into constructing and defining systems of landscape classification relevant to the Bioregional Assessment Programme. The Programme has sought to understand the limitations and relevance of potential classification systems, and thus has developed and justified a consensus choice for the classification or combination of classifications that best matches the demands of a given bioregion or subregion. The reality is that no one existing classification is likely to fully satisfy the needs of the analysis given that the interests of BAs fall across both ecological systems and human systems (including agricultural production systems, industrial and urban uses). The choice is guided by the overall objective of reducing the complexity of the analysis task, which can be achieved by choosing a classification where the individual classes are as homogeneous as possible in their response to the water-related impacts of the coal resource development. There is a trade-off between adding new classes to achieve homogeneity and increasing the specificity of the resulting analysis. If an assessment was undertaken at a different spatial scale, an alternative classification may be appropriate in getting that balance right.

The landscape classification also allows the effort to be concentrated on those landscape classes that are water dependent. An additional consideration is that in large bioregions or subregions, water-dependent landscape classes may not be near coal resource developments so are *very unlikely* to be impacted. The Assessment team should use the hazard analysis and preliminary hydrological modelling to analyse the spatial extent (or footprint) of important CSG- and coal mine-related hazards, and exclude from detailed analysis those landscape classes with negligible potential impact.

2.3.8 Two assessment time points

The receptor impact models are constructed to predict receptor impact variables (representing ecological changes) at particular points in time. The potential impact can depend strongly on the time of that assessment, and may be complicated by the (potentially) long lags that can occur in groundwater systems and between the hydrological change and ecological response.

Predictions are restricted to two time points given that the significant uncertainties about the dynamics of these ecosystems translates into large uncertainties in the experts' predictions. This restricted analysis is simpler to perform.

In BAs, ecosystem impacts are considered for two time points: 2042 and 2102. The reference year of assessment is 2012. Broader hydrological changes are also considered as maximum impacts across the full 90-year time series from 2013 to 2102.

The time point 2042 for ecosystem impacts is chosen based on a number of considerations. First, the nature of the CRDP means that the features of the identified developments may quickly change over time (e.g. the mine design and scheduling originally proposed in the development application or environmental impact statement may be modified), so short-term analyses are important. In addition, the broader community will be naturally interested in the changes that they will experience in their lifetimes. This suggests choosing a time point in the relatively near future and at the height of coal resource development.

While surface water hydrological regimes may return to something close to their pre-development state in the short-to-medium term after site rehabilitation and closure, groundwater impacts may continue to occur over the longer term and ecological systems may not respond as quickly. The time point 2102 is chosen to represent the enduring impacts of these developments to the landscape.

2.3.9 Use of experts where empirical data are limited

Expert elicitation is central to a BA. It supports the choice of some parameter ranges for the numerical hydrological models. It underpins the receptor impact modelling by summarising the range of the potential ecosystem response for a given change in hydrology.

In many cases limited data are available to make formal inference from. Because of this, expert interpretation and opinion will be needed to form a coherent assessment. The use of experts requires considerable care and effort. Poorly staged elicitation approaches can lead to frustration and disengagement of key experts, leading to poor quality and potentially biased data. Facilitation must ensure that the questions are clearly defined and interpretable by the experts. Wide variation in opinions between experts means that the experts must be carefully chosen in consultation with the client. Motivation of the experts is also essential and again the client may be able to assist and increase participation by key experts in the BA process.

It is important to develop a tractable elicitation scenario that is not too difficult or complex for general experts, due to the large number of bioregions or subregions and landscape classes combined with multiple timescales, receptor impact variables and hydrological response variables to consider within each receptor impact model. This is achieved by careful design of the elicitation process, drawing on the principles of optimal experimental design (companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018a)).

2.3.10 Qualitative mathematical modelling to estimate direct and indirect impacts and choose key variables

Qualitative mathematical modelling is described in detail in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018a). It has several key roles in a BA: (i) it provides a graphical conceptualisation of the landscape ecosystem, identifies the critical hydrological processes that support the ecosystem's components and processes, and identifies how these may change due to coal resource development; (ii) it enables the Programme to predict the changes due to direct and indirect impacts on the ecosystem; and (iii) it provides a transparent mechanism for selecting hydrological response variables and receptor impact variables to be used in receptor impact models.

An example of a signed digraph (SDG) output from the qualitative mathematical modelling for the 'Perennial – gravel/cobble streams' landscape class in the Gloucester subregion is presented in Figure 6 to provide context for a description of the two roles that follows.

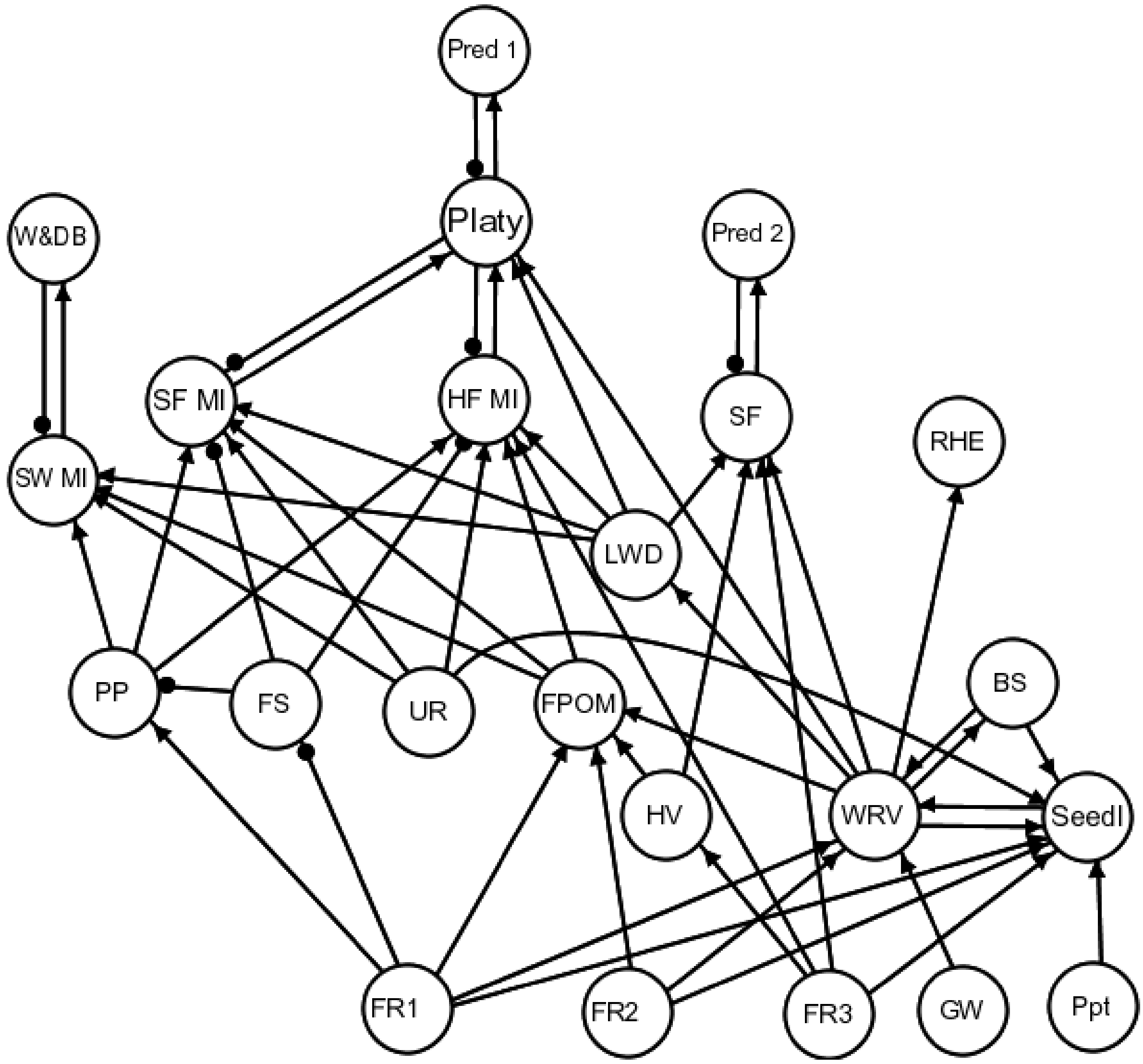

Figure 6 Example of a signed digraph of a riparian-dependent community in reaches in the 'Perennial – gravel/cobble streams' landscape class for the Gloucester subregion

Example only; do not use for analysis. This is an early draft of a figure published in companion product 2.7 for the Gloucester subregion (Hosack et al., 2018b). See Hosack et al. (2018b) for full explanation. Variables are: bank stability (BS), fine particulate organic matter (FPOM), fine sediments (FS), flow regimes (FR1, FR2 and FR3), groundwater (GW), high-flow macroinvertebrates (HF MI), herbaceous vegetation (includes aquatic macrophytes) (HV), large woody debris (LWD), platypus (Platy), primary production (PP), precipitation (Ppt), predators (Pred 1 and Pred 2), regent honeyeater (RHE), seedlings (Seedl), slow-flow macroinvertebrates (SF MI), stuttering frogs (SF), still-water macroinvertebrates (SW MI), upstream recruitment (Ur), wading and diving birds (W&DB); woody riparian vegetation (WRV).

2.3.10.1 Direct and indirect impacts

The BA methodology (Barrett et al., 2013) requires 'explicit assessment of the potential direct, indirect and cumulative impacts of CSG and coal mining development on water resources' together with an analysis of the associated uncertainties, but does not provide guidance on how this will be achieved. The BA methodology defines direct and indirect impacts, respectively, as:

- '… those associated with CSG and coal mining developments that impact on natural resources without intervening agents or pathways'

- '… those impacts on receptors (within water-dependent assets) that are produced as a result of a pathway of cause and effect. This causal pathway may be simple or complex. Sometimes indirect impacts are referred to as second- or third-level impacts, or secondary impacts (Walker and Johnston, 1999)'.

To operationalise these definitions, direct and indirect impacts need to be identified in an unambiguous fashion in a stressor conceptual model – that is, a conceptual model that identifies how stressors (here, changes to hydrological processes) interact with components and processes of the ecosystem.

Direct and indirect impacts may be distinguished via qualitative mathematical modelling by presenting the stressor conceptual model for an ecosystem (landscape class) as a signed digraph. From the graph structure it is possible to examine the causal pathways that link hydrological response variable to the receptor impact variable. Pathways with just one link in the SDG are formally direct impacts on the receptor impact variable. Pathways with two or more links, which thereby involve other system variables, are formally indirect impacts.

The principal concern in BAs is with press perturbations – that is, changes in hydrological response variables that are sustained for a relatively long time period, for example, over much larger time frames (many decades) than the generation times of the potential receptor impact variables (days to decades) The sustained nature of this type of perturbation, in contrast to pulse perturbations, provides time for the knock-on effects to be felt throughout the entire system.

By representing conceptual models of landscape classes as SDGs, it is possible to make qualitative predictions of impacts to variables (i.e. direction but not magnitude of change) from sustained hydrological changes. This analysis enables comparison of the predicted direction of change from the qualitative mathematical analysis with the quantitative analysis of the receptor impact variable.

2.3.10.2 Choice of hydrological response variables and receptor impact variables

Qualitative mathematical modelling supports two of the most important choices during the receptor impact modelling: the choice of hydrological response variables and receptor impact variables.

There are typically tens to hundreds of potential hydrological response variables that can be modelled using the groundwater and surface water models, but the receptor impact modelling must by necessity be limited to using just a few per landscape class to ensure that the elicitation requirements of the subsequent receptor impact models are reasonable and achievable. The choice of hydrological response variables to include in the receptor impact models should be guided by the results of the hazard analysis, and the constraints and restrictions on the scope of the analysis (Section 2.3.3). As BAs are primarily concerned with press perturbations, the characteristics of extent, magnitude, duration and rate of impact should also influence the choice of hydrological response variables.

There are also typically hundreds to thousands of potential receptor impact variables, which are indicators of ecosystem condition, across the assets of a bioregion or subregion. This choice is circumscribed to some extent by the definition of landscape classes, but still within the qualitative mathematical models and conceptual models of these landscape classes tens of potential receptor impact variables may be anticipated, when by necessity the limitation is for no more than a few per landscape class given workshop logistics and constraints with expert availability. The complexities of the potential direct and indirect effects associated with press perturbations suggest a priori that receptor impact variables at the base of complex food webs are less likely to be involved in complex indirect impact pathways, thereby making the elicitation task more tractable and focusing the analysis on a key underpinning component of the system. The generation time of the receptor impact variables, in the context of press versus pulse perturbations, should also be considered and should also influence this choice.

The choice of impact variables also needs to be framed by the expected audience, which includes the primary audience of the Independent Expert Committee on Coal Seam Gas and Large Coal Mining, regulators, and industry proponents, but expands to wider range of interests for the community. There will be experts about particular species and experts about particular locations. There will be experts about particular agricultural or ecological systems and experts about particular taxa. Members of the general public will each have their own beliefs and understandings of these systems, and an associated set of values. The Programme needs to be conscious of the expectations of this community, and the natural tension that arises between ensuring that the risk analysis is achievable (with the current operational constraints) but at the same time relevant to as much of the community as possible. This can be achieved, for example, by choosing receptor impact variables that simplify the elicitation task and speak to broad sections of the community, and by using the narrative in the analysis to broaden the assessment to other more specific sections of the community. For example, basal vegetation variables can speak to diverse segments of the expected audience when interpreted, for instance, in terms of forest cover. Companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018a) describes the specific criteria used to guide the selection of receptior impact variables in more detail. These include:

- *Is the response variable directly affected by changes in hydrology?* These variables typically have a lower trophic level, and focusing on direct (signed digraph arcs of length one) impacts helps alleviate the elicitation burden imposed on experts during the construction of the receptor impact models.
- *Is its status important in maintaining other parts of the 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. Again, these types of variables will typically have a lower or mid-trophic level.
- *Is it something that the available expertise can provide an opinion on?* There is a need to be pragmatic and make a choice of receptor impact variable that plays to the capabilities and knowledge base of the experts that are available at the time the receptor impact models are created.
- *Is it something that is potentially measurable?* This is essential for (in)validation of the predicted impacts and in the subsequent design of monitoring strategies that close the risk analysis loop by testing, comparing its predictions with observations.

- *Will the community understand and accept the relevance and credibility of the receptor impact variables for a given landscape class?* This reflects the communication value of the receptor impact variable.

2.3.11 Automation of the analysis

The task of predicting impacts and risks is substantial. The bioregions are large; the water-dependent assets are numerous, extensive and overlapping; and the many potential hydrological and ecological changes are relevant and need to be summarised in various ways.

Therefore, a systematic automated approach is used to assess the impacts on and risks to landscape classes and water-dependent assets. This requires a common spatial resolution of the *assessment unit* across a given bioregion or subregion (typically 1000 x 1000 m, based primarily on the underlying resolution of the groundwater modelling) so that results at these assessment units can be aggregated to different scales: regional, landscape class or individual asset. A key aspect of this approach is the translation from a spatial database representation to a relational database representation using the assessment units as the construct that holds and transfers the information. More details are outlined in Appendix A.

This automation ensures consistency and the ability to meet the key transparency requirement of the Programme.

3 High-level logic and workflow

3.1 Overview

The design choices outlined in Section 2.3 respect the objectives and chain of causation described in Section 2.1 and constraints in Section 2.2, and results in a number of design elements in the impact and risk submethodology. These individual design elements are summarised in Figure 7, which presents the high-level logic and workflow that culminates in the impact and risk analysis.

Given the most likely coal resource development in a region, a systematic hazard analysis provides a basis for describing the nature and severity of potential risks by identifying the potential causal pathways that may lead to changes in surface water and groundwater. Coupled with the conceptual understanding of the regional geology and hydrogeology, these pathways are embedded in regional hydrological models that make predictions at specific locations. Uncertainty is propagated through hydrological models by basing predictions upon plausible distributions of model parameters rather than fixed values. The large number and diversity of ecological assets is addressed by classifying ecosystems into landscape classes that, while still subject to some uncertainty, are expected to respond similarly to changes in groundwater and/or surface water.

For those landscape classes that may experience hydrological change, qualitative mathematical modelling is used to produce SDGs that summarise the key interactions between ecosystem components and their dependence on hydrology. The qualitative mathematical modelling process captures direct and indirect effects that may occur following changes to the hydrology as a result of coal resource development. Qualitative mathematical modelling also underpins the choice of important hydrological response variable predictions, to come from the hydrological models, and the receptor impact variables that are to be used as ecosystem indicators for that landscape class.

Receptor impact models for a landscape class are functions that translate potential change in hydrological response variables into predicted changes in a receptor impact variable (as an indicator of ecosystem condition). They are constructed on the basis of a carefully structured expert elicitation and incorporate both uncertainty in the input hydrology and uncertainty in the functional relationship as characterised by the elicited responses from experts.

Predicted distributions of the maximum hydrological change at particular locations across the simulation period (2013 to 2102), for hydrological response variables at particular locations in the short term (2013 to 2042) and long term (2073 to 2102), and for receptor impact variables at particular locations at the end of the short term (2042) and at the end of the long term (2102), underpin the assessment of impact and risk. Predictions at specific locations may be summarised and aggregated for assessing impacts and risks for landscape classes or individual water-dependent assets. The predicted distributions are a result of the probabilistic treatment of uncertainty through a modelling chain that considers the receptor impact modelling as conditionally independent given the hydrological response variables, underpinning the quantitative assessment of impact and risk.

Narratives, based on logic and knowledge, to describe possible impacts and implications of developments may also be important. The ecological impacts box within the impact analysis in Figure 7 emphasises this for some landscape classes that have qualitative models and receptor impact modelling, some that only have qualitative models, and others that are restricted to other conceptual models and existing literature. There is a synergy between all these parts. A good analysis will use all of these devices in concert to develop a compelling BA.

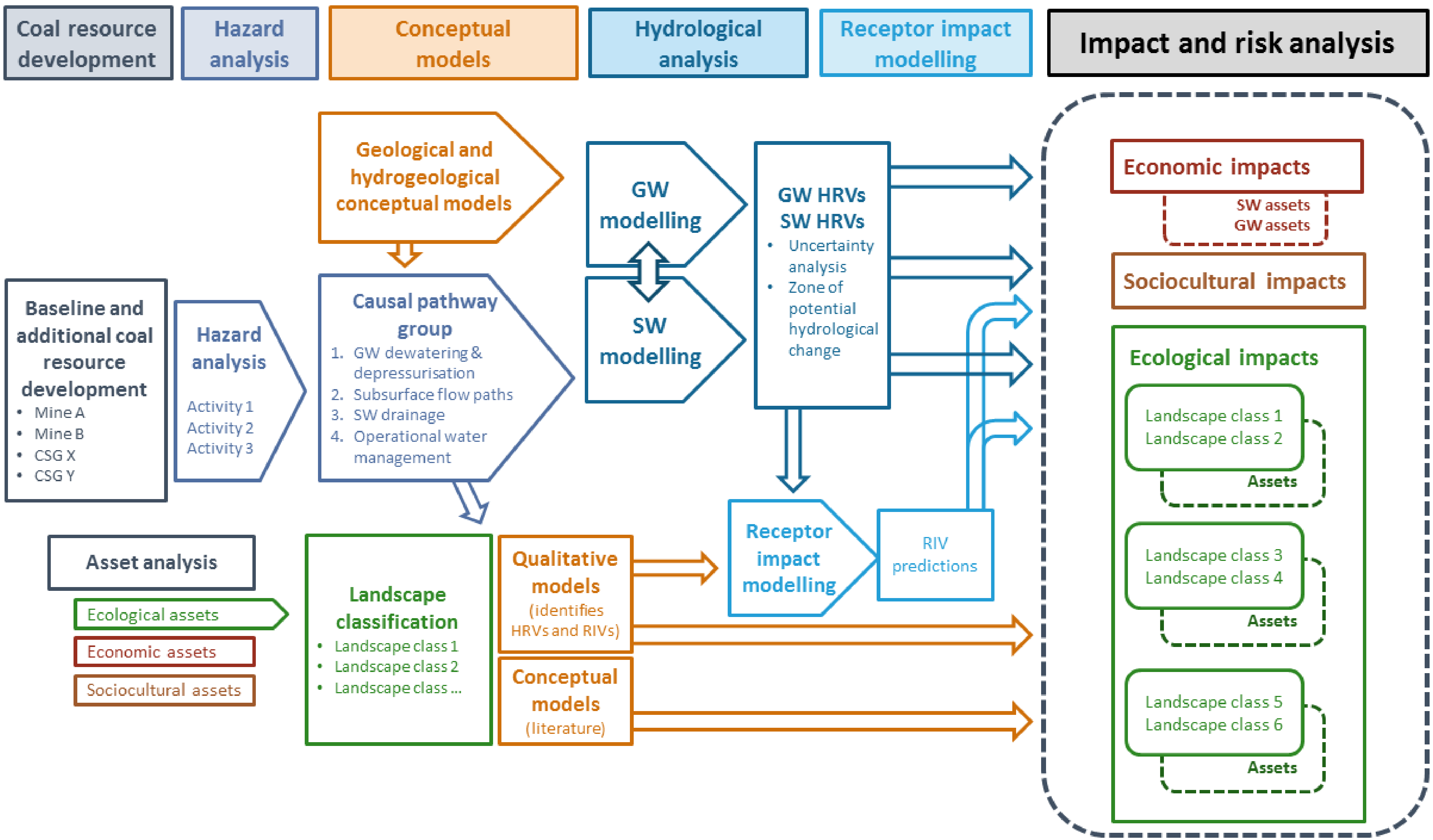

Figure 7 Overview of the workflow, which generally builds from left to right, and culminates in the impact and risk analysis

GW = groundwater; HRV = hydrological response variable; SW = surface water; RIV = receptor impact variable

While not necessarily evident in Figure 7, there is a strong focus on progressively ruling out potential impacts, where possible, both spatially and in terms of specific groundwater or surface water effects, so as to concentrate the attention of the assessment where potential impacts have a greater probability of occurring. This process starts with the application of a hazard analysis to guide choices encountered during the analysis. Where impacts are likely to be small in a particular circumstance, then scarce resources are better allocated elsewhere in the analysis. For instance, landscape classes are only considered in the impact and risk analysis where there are potential hydrological changes attributable to additional coal resource development.

3.2 Description of workflow leading to assessment of impact and risks

This section provides further details on the components depicted in Figure 7 that lead to the impact and risk analysis.

3.2.1 Coal resource development

The coal resource development pathway (CRDP) is considered the most likely future, based on the analysis and expert judgment of the Assessment team in consultation with state regulators and industry at a particular point in time. The creation of the CRDP is described in detail in companion submethodology M04 (as listed in Table 1) for developing a coal resource development pathway (Lewis, 2014). Product 1.2 (coal and coal seam gas resource assessment) assesses the current, historical and potential future coal resource development in a bioregion or subregion. The CRDP used as the basis of the assessment is documented in product 2.3 (conceptual modelling).

The CRDP may ultimately be implemented in different ways (e.g. changes to timing) or the list of developments may even change (e.g. a proponent may withdraw for some reason). This reflects the dynamic nature of resource investment decision making, which may ultimately be impacted by diverse economic, political or social factors. Consequently, the CRDP needs to be viewed as an indicative scenario that provides value in highlighting potential changes for water resources and water-dependent assets that may need to be considered further in local analyses or conditions. Equally as important, the CRDP plays an important role in identifying where changes will not occur and thus flagging where potential impacts to water resources and water-dependent assets are *very unlikely*. As part of the indicative nature of the two futures considered in BA (baseline and CRDP), it is important to recognise that factors such as climate change or land use are held constant between the two futures.

3.2.2 Hazard analysis and causal pathways

The dedicated hazard analysis is a systematic and structured process to identify potential risks to water-dependent assets by considering the activities that occur as part of coal resource development in a region and the potential chain of effects that they may cause that could impact water resources and water-dependent assets.

The hazard analysis methodology used in bioregional assessments (BAs) is described in the companion submethodology M11 (as listed in Table 1) for analysing impacts and risks (Ford et al., 2016). In brief, the hazards arising from coal resource development are assessed using *Impact Modes and Effects Analysis* (IMEA). The hazards are firstly identified for all the *activities* (*impact causes*) and *components* in each of the five *life-cycle stages*. For coal seam gas (CSG) operations the stages are: (i) exploration and appraisal, (ii) construction, (iii) production, (iv) work-over, and (v) decommissioning. For coal mines the stages are: (i) exploration and appraisal, (ii) development, (iii) production, (iv) closure, and (v) rehabilitation. The hazards are scored on the basis of the perceived severity of the potential impact, the perceived likelihood of the hazard occurring and the detectability of the hazard under current industry standards and regulatory regimes.

The hazard analysis reflects the conceptual models and beliefs that domain experts hold about the ways in which coal resource development might impact surface water and groundwater, and the relative importance of these potential impacts. As a result, the analysis enables these beliefs and conceptual models to be made transparent.

The hazard analysis provides a comprehensive list of hazards. Only water-mediated impacts, and specifically those related to water quantity, groundwater level or water resource availability are in scope for BA. Potential water quality impacts considered are limited to salinity and are only addressed qualitatively, though the process of the assessment identifies other water quality attributes that may be affected by activities that occur as part of the coal resource development.

BAs are also primarily concerned with those surface water and groundwater hydrological effects that may accumulate, either over extended time frames or as a result of multiple coal resource developments. These typically correspond to changes in surface water and groundwater that are sustained over long periods of time, sometimes decadal, and which may create the potential for flow-on effects through the wider hydrological system. Many activities related to coal resource development may cause only local or on-site changes to surface water or groundwater. These are not considered in BAs because they are assumed to be adequately managed by site-based risk management and mitigation procedures, and are unlikely to create potential cumulative impacts.

There is considerable structure and hierarchy within these lists of hazards, and it is reasonable to aggregate or consider hazards with the same causal pathway together even if they occur because of different activities or at different life-cycle stages or at different time scales. These aggregated causal pathways are generic and have substantial commonality between bioregions and subregions. Four causal pathway groups are specified to be used consistently in BAs:

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

For more detail about these causal pathway groups, as well as the causal pathways within them, refer to companion submethodology M05 (as listed in Table 1) for development of a conceptual model of causal pathways (Henderson et al., 2016).

Conceptual models of causal pathways are developed to characterise the *causal pathways*, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. The conceptual models of causal pathways bring together a number of other conceptual models developed in a BA, for both the baseline and the CRDP. The landscape classes and the hazard analysis are also important inputs to the process. Emphasising gaps and uncertainties is as important as summarising what is known about how various systems work.

The causal pathways play a critical role in focusing a BA on the coal resource development impacts and their spatial and temporal context. They provide a basis for ruling out potential impacts for some combinations of location and assets; for example, a particular type of wetland might be beyond the reach of any type of potential impact given the activities and location of the specific coal resource development in the bioregion or subregion. The causal pathways also underpin the construction of surface water and groundwater models, and frame how the model results are used to determine the severity and likelihood of impacts on water and water-dependent assets.

3.2.3 Conceptual modelling

The conceptual models of the geology and hydrogeology of a bioregion or subregion are critical to the analysis. This ensures that the assessment considers all reasonable possibilities about the geological composition and architecture, and the hydrological components and processes that may occur, even if only the most plausible case is implemented in the hydrological modelling and uncertainty analysis.

The geology and hydrogeology of a bioregion or subregion is complex. The representation in the conceptual model needs to trade-off including detail that may have no material effect on the outcomes with oversimplification that will not survive critical scrutiny. The key guide to choosing an elaboration is to consider its plausibility and potential impact on the final results. Models that are implausible or those that will not materially change the final analysis should not be pursued.

Conceptual modelling of geology and hydrogeology is typically described in product 2.1-2.2 (observation analysis, statistical analysis and interpolation) (where any geological models constructed are described), product 2.3 (conceptual model of causal pathways) and product 2.6.2 (groundwater numerical modelling). The companion submethodologies M05 for developing a conceptual model of causal pathways (Henderson et al., 2016) and M06 for surface water modelling (Viney, 2016) and M07 for groundwater modelling (Crosbie et al., 2016) (as listed in Table 1) also contain important additional detail.

Conceptual models also need to be developed for landscape classes that are potentially impacted. These conceptual models serve a number of purposes in the analysis. They are a communication tool that represents understanding of the systems to assist the Assessment team to discuss potential impacts to the bioregion or subregion. They are also the basis for justifying choices about particular response and impact variables. There are a variety of methods for constructing conceptual models (described in detail in companion submethodology M05 (Henderson et al., 2016), some of which have already been extensively used to describe the potential impacts of CSG extraction and coal mining. All of these techniques are permissible in the initial stages of the conceptual modelling process, but the impact and risk analysis methodology requires that conceptual models are eventually translated into SDGs (Puccia and Levins, 1985) of landscape classes. These allow the Assessment team to develop qualitative mathematical predictions and assess possible direct and indirect ecological impacts.

The construction of qualitative mathematical models for landscape classes and their specific role in receptor impact modelling is described in detail in companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018a).

3.2.4 Hydrological analysis and uncertainty analysis

Surface water models and *groundwater models* are developed and implemented in order to represent and quantify the hydrological systems and their likely changes in response to coal resource development (both baseline and CRDP). Models are developed within the context of the coal resource development, the potential hazards and causal pathways, and the conceptual understanding of the regional hydrology, geology and hydrogeology.

Surface water models are drawn from the Australian Water Resources Assessment (AWRA) modelling suite, which includes the landscape model, AWRA-L, for streamflow prediction and river systems model, AWRA-R, for river routing and management. The rationale for this choice among alternative surface water hydrological models is described in companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016). The river systems model is only used in a subset of bioregions or subregions and depends on the nature of the river regulation and the availability of existing streamflow data. The groundwater modelling is regional, and the choice of model type and coding is specific to a bioregion or subregion depending on data availability and the characteristics of the coal resource development in the area. For more details, refer to companion submethodology M07 (as listed in Table 1) on groundwater modelling (Crosbie et al., 2016).

The hydrological models numerically estimate values for the *hydrological response variables,* which are further analysed and transformed for the impact analysis. The hydrological response variables are subjected to *sensitivity analysis* and *uncertainty analysis,* which test the degree to which each of the model inputs (parameters) affects the model results. It does this by running the model thousands of times and randomly varying the input parameters within a precisely defined set of plausible ranges. The most influential parameters identified are taken into an uncertainty analysis, where more carefully chosen prior distributions for those parameters are propagated through to model outputs.

The potential hydrological changes under the coal resource development futures (baseline and CRDP) are summarised through a set of surface water and groundwater hydrological response variables. Many of these focus on maximum possible change between the baseline and CRDP across the 90-year simulation window (e.g. maximum additional groundwater drawdown). Given the focused uncertainty analyses, these are summarised at computational or model nodes in the surface water and groundwater modelling (products 2.6.1 and 2.6.2) in Component 2. For the impact analysis and reporting, the hydrological response variables are interpolated to the extent of the model domains for surface water and groundwater models.

The hydrological changes may be summarised by one or more *zones of potential hydrological change*. These are described in detail in Section 4.1.1 and consider the thresholds and probabilities across multiple hydrological response variables and define a zone that is useful for reporting against. One important role of the zone of potential hydrological change is to identify landscape classes that need to be investigated further through qualitative modelling and receptor impact modelling. Landscape classes or assets that lie outside of the zone of potential hydrological change are *very unlikely* to experience any hydrological change due to additional coal resource development.

Not all hydrological changes are able to be modelled numerically for reasons that include scale, lack of existing data and model complexity. In some cases hydrological changes may be specified conceptually or based on scientific logic, for example, salinity impacts upstream of a coal mine may not be able to be modelled but may be ruled out of consideration given the known causal pathways and the implausibility of that change occurring.

There is a central focus on characterising the range or distribution of potential outcomes hydrologically (i.e. the surface water or groundwater hydrological effects) by considering the uncertainty as fully as possible in all predictions. For example, groundwater models are run many thousands of times using a wide range of plausible input parameters for many of the critical hydraulic properties, such as the hydraulic conductivity and storage coefficients of all modelled hydrogeological layers. This differs from the traditional deterministic approach used more routinely for surface water and groundwater modelling and is driven by the need for a quantitative representation of the predictive uncertainty through probability distributions that allow BA to consider the likelihood of impacts or effects of a specified magnitude.

The dedicated uncertainty analysis undertaken for the hydrological models within BAs is described in detail in companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016). Full details of the numerical modelling for surface water and groundwater are covered in companion submethodology M06 (Viney, 2016) and companion submethodology M07 (Crosbie et al., 2016), respectively.

3.2.5 Receptor impact models

Receptor impact models are statistical functions that translate the modelled hydrological changes into the distribution of potential ecosystem outcomes that may arise from those changes. Within BAs, 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. For instance, the projected foliage or percent canopy cover might be selected as a receptor impact variable for assessing the condition of riparian or floodplain vegetation communities, and that may be considered to depend on the number of overbank flow events, the number of overbench flow events and the depth to groundwater.

Receptor impact models are relevant to specific landscape classes, and play an essential role in quantifying potential impacts for water-dependent assets that may have ecological or sociocultural value. In the ecological scientific literature, receptor impact models are often known as 'ecological response functions' (Arthington et al., 2010; Overton et al., 2009; Poff and Zimmerman, 2010).

Receptor impact models could be based on empirical data if it existed. In practice the empirical information is usually incomplete so structured elicitation of experts' beliefs is used to integrate expert knowledge into the receptor impact models.

Where available, receptor impact modelling makes a valuable contribution to the impact and risk analysis in a BA. The modelling encapsulates understanding about the impacts of changes in hydrology over the assessment period on potential affected ecosystems and water-dependent assets. It is a key step of the impact and risk analysis as it converts the potentially abstract information about hydrological changes to quantities that stakeholders care about and can more readily understand and interpret. In particular, outcomes of the modelling will relate more closely to their values and beliefs and therefore support community discussion and decision making about acceptable levels of development.

Receptor impact models are relevant to specific landscape classes. They describe the range of possible changes in a receptor impact variable across a landscape class that might be observed for a given hydrological change (i.e. changes to the hydrological response variables). The range of possible changes reflects the experts' uncertainty about the response of the receptor impact variables to a given hydrological change, and the experts' beliefs about the heterogeneity within a landscape class and the variability in response that this creates. The estimated receptor impact variable is thus not the predicted response at a particular assessment unit but rather the predicted response across the landscape class for that hydrological change.

Within BAs examples of receptor impact variables include the projected foliage cover, the abundance of macroinvertebrate families, the presence of tadpoles, mean hyporheic taxa richness, the abundance of riffle breeding frogs, the abundance of hydropsychidae larvae or catfish abundance within a specific spatial frame. Predictions of receptor impact variables become an important line of evidence in assessing potential ecosystem or asset impacts, but should be considered in conjunction with the qualitative mathematical models, broader hydrological changes, local information and other information sources (e.g. data from remote sensing).

Receptor impact modelling and the process for creating receptor impact models is described in detail in companion submethodology M08 (as listed in Table 1) (Hosack et al., 2018a). This includes a dedicated tabulation of their assumptions, and the implications of those assumptions.

4 Impact and risk predictions for assets and landscape classes

4.1 Predictions at assessment units

The design choice that requires hydrological predictions to be possible at any location in the landscape (described in Section 2.3.5) outlines the importance of being able to make predictions at individual locations (nominally assessment units) as part of the impact and risk analysis. These predictions are central to the workflow illustrated in Figure 7.

4.1.1 Hydrological response variables

Surface water and groundwater hydrological models make predictions of the hydrological response variables at model nodes or stream nodes. The range or distributions of these predictions are typically summarised by a series of percentiles – nominally the 5th through to the 95th in 5% increments.

For groundwater, the predictions of individual percentiles of maximum drawdown are interpolated to the assessment units to provide complete coverage across the assessment extent. Details of this allocation or interpolation are described in Section 4.1.1.1. This means that it is possible to represent the median (50th percentile), for instance, of maximum drawdown under the baseline and under the coal resource development pathway (CRDP), and the difference in drawdown that is attributable to additional coal resource development in the bioregion or subregion.

More generally, the 5th, 50th and 95th percentiles are used to represent the predictive uncertainty for drawdown and provides the ability for the reader to bound the potential drawdown. While the 50th percentile represents the centre of the distribution for maximum groundwater drawdown, the 5th and 95th percentiles provide the lower and upper bounds. For any given assessment unit in the modelled domain, it is *very unlikely* that drawdown will either be smaller than the 5th percentile or exceed the 95th percentile.

For surface water, a series of interpolation rules are created that map the predictions of percentiles at stream nodes to stream reaches or links. Assessment units that intersect with the reaches or links can then access the predictions from that reach or link. In some cases it is not possible or appropriate to interpolate between certain stream nodes or beyond some modelled stream nodes. For example, it is typically difficult to interpolate volumetric surface water hydrological response variables beyond modelled stream nodes to headwater streams given the changes in flow.

The allocation or interpolation for surface water is described in more detail in Section 4.1.1.1, with any subregion-specific differences documented in product 3-4 (impact and risk analysis).

The hydrological changes may be summarised by one or more *zones of potential hydrological change* as discussed in Section 3.2.4.

A meaningful change in drawdown is defined in all bioregional assessments (BAs) as the area with at least a 5% chance of exceeding 0.2 m drawdown in the relevant aquifer. Groundwater impacts of coal mines and CSG projects are regulated under state legislation and state regulatory and management frameworks. The 0.2 m drawdown threshold adopted in BAs is consistent with the most conservative minimal impact threshold under the *NSW Aquifer Interference Policy* (NSW Office of Water, 2012) and Queensland's *Underground water impact report for the Surat Cumulative Management Area* (DNRM, 2016).

For surface water, the zone of potential hydrological change is defined across the nine hydrological response variables listed in Table 3. For the 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 change at any location is if there is at least a 5% chance of there being at least a 1% change in the variable. That is, if 5% or more of model replicates show a maximum difference between CRDP and baseline projections of 1% or more (relative to the baseline value). For four of the frequency-based metrics (high-flow days (FD), low-flow days (LFD), length of low-flow spell (LLFS) and zero-flow days (ZFD)), the threshold change at any location is if there is a greater than 5% chance of there being a maximum change in the variable of at least 3 days in any year. For the final frequency-based metric (low-flow spells (LFS)), the threshold change at any location is if there is a greater than 5% chance of there being a change in the variable of at least two spells in any year. There are many surface water hydrological response variables to weigh up, and a consideration needs to be made as to whether the interest is in a subset of surface water hydrological response variables or changes across any of them.

Table 3 Thresholds for individual surface water hydrological response variables used to define the surface water zone of potential hydrological change

Hydrological response variable	Units	Description	Threshold
AF	GL/year	The volume of water that discharges past a specific point in a stream in a year. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	≥5% chance of ≥1% change in AF
P99	ML/day	Daily flow rate at the 99th percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	≥5% chance of ≥1% change in P99
IQR	ML/day	Interquartile range in daily flow; that is, the difference between the daily flow rate at the 75th percentile and at the 25th percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	≥5% chance of ≥1% change in IQR
FD	days	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 (from 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'.	≥5% chance of a change in FD ≥3 days in any year
P01	ML/day	Daily flow rate at the 1st percentile. This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102).	≥5% chance of ≥1% change in P01 and change in runoff depth >0.0002 mm
ZFD	days	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).	≥5% chance of a change in ZFD ≥3 days in any year
LFD	days	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.	≥5% chance of a change in LFD ≥3 days in any year
LFS	number	Number of low-flow spells per year (perennial streams only). This is typically reported as the maximum change due to additional coal resource development over the 90-year period (from 2013 to 2102). A spell is defined as a period of contiguous days of flow below the 10th percentile threshold.	≥5% chance of a change in LFS ≥2 spells in any year
LLFS	days	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).	≥5% chance of a change in LLFS ≥3 days in any year

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 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).

While there is the intention is to be conservative in defining this zone of potential hydrological change in BA so that there is confidence in areas and water-dependent assets that are assessed as not impacted, it is possible in principle to repeat the process with different thresholds (and that speak to specific values that are important to key users) given the model data will be publicly available on data.gov.au.

Landscape classes or assets that lie outside of the zone of potential hydrological change are *very unlikely* to experience any hydrological change due to additional coal resource development. Where an asset or landscape class, either wholly or partially, intersects with the zone of potential hydrological change, there is the potential for impact. It is important to stress that this does not imply that there is impact – only that it cannot be ruled out on the basis of the hydrological change and that further investigation is required using qualitative mathematical modelling, receptor impact models and other lines of evidence. That further work also involves considering the nature of the water dependency of particular landscape classes within the zone of potential hydrological change. If a landscape class is not considered water dependent (e.g. ‘Production from dryland agriculture and plantations’), then potential impacts to that landscape class may be ruled out.

Multiple zones of potential hydrological change can be considered and reported against. Given the number of near-surface assets, the most important zone relates to the hydrological changes in the uppermost geological layers using spatially explicit, probabilistic estimates of hydrological change from the regional groundwater models. For the purposes of BA, this is known as the *regional watertable* and is used to assess potential impacts to key surface ecosystems (landscape classes (except springs), ecological assets and sociocultural assets). In the case of groundwater bores and springs, it is important to determine the source aquifer of each individual bore or spring for the impact and risk analysis. The source aquifer for each bore or spring is identified from existing datasets. Where this information is not available, the assessment will typically assume that the bores or springs access the shallowest hydrogeological layer in that assessment unit (i.e. the regional watertable). It is, however, important that this is noted as it may have implications for the impact and risk analysis; for example, if it is not known which aquifer a spring or bore accesses, it is not possible to complete quantitative assessment for springs and bores.

4.1.1.1 Allocating modelling node results to assessment units

Surface water and groundwater modelling and uncertainty analyses are completed at specific points in the landscape called nodes. For the impact and risk analysis, it is necessary to interpolate those modelling results across the assessment extent so that inferences can be made about potential changes that may be experienced by particular ecosystems (landscape classes) and water-dependent assets. This is achieved by defining a zone of potential hydrological change, based on the union of a groundwater zone of potential hydrological change and a surface water zone of potential hydrological change, and allocating (where relevant) a groundwater modelling node and a surface water modelling node to every assessment unit within that zone.

The allocation of groundwater nodes to an assessment unit is achieved by selecting the node closest to the centroid of the assessment unit. This selection is manually checked to ensure the linking is hydrogeologically sound (e.g. to avoid selecting nodes that cross important geological boundaries).

Surface water modelling interpolation is achieved through a process of allocating node results to river reaches that extend upstream and/or downstream from the point of an individual modelling node. The first step is to select a spatial line network to represent the streams of the region. This stream network is broken into sections named reaches, as per the surface water conceptual model of the bioregion or subregion.

Initial assessment units are selected by way of their intersection with a buffered version of the stream reaches network. The size of the buffer is bioregion- or subregion-specific choice and is selected by expert judgement and informed by the specific landscape attributes of the bioregion or subregion. A further selection of assessment units is applied to include neighbours that are considered hydrologically connected by way of their intersection with water-dependent landscape class features, such as lowland streams, upland streams or floodplains.

At this stage, each reach is allocated one of four values: *modelled impact* via a modelled node, *potentially impacted* but not modelled, *no impact*, or an *unknown impact* as the reach was not part of the original conceptual model. These reach attributes determine their connection and status within the impact and risk analysis calculations.

To complete the process, all assessment units selected within the surface water subset of the zone of potential hydrological change are allocated a stream reach to determine the potential impact. The stream reach to assessment unit relationship is exclusively 1:1 and governed by the following hierarchical rule set. Units within the surface water zone of potential hydrological change but no intersecting reaches are allocated the nearest reach. Units containing a single intersecting reach are allocated that reach. For units with multiple intersecting reaches, a priority allocation is applied as: modelled change, assumed change (potential impact), modelled no change, or assumed no change.

The combination of assessment units that make up the surface water zone of potential hydrological change is reviewed by hydrology experts to ensure that assessment unit selections are hydrologically valid.

The selection of all assessment units included within both the surface water and groundwater modelled areas creates the zone of potential hydrological change upon which the impact and risk analysis is completed.

4.1.2 Receptor impact variables

Receptor impact models make predictions about the response of receptor impact variables (ecosystem indicators) to one or more hydrological response variables. When the range or distribution of possible changes in those hydrological response variables is considered, and translated using a receptor impact model, it results in a distribution of receptor impact variable predictions. This distribution represents the range of possible outcomes for the receptor impact variable and incorporates the uncertainty in both the hydrological response variables and the uncertainty in the ecosystem response to that hydrological change as characterised by the uncertainty in the receptor impact model (Section 3.2.5).

Predictions can be made at an assessment unit based on the changes in those hydrological response variables at that assessment unit. It is important to note that those predictions are a predicted response *across* the landscape class for the local hydrological change in that assessment unit. They thus represent the predicted response in the receptor impact variable for all locations across the landscape class given that level of hydrological change.

These predictions may be extended to areas of interest (e.g. stretches of river) by applying the receptor impact models at different assessment units and using the changes in hydrological response variables at each of those assessment units. Landscape class scale is the natural level of aggregation given that the elicitation for the receptor impact models is conducted at that scale. The aggregation to the landscape levels weights the contribution of each assessment unit by the amount of the landscape class contained in each assessment unit. This weight could be linear, as in the case of landscape classes defined by stream reaches, or by area, as in the case of some groundwater-dependent forested landscape classes.

The receptor impact variables and hydrological response variables used in the receptor impact modelling are selected using the qualitative mathematical modelling (see Section 2.3.10.2), and are summarised in Table 4 and Table 5, respectively. The hydrological response variables are based on the averages over the short term (2013 to 2042) and long term (2073 to 2102) rather than the maximum change over the 90-year simulation period as used for the standard hydrological response variables (Table 3).

Table 4 Summary of the hydrological response variables used in the receptor impact models

This is the entire suite of hydrological response variables used in bioregional assessments; each subregion uses only a subset of these hydrological response variables.

Hydrological response variable	Definition of hydrological response 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). This is typically reported as the maximum change due to additional coal resource development.
tmaxRef	The year that the maximum difference in drawdown relative to the reference period (1983 to 2012) (dmaxRef) occurs
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.
EventsR0.2	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 0.2 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.
EventsR2.0	The mean annual number of events with a peak daily flow exceeding the threshold (the peak daily flow in flood events with a return period of 2.0 years as defined from modelled baseline flow in the reference period (1983 to 2012)). This metric is designed to be approximately representative of the number of overbank flow events in future 30-year periods. This is typically reported as the maximum change due to additional coal resource development.
LME	The maximum length of spells (in days per year) with low flow, averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.
LQD	The number of days per year with low flow (<10 ML/day), averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.
QBFI	Ratio of total baseflow generation to total streamflow generation, averaged over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.
ZMA	The maximum length of spells (in days per year) with zero flow over a 30-year period. This is typically reported as the maximum change due to additional coal resource development.
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.
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.

Table 5 Summary of the receptor impact variables used in the receptor impact models

Receptor impact models may use all or a subset of the stated hydrological response variables for each receptor impact variable.

Receptor impact variable (with associated sample units)	Hydrological response variables
Annual mean percent canopy cover of woody riparian vegetation (predominately *Casuarina cunninghamiana, Melia azedarach, Eucalyptus amplifolia, E. tereticornis* and *Angophora subvelutina*) in a transect 20 m wide and 100 m long covering the bottom of the stream bench to the high bank	dmaxRef tmaxRef EventsR0.3 EventsR3.0
Annual mean projected foliage cover (m^2/m^2) of sclerophyll forest (predominately *Angophora costata*, *Corymbia gummifera*, *Eucalyptus capitellata*, *Banksia spinulosa*) in a 0.25 ha plot	dmaxRef tmaxRef
Mean annual projected foliage cover (m^2/m^2) of woody riparian vegetation (predominately *Eucalyptus tereticornis, Casuarina cunninghamiana* and *Eucalyptus camaldulensis*) in a 0.25 ha transect extending from the channel to the top of the bank (including floodplain overbank)	dmaxRef tmaxRef EventsR0.3 EventsR3.0
Annual mean percent foliage cover of woody riparian vegetation (target species include *Eucalyptus camaldulensis* and *Melaleuca* spp.) in a transect 10 to 15 m wide and 100 m long covering the stream channel to the top of the stream bank	dmaxRef LQD EventsR2.0
Annual mean projected foliage cover of forests dominated by river red gum (*E. camaldulensis*)	EventsR3.0 dmaxRef tmaxRef
Annual mean projected foliage cover of species group that includes: Casuarina, yellow box, Blakely's red gum, *Acacia salicina*, *Angophora floribunda*, grey box. Transect of 50 m length and 20 m width that extends from first bench ('toe') on both sides of stream	EventsR3.0 dmaxRef tmaxRef
Annual mean projected foliage cover of species group that includes: yellow box, white cypress pine, Eucalyptus crebra, dirty gum, Blakely's red gum, *Angophora floribunda*, *Eucalyptus fibrosa*, fuzzy box. Transect of 50 m length and 20 m width that extends from first bench ('toe') on both sides of stream	ZQD dmaxRef tmaxRef
Mean abundance of larvae of the Hydropsychidae family (net-spinning caddisflies) in a 1 m^2 sample of riffle habitat	ZQD ZMA
Annual mean abundance (30 years, >33 sites/year) of the mayfly *Offadens* (family Baetidae), 3 months after the wet season in a 2 m × 0.5 m (1 m^2) area of riffle habitat	LQD LME
Mean abundance of the eel-tailed catfish (*Tandanus tandanus*) in a 600 m2 transect (100 m by 6 m) whose long axis lies along the mid-point of the stream	ZQD QBFI
Mean probability of presence of the riffle-breeding frog (*Mixophyes balbus*) in a 100 m transect	ZQD ZMA
Probability of presence of tadpoles from *Limnodynastes* genus (species *dumerilii*, *salmini*, *interioris* and *terraereginae*), sampled using standard 30 cm dip net	EventsR3.0 ZQD ZME
Average number of families of aquatic macroinvertebrates in riffle habitat sampled using the NSW AUSRIVAS method for riffles	ZQD ZME
Average number of families of aquatic macroinvertebrates in instream pool habitat sampled using the NSW AUSRIVAS method for pools	ZQD dmaxRef tmaxRef
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)	ZQD ZMA

The hydrological response variables that are used in the receptor impact models are also based on the suite of runs of the surface water and groundwater hydrological models rather than the percentile summaries described in Section 4.1.1. The reason for this is that the runs preserve the correlation (dependence) between the individual hydrological response variables. This means when receptor impact models use two or more hydrological response variables, realistic combinations of hydrological response variables occur with the correct frequency. For instance, if the number of overbank and overbench events are positively correlated (or more generally positively dependent), it would be more likely that if one event measure is high (or low) then the other is also likely to be high (or low). If each hydrological response variable is treated independently, that correlation constraint is not considered and the enhanced frequency of high (or low) overbank flows and high (or low) overbench flows is lost in the simulations

While the surface water and groundwater models are loosely coupled, the runs operate on different time steps and the dependence between individual surface water and groundwater runs is maintained. For the surface water hydrological response variables used in receptor impact modelling the correlation is maintained within high-flow hydrological response variables and low-flow hydrological response variables but not between them. In practice this is of no consequence as individual receptor impact models are almost always constructed using either low-flow or high-flow hydrological response variables but not both.

4.2 Predictions for landscape classes and assets

The overarching purpose of BAs is to quantify potential impacts and risks to water resources and water-dependent assets due to coal resource development. This requires predictions of potential hydrological changes (through *hydrological response variables*) and potential ecosystem change (through *receptor impact variables*) to be made at locations (assessment units) that are relevant to that water resource or asset and at key points in time.

Predictions across the extent of an individual water resource or a water-dependent asset can then be aggregated or presented in various ways to create a summary of impact or risk. If those locations are representative of the water resource or asset then a simple unweighted summary across those locations is representative.

Landscape classes have been introduced as a classification of biophysical ecosystems in response to the large numbers of assets. Within a landscape class the ecosystem is expected to be relatively homogenous in the key hydrological drivers and how it responds to them – relative to the differences between landscape classes. To a large degree individual landscape classes can be considered as an ‘ecosystem asset’ and the prediction and summary challenges relevant to landscape classes are also relevant to water-dependent assets. To assess potential impacts on and risks to a landscape class requires predictions to be made at locations that are relevant to that landscape and at key points in time. If predictions are made across a set of locations that are representative, they may be aggregated and summarised to emphasise the potential impact and risk.

While water-dependent assets and landscape classes may be polygonal (e.g. groundwater-dependent vegetation ecosystems), linear (e.g. parts of a stream ecosystem) or points (e.g.

individual springs), the concept of aggregating or summarising across those assessment units that pertain to that asset or landscape class persists. Chapter 6 outlines some of the specific choices for reporting and communicating the predicted impacts and risks for landscape classes and assets.

4.3 Systematically processing the data

There are a very large number of multi-dimensional and multi-scaled datasets that are used in the impact and risk predictions, and the analysis more generally, for each BA. These include model outputs, and ecological, economic and sociocultural data from a wide range of sources. Part of the approach used to manage these multiple dimensions and produce meaningful results is to adopt a clear spatial framework as an organising principle. While the inherently spatial character of every BA is important and must be addressed, it is also essential that the temporal and other dimensions of the analysis do not lose resolution during data processing. For example, knowing where a potential impact may take place is obviously important, but so is knowing what kind and level of impact and which assets may be affected.

The design of the system for ingesting, managing and producing data useful for analysis purposes is based on a spatially-enabled open source relational database (PostGRES) with strong provenance tracking capability. The data are organised into *impact and risk analysis databases* to enable efficient management. Only data that are registered as datasets at data.gov.au are ingested and used. There are multiple stages of processing the data to ensure compliance with the information model and database normalisation requirements.

The purpose of the databases is to produce result datasets that integrate the available modelling and other evidence across the assessment extent of the BAs. The resulting datasets are required to support the BA analyses. These data are delivered to the Assessment teams as a series of queries the teams have developed in collaboration with the database management team. These queries can be loaded by the Assessment teams into data analysis software, such as ArcGIS, QGIS, and statistical analysis environments, such as R and Python.

Appendix A provides further detail about the approach undertaken to manage this data and the queries required from it. The following sections explain the analyses the Assessment teams need to produce, with detail on how to communicate and report the results.

5 Reporting and communicating impacts and risks

5.1 Overview

Barrett et al. (2013) (the BA methodology) considered the impact and risk analysis as separate but intimately linked components (see Figure 1). As the BA methodology has been applied to particular assessments it has made sense to combine the impact analysis (Component 3) and risk analysis (Component 4) and present a joint product 3-4 (impact and risk analysis).

The impact analysis quantifies the magnitude or extent of the hydrological or ecosystem change that may eventuate from coal resource development. This includes considering indirect impact and cumulative impacts. The risk analysis is related but considers not only the magnitude and extent of the potential change (or impact), but also the likelihood of that impact eventuating.

5.2 Impact and risk profiles

The development through Component 1: Contextual information and Component 2: Model-data analysis (Figure 3) provides the foundations for assessing potential impacts and risks to water resources and water-dependent assets due to coal resource development in a bioregion or subregion. The subsequent prediction of potential hydrological changes (via hydrological response variables) and ecosystem changes (via receptor impact variables amongst other lines of evidence), and the consideration of the magnitude and likelihood of specific changes, enables the impacts and risks to be quantified.

Across the four components of a full BA this results in a substantial information base that includes coal resource developments, hazards and causal pathways, asset registers and asset classes, landscape classes and landscape groups, predictions of hydrological change, and predictions of ecosystem change. There are challenges to summarise and synthesise this information base in a structured and insightful manner.

The information base, and the impact and risk analysis, are reported and communicated in three profiles for a bioregion or subregion. These are summarised in Figure 8 and include:

- a characterisation of the *hydrological impact*, including the summary of changes in the hydrological response variables, the identification of one or more zones of potential hydrological change, and a discussion of changes that are in scope but that are not modelled quantitatively
- a *landscape class profile*, which rules out landscape classes that are outside the zone of potential hydrological change. For landscape classes within the zone, the profile assesses the hydrological changes (through hydrological response variables) and the ecological changes (through receptor impact variables) that individual landscape classes may experience. Note that receptor impact models may be developed for a prioritised subset of landscape classes

within the zone, with the landscape class priority governed by factors such as the spatial extent, legislative significance and the availability of external scientific expertise for the qualitative mathematical modelling or expert elicitation

- an *asset profile*, which summarises potential hydrological changes for surface water and groundwater economic assets and rules out ecological assets that are outside the zone of potential hydrological change. For ecological assets within the zone of potential hydrological change, the changes individual assets may experience are summarised by hydrological response variables (for hydrological changes) and receptor impact variables (for ecological changes).

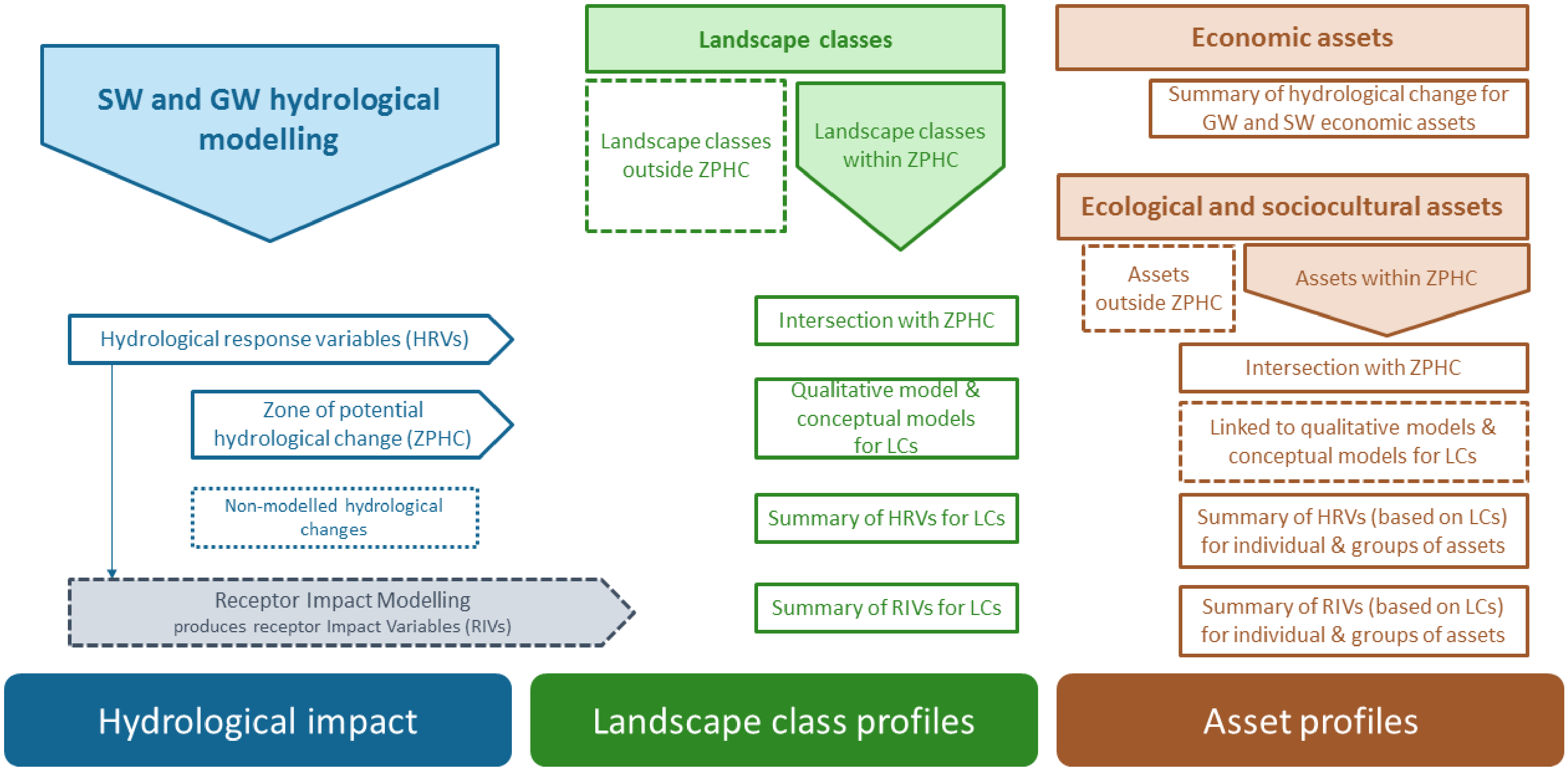

Figure 8 Summary of three core components of the impact and risk analysis – a summary of the potential hydrological change, an impact profile through the landscape classes and groups, and an impact profile through economic, ecological and sociocultural water-dependent assets

GW = groundwater; LC = landscape class; SW = surface water

Different BAs may use subsets of these profiles. For instance, if no receptor modelling is conducted, the assessment of change for ecological assets and landscape classes is limited to summarising the changes in the hydrology that ecological asset and landscape class may experience.

The focus on ruling out potential impacts is emphasised in all three profiles in Figure 8. The hydrological analyses define a zone of potential hydrological change beyond which meaningful hydrological changes are considered *very unlikely* (less than 5% chance of exceeding the given change beyond the zone based on the distribution of modelled predictions). Those landscape classes and assets that do not intersect with the zone of potential hydrological change are ruled out from potential impacts and not analysed further. Where there is intersection, asset or landscape class centric summaries are necessary for hydrological response variables and receptor impact variables that are available and pertinent to that asset or landscape class. For the most part, that relevance is determined by the qualitative mathematical model and receptor impact modelling for the landscape class.

In bioregions or subregions without relevant modelled or empirical data, the impact and risk analysis needs to work within the constraints of the available information and the scale of the analysis while respecting the aspirations and intent of the BA methodology. This might mean that the uncertainties are large enough that no well-founded inferences can be drawn – that is, the hazards and potential impacts cannot be positively ruled out.

The structure within product 3-4 (impact and risk analysis) directly follows the three impact profiles in Figure 8. The following subsection provides additional guidance around each of these profiles.

5.2.1 Hydrological impacts

The focus of this profile is on describing the surface water and groundwater hydrological changes at regional scale. It should use the hydrological response variables that are routinely available across the bioregion or subregion and seek to provide additional interpretation and context over product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling) by considering the hydrological implications of any changes. For instance, is it likely that a perennial stream may become more intermittent based on changes to the hydrological response variables?

As part of that narrative it is important to characterise the hydrological changes that may eventuate across the bioregion or subregion under the baseline coal resource development (baseline). While the primary focus of BA is on the impacts that may be attributable to additional coal resource development, the implications of that impact may depend critically on the potential hydrological changes that are already occurring under baseline (i.e. the implication of an additional 0.80 m of drawdown may be quite different if the drawdown under baseline is 0.5 m, 5 m or even 50 m).

Context may come from other sources as well. For instance, putting the hydrological change due to additional coal resource development in the context of the interannual variability will allow the reader to appreciate if the changes that may occur due to additional coal resource development are already experienced by the ecosystem. If that ratio is small, this suggests any change due to coal resource development is swamped by the interannual variability.

A primary focus of this section is on understanding the potential hydrological changes due to additional coal resource development, and using those to define a zone of potential hydrological change that encapsulates potential surface water and groundwater changes. Once defined it provides a key filter for ruling out potential impacts. Landscape classes or assets that fall outside the zone of potential hydrological change are assessed as being *very unlikely* to have any impact. For landscape classes that are either partially or wholly within the zone of potential hydrological change further investigation is required and is described in Section 5.2.2 and Section 5.2.3.

Throughout the hydrological analysis the intent should be to try to characterise and understand predictions of hydrological response variables. It is much less about the attribution, and what particular causal pathway contributed the change, as the modelling integrates different causal pathways, and much more about the effect itself and understanding it relative to the interannual variability that is experienced under baseline. Where possible, it is valuable to identify specific causal pathways because it may assist with mitigation strategies and inform monitoring that should be undertaken.

It is essential to frame the hydrological analysis more broadly than modelled work because that aligns with the intent and breadth of the hazard analysis. All in-scope hazards should be considered whether that be by numerical hydrological modelling, site-based management processes or other processes. For instance, while changes in salinity are not modelled by surface water and groundwater models in BAs, it is important to draw on existing knowledge and understanding of key system processes and concepts to provide the input to a qualitative analysis. As another example, in many cases parts of the stream network cannot be modelled or interpolated from the existing model nodes but may experience impacts. It is essential that these impacts (and those to any associated ecosystems) are identified and carried through in the analysis even though they cannot be quantified.

5.2.2 Landscape class profile

The landscape class profile considers impacts and risks to landscape classes. The underpinning landscape classification summarises the surface ecosystems with similar physical, biological and hydrological characteristics. It is a key construct in addressing the large number of water-dependent assets, reducing some of the complexity to focus on the important processes, functions and interactions, and in addressing the needs of a regional-scale assessment. It is the resolution at which receptor impact models are developed and applied. From an impact and risk perspective the landscape classification is a crucial vehicle for understanding and communicating potential impacts through their more aggregated system-level view.

For an individual landscape class, a primary question is whether that landscape class intersects with the zone of potential hydrological change. Landscape classes or assets that lie outside of the zone of potential hydrological change are *very unlikely* to experience any hydrological change due to additional coal resource development. The assessment consequently infers there are no potential ensuing impacts to that landscape class, and those parts of water-dependent assets that are within that landscape class, on the basis of those hydrological changes considered within BAs.

Where a landscape class, either wholly or partially, intersects with the zone of potential hydrological change, there is the potential for impact. This does imply that there is impact, only that it cannot be ruled out on the basis of the analysis thus far. It is useful to summarise that intersection, and characterise the extent of the landscape class that is within the zone of potential hydrological change compared to that part that is outside and thus *very unlikely* to experience any hydrological change. This task is sometimes termed an ‘overlay analysis’ within BA. There are times when the spatial context may be important. For instance, if an entire landscape class is contained within the zone it may receive additional scrutiny.

The qualitative mathematical model for a landscape (Section 2.3.10; and companion submethodology M08 (as listed in Table 1) for receptor impact modelling (Hosack et al., 2018a)) identifies the important hydrological drivers (hydrological response variables) for that landscape class. The receptor impact modelling process also identifies key ecosystem indicators (receptor impact variables) from the qualitative mathematical model and expert consultation. Receptor impact models subsequently make predictions of those receptor impact variables for all locations (with the required modelled hydrology) within the landscape class.

Characterising the potential impacts to a landscape class involves summarising the: (i) potential hydrological changes that landscape class may experience (via landscape class specific hydrological response variables which may differ from some of the routinely calculated hydrological response variables used in the surface water and groundwater modelling; see Table 4), and (ii) the potential ecosystem change that landscape class may observe (via landscape class specific receptor impact variables). Those summaries can be in the form of:

- maps of landscape classes that show predictions of hydrological response variables or receptor impact variables at individual assessment units
- tables or figures that summarise the extent of the landscape class that may receive varying categories of changes in those specific hydrological response variables and receptor impact variables. This extent may be summarised as an area for polygon landscape classes, length for linear landscapes classes (e.g. riverine), or counts for point landscape classes (e.g. springs) depending on the nature of the landscape class
- an aggregated summary of change in hydrological response variables or receptor impact variables across that landscape class (e.g. contrasting distributions of a receptor impact variable between the baseline and CRDP). Composite maps of risk across multiple receptor impact variables for a landscape class or landscape group may be used to provide a spatial context to potential risk, and indicate where future effort should be directed.

These options are summarised in Figure 9. Given that there are predictive distributions for the potential change in the hydrological response variables and the receptor impact variables, there are choices to be made as to how those distributions are summarised through maps, tables or figures. The approach adopted is use the 5th, 50th and 95th percentiles or the equivalent framed in terms of exceedance probabilities.

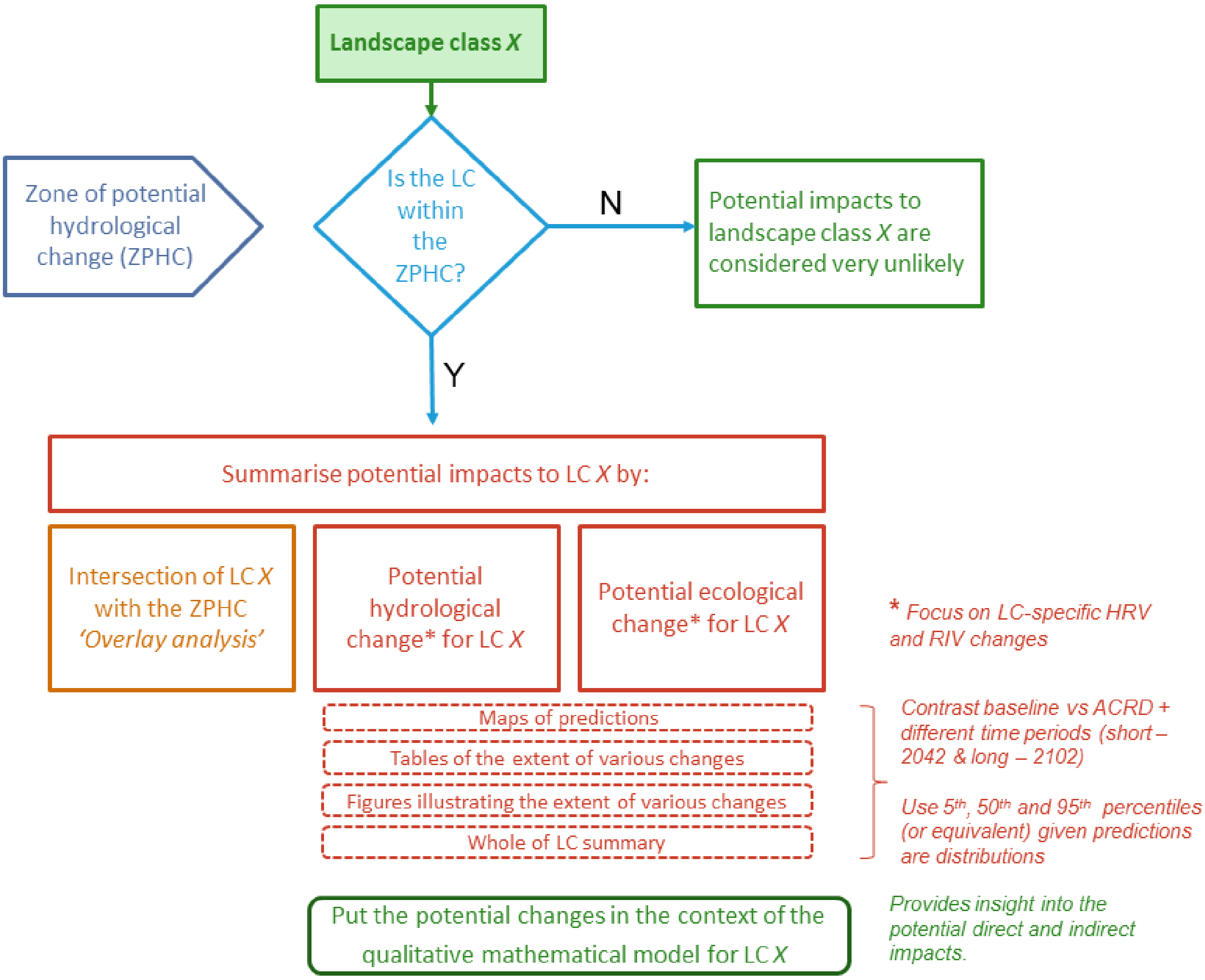

Figure 9 Landscape class summary of potential impacts

ACRD = additional coal resource development; HRV = hydrological response variable; LC = landscape class; RIV = receptor impact variable

For predictions of receptor impact variables it is important to note that these predictions represent the predicted change in receptor impact variables across the landscape class for that change in hydrological response variable at that assessment unit. These do not represent predictions of receptor impact variables at that location, but rather the average prediction across the landscape class for that change in hydrology.

Throughout these summaries there are two key contrasts for each landscape class. The first contrast is between the predictions of the hydrological response variables or receptor impact variables under the baseline against those changes attributable to additional coal resource development. If there are changes under the baseline, this may indicate the potential for ecosystem change irrespective of additional coal resource development. Where the changes attributable to additional coal resource development are evident, this may indicate the effect of those additional coal mines or CSG operations.

The second contrast is between the two time points – the 30 years to 2042 as an indication of potential impacts near peak production, and the 30 years to 2102 as an indication of potential enduring impacts from coal resource development in the bioregion or subregion.

5.2.2.1 Example: Maranoa-Balonne-Condamine subregion

Figure 10, Figure 11 and Table 6 present a (draft) example from the ‘Non-floodplain or upland riverine (including non-GAB GDEs)’ landscape group within the Maranoa-Balonne-Condamine subregion. The ‘Non-floodplain or upland riverine (including non-GAB GDEs)’ landscape group includes ecosystems that are dependent on upland streams and wetlands that are not associated with alluvial systems and non-Great Artesian Basin groundwater-dependent ecosystems (non-GAB GDEs). There are nine landscape classes within the ‘Non-floodplain or upland riverine (including non-GAB GDEs)’ landscape group. Refer to product 2.3 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2016) for further description of the landscape classes.

Figure 10 focuses on additional coal resource development around two mines – an expansion at New Acland and a new mine at ‘The Range’. The groundwater zone of potential hydrological change is highlighted in orange. The ‘Non-floodplain or upland riverine (including non-GAB GDEs)’ landscape group within the zone is shaded by the groundwater drawdown attributable to additional coal resource development. This represents some of the change in hydrology that may be experienced by this landscape group that is attributable to additional coal resource development. While only groundwater changes are modelled in the Maranoa-Balonne-Condamine subregion, in other bioregions and subregions hydrological response variables that are identified as important to the landscape class (or group) of interest should also be shown in this way. In areas where there is no change in hydrological response variables the inference would be that there is no change in the receptor impact variables and therefore no impact expected for that landscape class.

Figure 11 presents the cumulative area or length of the ‘Non-floodplain or upland riverine (including non-GAB GDEs)’ landscape group that will receive varying levels of drawdown for groundwater predictions at the 5th, 50th and 95th percentiles. For groundwater drawdown, the 5th percentile can be interpreted as saying that it is *very likely* that at least this area or length will receive a given level of drawdown. The 95th percentile means that it is *very likely* that at most this area or length will receive a given level of drawdown. Figure 11 aggregates the cumulative areas or lengths across the nine landscape classes in the landscape group. The bottom panels in Figure 11 present a scatterplot of the additional drawdown versus the baseline drawdown by assessment unit. This representation makes it possible to see the interaction between the two drawdowns, and indeed if additional drawdown coincides with areas already receiving drawdown under baseline or not.

Table 6 cross tabulates the areas and lengths within the ‘Non-floodplain or upland riverine (including non-GAB GDEs)’ landscape group for three specific choices of additional drawdown (>0.2 m, >2 m and >5 m) and for the groundwater predictions at the 5th, 50th and 95th percentiles. A similar table can be created for the baseline drawdown. The tabulated areas and lengths can be extracted visually from Figure 11 but are much clearer in Table 6.

Analogous cumulative tables and figures can be created for other hydrological response variables and equally receptor impact variables that are relevant to the ‘Non-floodplain or upland riverine (including non-GAB GDEs)’ landscape group. The intent with each table or figure is to highlight areas or lengths that may experience varying levels of change in hydrological response variables or receptor impact variables under both the baseline and due to additional coal resource development.

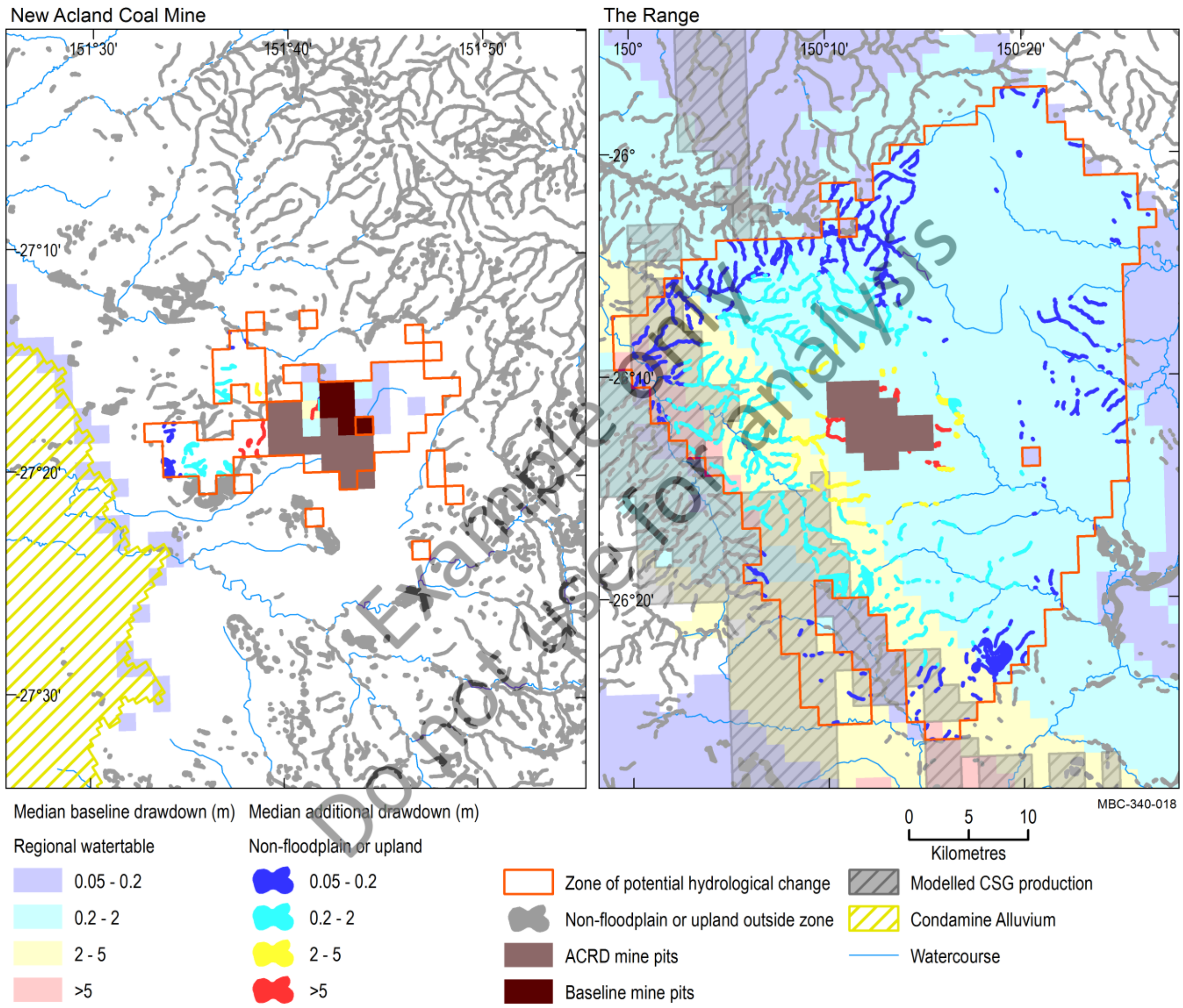

Figure 10 'Non-floodplain or upland riverine (including non-GAB GDEs)' landscape group: location of remnant vegetation and stream network contained within the zone of potential hydrological change in the Maranoa-Balonne-Condamine subregion

Example only; do not use for analysis. This is an early draft of a figure published in companion product 3-4 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2017). See Holland et al. (2017) for full explanation and interpretation of the final results, which might vary from that shown here.
Median is the 50th percentile. Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development. Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development. Landscape classes within operational and proposed pits are not included in this analysis. ACRD = additional coal resource development, CSG = coal seam gas, GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem

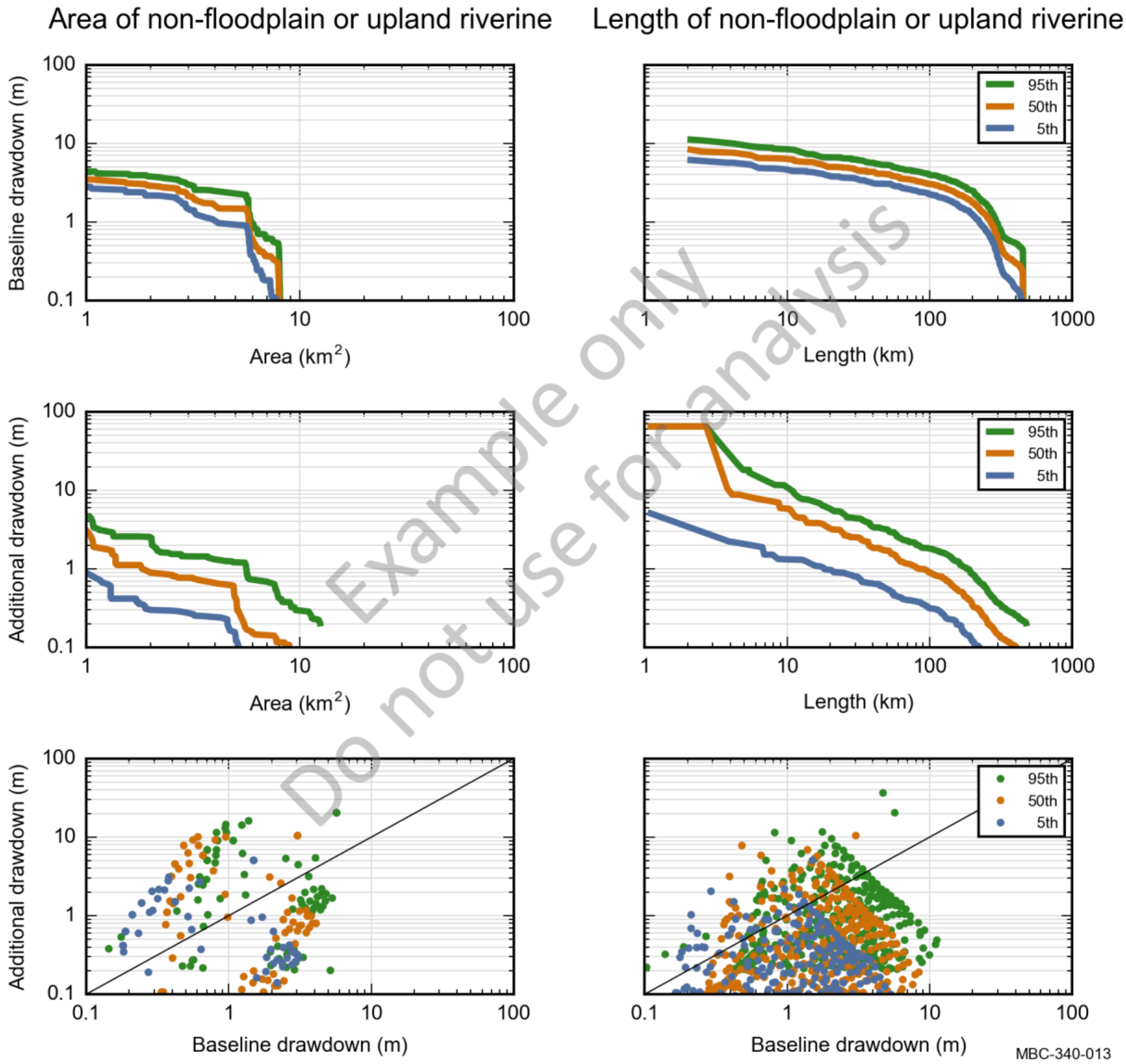

Figure 11 'Non-floodplain or upland riverine (including non-GAB GDEs)' landscape group: area (km^2) and stream network length (km) that exceed the 5th, 50th and 95th percentile estimates of baseline drawdown and additional drawdown within the zone of potential hydrological change in the Maranoa-Balonne-Condamine subregion

Example only; do not use for analysis. This is an early draft of a figure published in companion product 3-4 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2017). See Holland et al. (2017) for full explanation and interpretation of the final results, which might vary from that shown here.
Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development. Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development. Landscape classes within operational and proposed pits are not included in this analysis. GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem

Table 6 'Non-floodplain or upland riverine (including non-GAB GDEs)' landscape group: area (km^2), stream network length (km) and number of springs (number) that exceed the 5th, 50th and 95th percentile estimates of baseline drawdown within the zone of potential hydrological change for the Maranoa-Balonne-Condamine subregion

Landscape class	Extent within assessment extent	Extent within zone of potential hydrological change	Extent with baseline drawdown >0.2 m			Extent with baseline drawdown >2 m			Extent with baseline drawdown >5 m		
			5th	50th	95th	5th	50th	95th	5th	50th	95th
Non-floodplain non-GAB GDE (km^2)	2551.1	11.1	4.0	4.5	11.1	0.3	0.9	1.7	0.0	0.3	0.8
Non-floodplain non-GAB GDE, near-permanent wetland (km^2)	2.9	0.0	–	–	–	–	–	–	–	–	–
Non-floodplain non-GAB GDE, temporary wetland (km^2)	32.8	0.0	–	–	–	–	–	–	–	–	–
Non-floodplain, near-permanent wetland (km^2)	46.6	0.5	0.3	0.4	0.5	0.0	0.1	0.2	0.0	0.1	0.1
Non-floodplain, temporary wetland (km^2)	195.2	0.9	0.3	0.3	0.9	0.0	0.1	0.2	0.0	0.0	0.1
Subtotal (km^2)	**2828.6**	**12.5**	**4.6**	**5.3**	**12.5**	**0.3**	**1.1**	**2.0**	**0.0**	**0.4**	**1.0**
Near-permanent upland stream (km)	159	0	–	–	–	–	–	–	–	–	–
Temporary upland non-GAB GDE stream (km)	2,119	8	–	–	–	–	–	–	–	–	–
Temporary upland stream (km)	21,757	469	346	452	453	124	182	221	6	22	55
Subtotal (km)	**24,035**	**477**	**346**	**452**	**453**	**124**	**182**	**221**	**6**	**22**	**55**
Non-GAB springs (number)	24	0	–	–	–	–	–	–	–	–	–
Subtotal (number)	**24**	**0**	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**–**	**–**

Example only; do not use for analysis. This is an early draft of a table published in companion product 3-4 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2017). See Holland et al. (2017) for full explanation and interpretation of the final results, which might vary from that shown here.
'–' means 'not applicable'. Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development. Landscape classes within operational and proposed pits are not included in this analysis. GAB = Great Artesian Basin, GDE = groundwater-dependent ecosystem.

5.2.2.2 Example: Namoi subregion

The landscape classification used in the Namoi subregion defined four 'lowland' riverine classes based on their topographical and geomorphological features (i.e. lowland), their water regime (i.e. permanent or temporary) and the likelihood of intersecting with known surface expression groundwater-dependent ecosystems (GDEs). Lowland streams include the Namoi River and its tributaries, and are low-gradient channels typically incised into alluvium with silt or sandy beds. There are limited riffles and fast water habitats in these streams and mostly pool habitat in those stream reaches with more temporary water regimes.

A receptor impact model for lowland riverine landscape classes modelled the relationship between cease-to-flow hydrological response variables (zero-flow days and maximum zero-flow spells) and average number of families of aquatic macroinvertebrate in edge habitat.

Surface water modelling data were available for approximately 46% of the total stream length classified as lowland riverine. The two most common lowland riverine landscape classes that are at risk from increases in the number of zero-flow days per year and annual maximum zero-flow spells are the 'Permanent lowland stream' and 'Temporary lowland stream' landscape classes.
The 'Permanent lowland stream' landscape class encompasses 979.6 km in the zone of potential hydrological change and includes the Namoi River and lower reaches of its major tributaries: Mooki River, Maules and Coxs creeks and Peel River. There is a 50% chance of an increase of 20 or more zero-flow days per year in 16.9 km of the stream network classified as 'Permanent lowland stream' during the 2013 to 2042 simulation period. Although a much larger portion of the stream network in the zone of potential hydrological change is classified as 'Temporary lowland stream' only 9.5 km is at risk of a 50% chance of an increase of 20 or more zero-flow days (averaged over 30 years) (subsequently referred to in this Chapter as 'zero-flow days') (for the 2013 to 2042 simulation period). As an example of the potential surface water changes, Figure 12 presents the modelled increase in zero-flow days in the 'Floodplain or lowland riverine' landscape group, which encompasses the 'lowland' riverine classes, in 2042 in the zone of potential hydrological change of the Namoi subregion.

Figure 13 summarises the receptor impact model, and the modelled relationship between the average number of families of aquatic macroinvertebrate in edge habitat and the two cease-to-flow hydrological response variables considered. The statistical model that sits behind Figure 13 is used to make the predictions of the average number of families of aquatic macroinvertebrate in edge habitat for the lowland riverine landscape classes.

Figure 14a summarises the distributions of the 5th, 50th and 95th percentiles of the predicted number of families of aquatic macroinvertebrates across the landscape class for the two modelled futures. While there is large uncertainty surrounding the average number of macroinvertebrate families under both the baseline and CRDP futures, and in the assessment years 2042 and 2102, there is no evidence that the number of macroinvertebrate families would differ between the two futures for either the 5th percentile, median or 95th percentile estimates. The 95th percentile estimate suggests that the number of macroinvertebrate families could be larger in 2102 than in 2042.

While Figure 14a emphasises the overall distribution of the number of families of aquatic macroinvertebrates under the two different futures and the two time points, the link between CRDP and baseline model predictions is lost (e.g. the smallest observation under the baseline does not necessarily correspond to the smallest under the CRDP). Figure 14b emphasises this linkage by presenting the distribution of the differences between the CRDP and baseline model predictions for assessment units in the lowland riverine landscapes class as boxplots. The ‘box’ collapses to the thick line at 0 because for many assessment units the baseline and CRDP predictions are identical, and therefore the difference is 0. Declines in average number of families of aquatic macroinvertebrates due to additional coal resource development are similar between the simulation periods and range from approximately –16 to –17 families at the 5th percentile to approximately –4 to –3 families at the 50th percentile. An increase in average number of families of aquatic macroinvertebrates was observed in the 95th percentile.

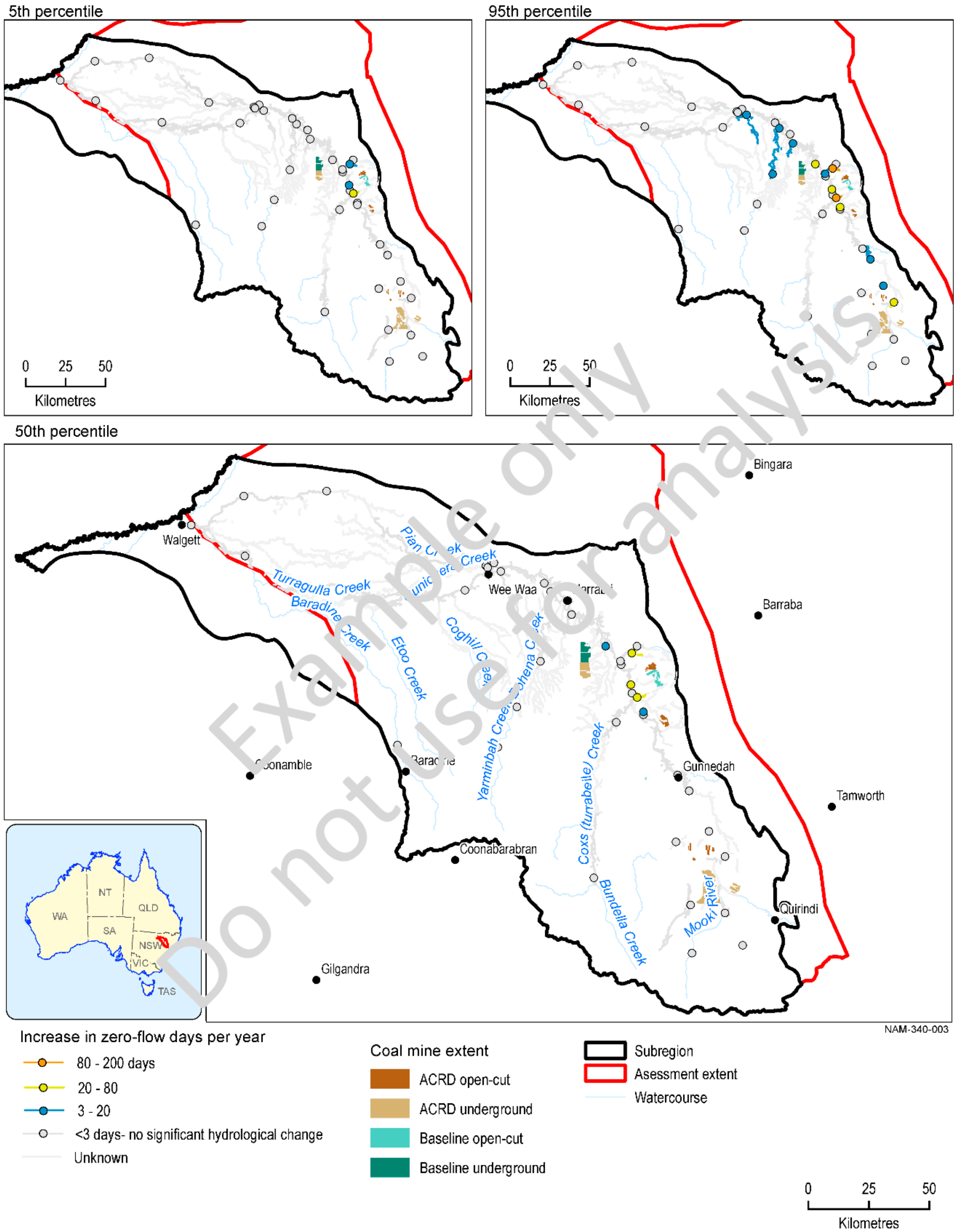

Figure 12 Modelled increase in zero-flow days in lowland streams in 2042 in the zone of potential hydrological change for the Namoi subregion

Example only; do not use for analysis. This is an early draft of a figure published in companion product 3-4 for the Namoi subregion (Herr et al., 2018). See Herr et al. (2018) for full explanation and interpretation of the final results, which might vary from that shown here.
The mine extent in the CRDP is the sum of the mine extent in the baseline and the additional coal resource development (ACRD).
zero-flow days = the number of zero-flow days, averaged over a 30-year period

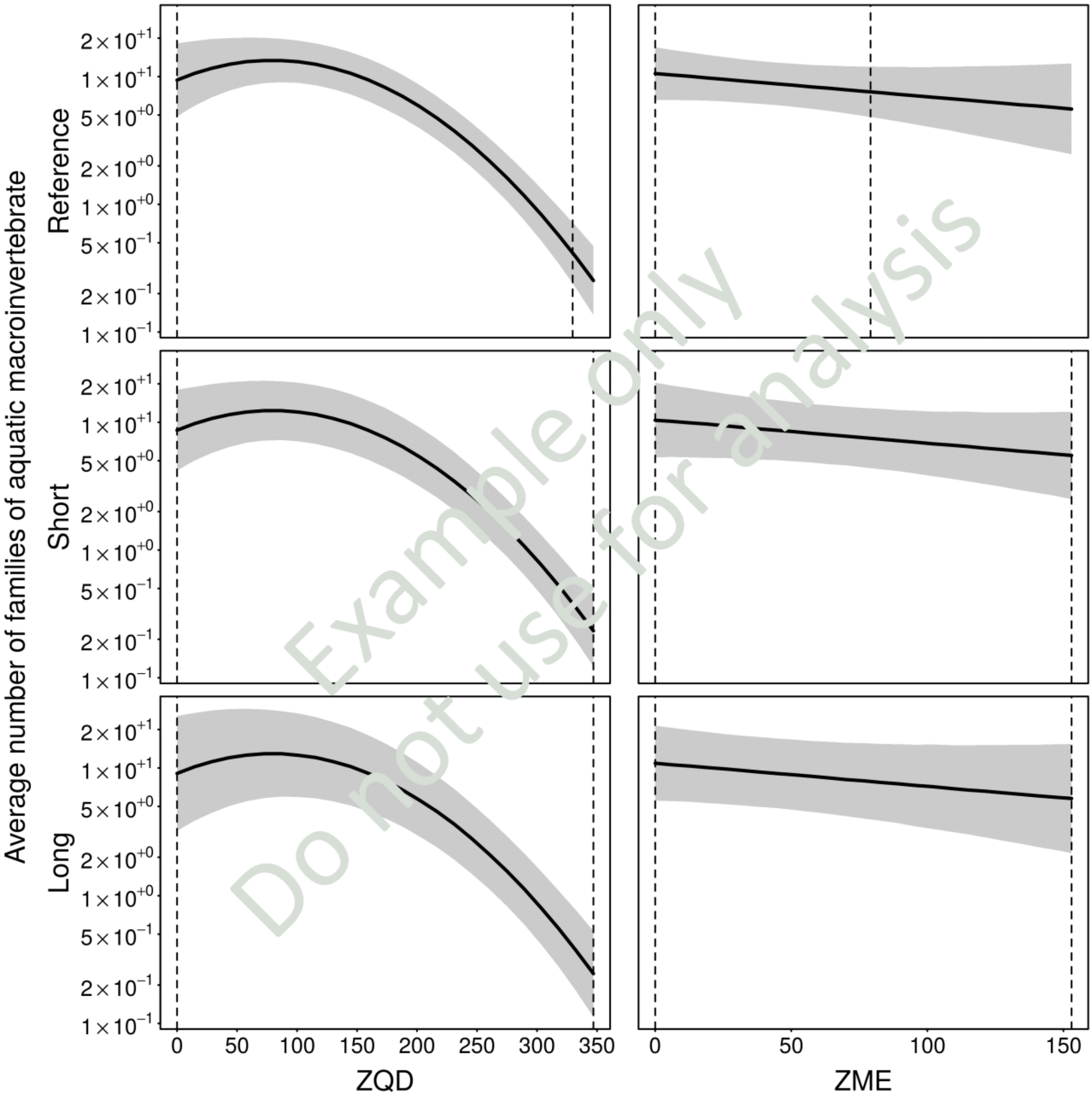

Figure 13 (Top row) Predicted mean (black line) and 80% central credible interval (grey polygon) of average number of families of aquatic macroinvertebrate in edge habitat in lowland riverine landscape classes under reference hydrological conditions. (Middle and bottom rows) Predicted future effect (mean = black line, 80% central credible interval = grey polygon) of each hydrological response variable on average number of families of aquatic macroinvertebrate in edge habitat in lowland riverine landscape classes, holding all other hydrological response variables constant at the midpoint of their elicitation range (during risk estimation all hydrological response variables vary simultaneously). Dashed vertical lines show hydrological response variable range used in the elicitation

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

Example only; do not use for analysis. This is an early draft of a figure published in companion product 2.7 for the Namoi subregion (Ickowicz et al., 2018). See Ickowicz et al. (2018) for full explanation and interpretation of the final results, which might vary from that shown here.

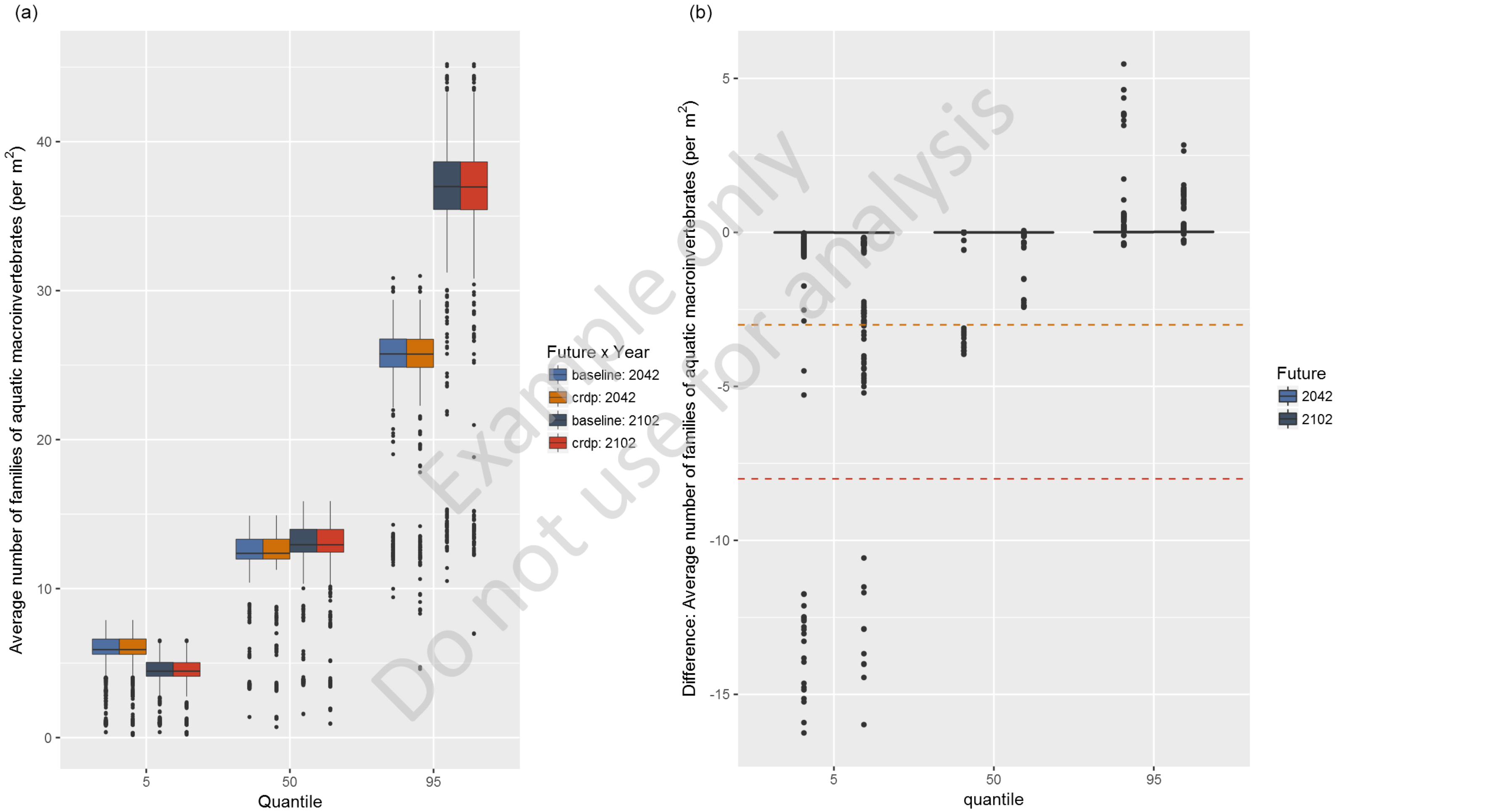

Figure 14 Modelled changes in average number of families of aquatic macroinvertebrates across the lowland riverine landscape classes. (a) Box and whisker plots of modelled average number of families of aquatic macroinvertebrates in 2042 and 2102 in lowland streams under both baseline and coal resource development pathway (CRDP) futures. (b) Differences in average number of families of aquatic macroinvertebrates between CRDP and baseline futures for each assessment unit containing lowland riverine landscape classes. The relevant thresholds used to delineate changes in the receptor impact variable associated with assessment units that are 'at some risk' and 'more at risk' are indicated by the orange and red dashed horizontal lines

Example only; do not use for analysis. This is an early draft of a figure published in companion product 3-4 for the Namoi subregion (Herr et al., 2018). See Herr et al. (2018) for full explanation and interpretation of the final results, which might vary from that shown here.

The lowland riverine landscape classes in the Namoi subregion sit within a broader ‘Floodplain or lowland riverine’ landscape group that also includes floodplain wetland landscape classes and floodplain riparian forest landscape classes. While a common qualitative mathematical model underpins the ‘Floodplain or lowland riverine’ landscape group, a receptor impact model for the presence of tadpoles in pools and riffles habitat is considered for the floodplain wetland landscape classes, and the projected foliage cover of dominant riparian trees (river red gum) is considered for the floodplain riparian forest landscape classes.

To provide an overall indication of ecosystem risk across the ‘Floodplain or lowland riverine’ landscape group, the results of these receptor impact models were aggregated. This was done using the differences in predictions between the CRDP and baseline futures and each assessment unit and for each receptor impact variable, where model data were available. Two risk thresholds were defined for each receptor impact variable based on the spread of modelled differences across the relevant assessment units in the landscape group. For the average number of families of aquatic macroinvertebrate, assessment units were considered to be ‘at minimal risk of ecological and hydrological changes’ for decreases less than 3, ‘at some risk of ecological and hydrological changes’ for decreases between 3 and 8, and ‘more at risk of ecological and hydrological changes’ for decreases greater than 8. These thresholds are intended to emphasise the assessment units within the ‘Floodplain or lowland riverine’ landscape group that may be more risk than other parts of the landscape group, and therefore worthy of more emphasis in any subsequent follow up with local analyses and monitoring. Analogous thresholds were also selected for the projected foliage cover and the probability of presence of tadpoles.

Figure 15 presents the risk composite for the three receptor impact models, whereby the highest level of risk determined from one or more receptor impact variable for any assessment unit defines the overall level of risk for that unit. The strength of this representation is in the comparison within the landscape group because it provides a measure of the relative risk and emphasises where attention should focus, and also where it should not. Where assessment units are assessed as ‘more at risk’ than other parts of the landscape class or group they may receive a higher level of hydrological change, and possibly one that may be commensurate with some ecosystem change. While receptor impact variables are chosen as indicators of ecosystem condition for a landscape class, a more detailed and local consideration of risk needs to consider the specific values at the location that the community are seeking to protect, for example, particular assets, because that will help identify meaningful thresholds. It is also necessary because that will help identify meaningful thresholds, it is also necessary to bring in other lines of evidence that include the magnitude of the hydrological change and the qualitative mathematical models.

The greatest concentration of ‘more at risk’ and ‘at some risk’ assessment units are located along the Namoi River and its tributaries, Maules Creek, Back Creek and Bollol Creek (Figure 15). The existing condition of these stream reaches considered to be exposed to ‘at some risk’ or ‘more at risk’ is defined by the NSW River Condition Index (Healey et al., 2012). Of the 1425 assessment units included in one or more of the impact models, 51 were predicted to be ‘at minimal risk’ and 29 ‘more at risk’, with most of these risk categories being determined by potential impacts on lowland riverine landscape classes and floodplain wetland landscape classes. This mapping suggests that the combined instream value (based on distinctiveness, diversity, naturalness and vital habitat values) is high to very high in those potentially impacted reaches of the Namoi River and of low to medium along the tributaries (Department of Primary Industries, 2017).

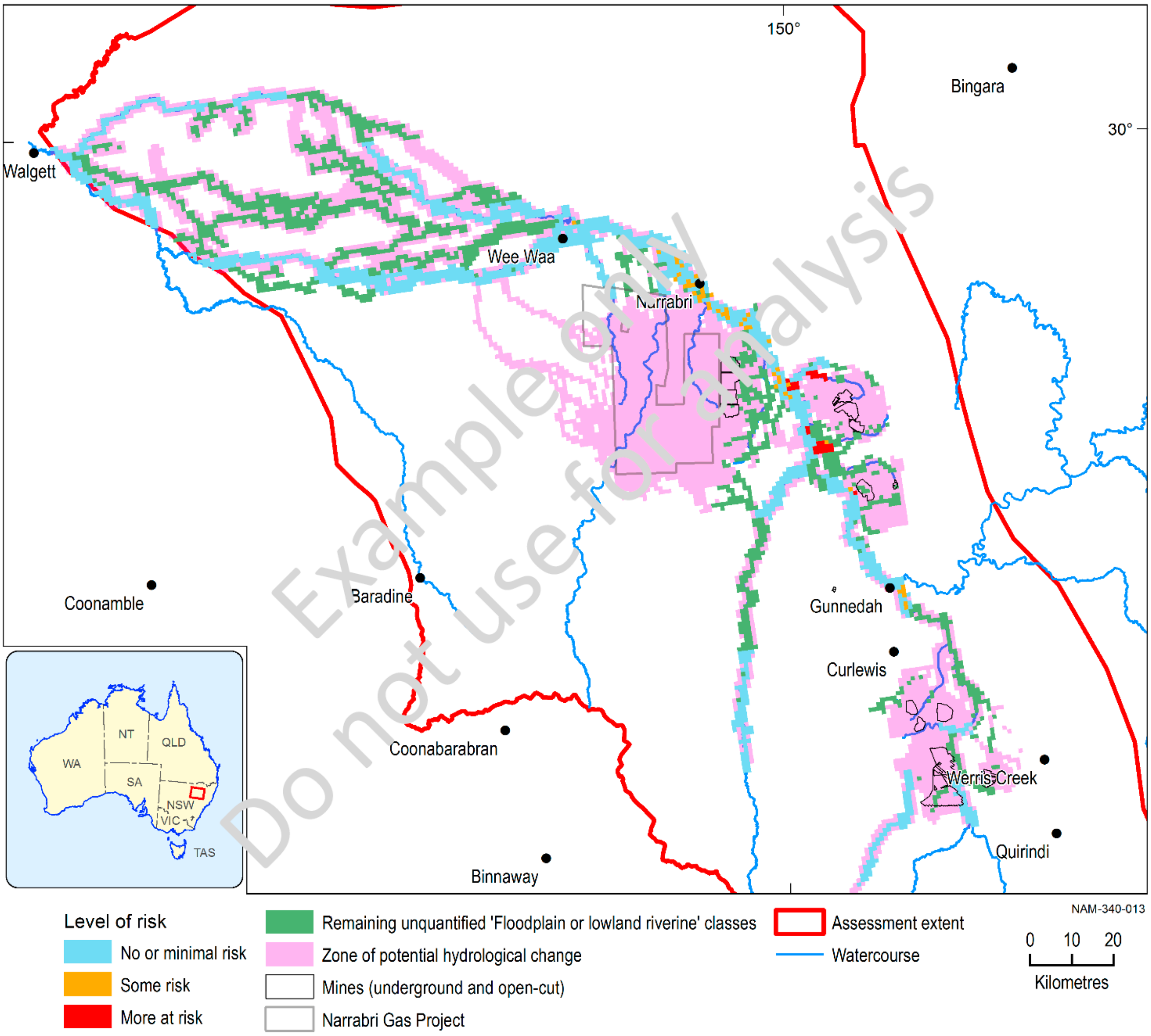

Figure 15 Composite risk map based on the results of receptor impact modelling across the 'Floodplain or lowland riverine' landscape group for the Namoi subregion

Example only; do not use for analysis. This is an early draft of a figure published in companion product 3-4 for the Namoi subregion (Herr et al., 2018). See Herr et al. (2018) for full explanation and interpretation of the final results, which might vary from that shown here.

The level of risk: 'at minimal risk', 'at some risk' and 'more at risk' is presented for different assessment units where the receptor impacts are modelled for the different landscape classes. Remaining assessment units for the relevant classes in 'Floodplain or lowland riverine' group without receptor impact modelling and surface water modelling are also shown (green). Extent captures areas with 'at some risk' or 'more at risk' assessment units.

Receptor impact modelling integrates understanding from the conceptual model of causal pathways, hydrological modelling and expert opinion to estimate potential impacts to ecosystems, where receptor impact variables are considered to be indicators of ecosystem condition.

Prediction of changes to receptor impact variables is ultimately one line of evidence. Any assessment of risk, particularly at a local scale, needs to be considered in conjunction with the broader hydrological changes that may be experienced, the qualitative mathematical models (which may help in assessing the implications of those changes, including any direct and indirect effects), and local data and information (e.g. local conceptual models or understanding). In some cases, if there is no change in the landscape class-specific hydrological response variables, it can be inferred that potential ecosystem change is *very unlikely*.

For some landscape classes qualitative mathematical models exist but receptor impact models were not constructed because of the lack of availability of enough specific external ecological expertise for that landscape class or the prioritisation of effort across the different assessments in the Programme. It follows that potential changes for that landscape can only be characterised by predicted hydrological changes. It is important to stress that hydrological changes do not imply that there is impact – only that it cannot be ruled out on the basis of the hydrological change and that further investigation is required. That further work involves considering the nature of the water dependency of particular landscape classes within the zone of potential hydrological change. If a landscape class is not considered water dependent (e.g. dryland agriculture), then potential impacts to that landscape class may be ruled out.

5.2.3 Profiles of water-dependent assets

The principal focus of BAs is water-dependent assets that are nominated by the community and may have a variety of values, including ecological, sociocultural and economic values. The water-dependent asset register (product 1.3) provides a simple and authoritative listing of the assets within the assessment extent that are potentially subject to water-related impacts. This register has been extended beyond the initial community and local natural resource management agency consultation by identifying additional assets in key Commonwealth and state databases, engagement through BA workshops, and other consultation processes on the identification of Indigenous assets. The assets identified are assessed by the Assessment team for several things, including their fitness for BA purposes, their location within the assessment extent, and their water dependency. Only those assets that satisfy these requirements are considered further in BAs as described in companion submethodology M03 (as listed in Table 1) on assigning impact variables and receptors to water-dependent assets (O'Grady et al., 2016).

The following sections describe the assessment of impact and risks through asset profiles for ecological, economic and sociocultural water-dependent assets in turn.

5.2.3.1 Ecological assets

The summary or profile of potential impacts for an individual ecological asset follows the same process as for an individual landscape class and as presented in Figure 9. It is important to note that the spatial extent of many ecological assets, especially particular flora or fauna, is usually a potential habitat distribution, rather than a definitive extent that categorically says that the asset must occur in this area.

An individual asset extent is intersected with the zone of potential hydrological change. If the water resource or water-dependent asset falls outside the zone, then any water-mediated impacts that are attributable to additional coal resource development are assumed to be *very unlikely*. If the extent of the water resource or water-dependent asset intersects with the zone of potential hydrological change, either partially or fully, then the data relevant to the water-dependent asset may be summarised in terms of the potential hydrological changes (including considering the intersection of the asset on different levels of hydrological change) and potential ecosystem changes using an identical approach as for individual landscape classes and presented in Figure 9.

One distinction is that the hydrological or ecosystem changes that an ecological water-dependent asset may experience are typically broken down by landscape class to ensure relevant hydrological response variables (and receptor impact variables) are used. If a water-dependent asset is contained within a single landscape class the summary is simply the landscape class-specific hydrological response variables and receptor impact variables, but constrained to those assessment units containing the asset. If a water-dependent asset extends across more than one landscape class, for example, a national park that may contain both riverine and terrestrial GDEs, an analogous summary is provided for each of those landscape classes. It is highly likely that different landscape classes will be represented by different hydrological response variables and receptor impact variables.

Figure 16 is an illustrative example that shows assessment units coloured by discrete landscape classes (different colours), the boundary of a single asset, and the groundwater zone of potential hydrological change. The area of the asset within the zone of potential hydrological change can be summarised. In this case the asset within the zone comprises two landscape classes. The potential impacts for that asset may be summarised via the percentile summaries for the landscape class-specific hydrological response variables and receptor impact variables under the different coal resource development futures.

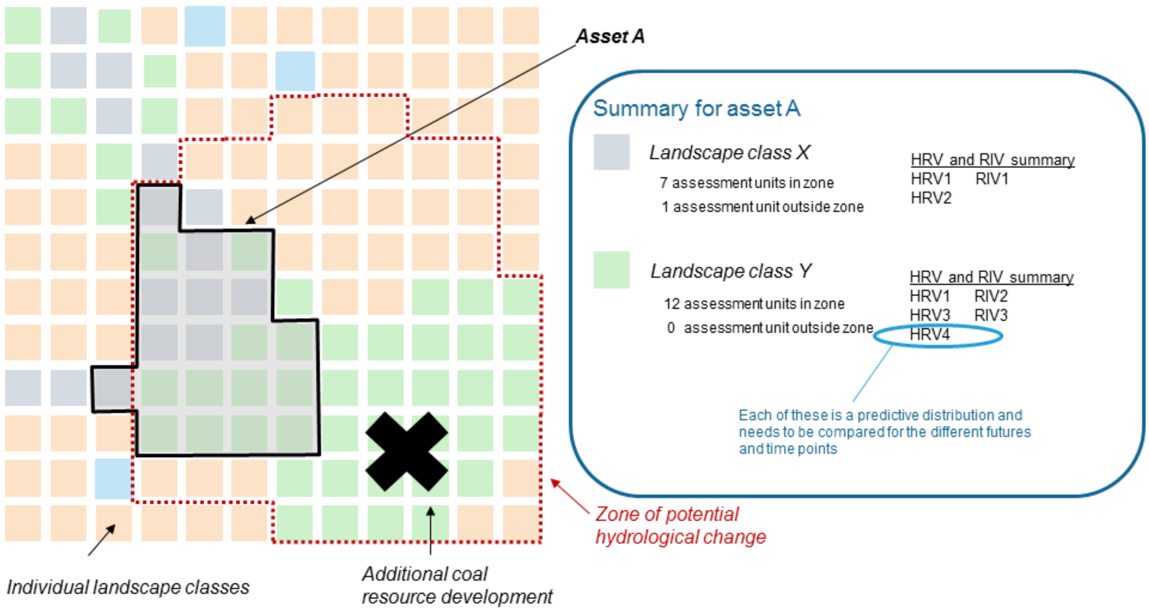

Figure 16 Illustrative example of how potential impacts to an asset are decomposed into landscape contributions and changes in hydrological response variables (HRVs) and receptor impact variables (RIVs) relevant to those respective landscape classes

Any broader interpretation of the direction and magnitude of the potential hydrological or ecosystem changes for an asset must rely heavily on the systems thinking and qualitative mathematical models for the component landscape classes, as they provide the ability to consider direct and indirect effects associated with changes in hydrological response variables or receptor impact variables.

Individual asset profiles should be created for all ecological assets. These summarise the extent of the asset, its composition in terms of landscape classes and their intersection with the zone of potential hydrological change. Then for each landscape class that occurs within a water-dependent asset, the distribution of the hydrological response variables and receptor impact variables under the baseline and CRDP are summarised. Where possible, the hydrological response variables are limited to those that are relevant to that asset. The individual asset profiles are available as part of the BA Explorer, available at www.bioregionalassessments.gov.au/explorer/XXX/assets where XXX is a three-letter code for a bioregion or subregion (e.g. ‘MBC’ for the Maranoa-Balonne-Condamine subregion).

Ecological water-dependent assets that do not partially or fully intersect the zone of potential hydrological change are assessed as *very unlikely* to be impacted and are not analysed further.

The reporting of individual assets in product 3-4 is partly informed through stakeholder consultation as part of a series of user needs workshops with the Commonwealth regulators, state regulators and industry.

There are too many assets and individual asset profiles for all of them to be directly reported on for product 3-4 (impact and risk analysis). While some individual assets may be reported for important context or because they are in some way iconic to the bioregion or subregion, there is a need to address the great majority by appealing to the structure and hierarchy within the water-dependent asset register (product 1.3) and by summarising impacts and risks to subgroups of assets. For instance, ecological assets are classified in the ‘Groundwater feature (subsurface)’, ‘Surface water feature’ and ‘Vegetation’ subgroups. Each subgroup is then divided into a number of classes, for example, the ‘Surface water feature’ subgroup divides into ‘River or stream reach, tributary, anabranch or bend’ class.

The choice of the asset subgroups to use is a decision for the Assessment team but needs to consider the hierarchy within the asset register, the number and nature of the water-dependent assets, where the impacts to landscape classes are likely to occur, and the ability to construct a compelling narrative around how hydrological change induced by coal resource development may impact water-dependent assets. The narrative should be supported by the conceptual modelling evidence base and the causal pathways and linkages back to the hazards.

The intersection of subgroups of assets with the zone of potential hydrological change is an important way of screening impacts to water-dependent assets. The extent may be summarised by area, length or number of points for each subgroup. Numbers of assets in a subgroup that fall within the zone may be tabulated.

5.2.3.1.1 Example: Maranoa-Balonne-Condamine subregion

Other plots and tabulations analogous to landscape classes but for asset subgroups may be useful. For example, Figure 17 considers an asset subgroup related to the threatened species and ecological communities listed under the Commonwealth’s *Environment Protection and Biodiversity*

Conservation Act 1999 in the Maranoa-Balonne-Condamine subregion. Figure 17 presents the median baseline drawdown and additional drawdown experienced by that asset subgroup in the zone of potential hydrological change in the vicinity of New Acland Coal Mine and The Range coal mine.

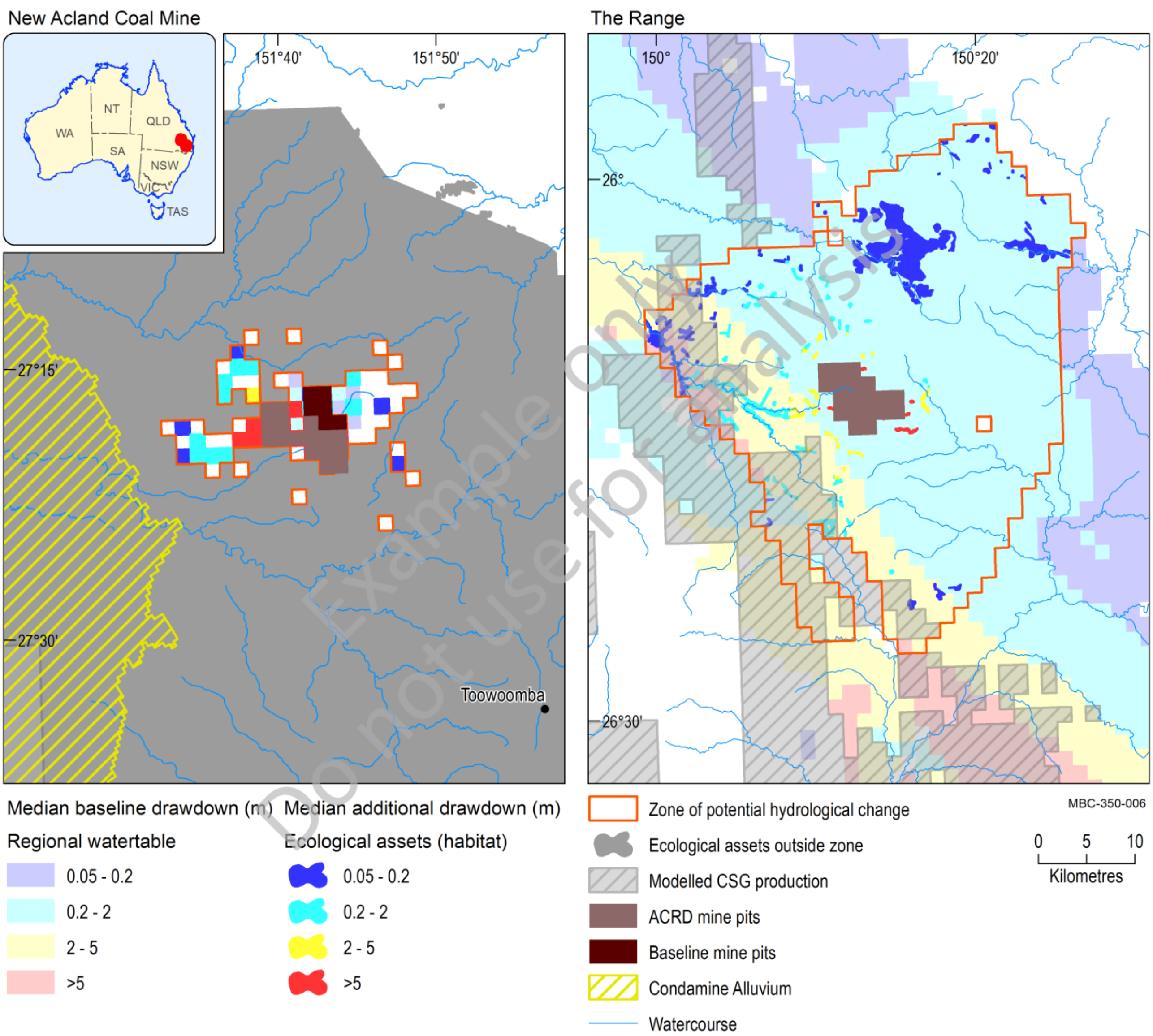

Figure 17 Median baseline drawdown and additional drawdown for threatened ecological communities listed under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999* in the zone of potential hydrological change in the vicinity of New Acland Coal Mine and The Range coal mine

Example only; do not use for analysis. This is an early draft of a figure published in companion product 3-4 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2017). See Holland et al. (2017) for full explanation and interpretation of the final results, which might vary from that shown here.
Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development. Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development. Areas within operational and proposed pits are not included in this analysis. ACRD = additional coal resource development, CSG = coal seam gas

While a direct hydrological response variable summary is possible here (because drawdown is available throughout the assessment extent), many assets and asset subgroups will need to be linked to their constituent landscape classes and the quantitative mathematical models that are constructed for them to provide a richer interpretation of the potential impacts.

5.2.3.2 Economic assets

Economic assets refer to water-dependent assets within a bioregion's or subregion's asset register for which the potential impacts due to coal resource development result in a readily measurable economic cost. Economic assets include the water resources themselves (i.e. water sources that are providing an economic benefit), the water supply works associated with accessing water from a water source (e.g. bores, pumps) and the entitlements and rights held by individuals or companies to use water for beneficial use.

The potential impacts from hydrological changes due to coal resource development include changes to water availability, reliability of supply and accessibility, which are the focus of the assessment of potential economic impacts. It is beyond the scope of BA to put a dollar value on the economic impacts, instead BAs identify the resources and water supply works that are potentially at risk.

Table 7 lists the economic asset classes within each bioregion or subregion. Economic water-dependent assets are confined to surface water and groundwater management zones or areas and comprise specific water access entitlements or rights and other water supply features or infrastructure. Within these classes there may be many individual asset elements (e.g. multiple water supply bores within a groundwater management zone).

Table 7 Economic water-dependent asset subgroups and classes

Subgroup	Class
Groundwater management zone or area (surface area)	A groundwater feature used for water supply
	Water supply and monitoring infrastructure
	Water access right
	Basic water right (stock and domestic)
Surface water management zone or area (surface area)	A surface water feature used for water supply
	Water supply and monitoring infrastructure
	Water access right
	Basic water right (stock and domestic)

Potential impacts to economic assets are tied more directly to potential hydrological changes than for ecological assets. There is no need for receptor impact modelling as the range of potential hydrological change can be considered against meaningful thresholds such as those specified by the *NSW Aquifer Interference Policy* (NSW Office of Water, 2012) or the requirements of water resource plans under Queensland's *Water Act 2000*.

The hydrological response variables relevant to assessing potential impacts due to additional coal resource development on economic assets in the subregions are:

- decrease in average annual flow – indicates a long-term change in water availability

- increase in the number of zero-flow days per year – indicates a change in reliability of water supply for water sources where the cease-to-pump rule is based on 'no visible flow' at specified points within the water source, or where the cease-to-pump rule is yet to be defined and individual licence conditions apply
- increase in the number of days when flow is below a specified flow rate – indicates a change in reliability of water supply for water sources where the cease-to-pump rule for a water source is based on a specified 'very low flow class' daily flow rate
- if system is regulated, and there are environmental water releases from the storages to meet minimum flow requirements, then difference in dam releases at nearest model nodes downstream of the storages. This provides measure of the extent to which more environmental water is needed to compensate for losses in streamflow due to additional coal resource development and potentially has an impact on the consumptive pool, hence available water determinations
- number of bores where 'make good' provisions (or equivalent) might apply with some probability (e.g. with at least a 5% chance as per zone of potential hydrological change). Under the *NSW Aquifer Interference Policy* (NSW Office of Water, 2012) the focus will be on bores in the greater than 2 m drawdown zone. In Queensland, the requirements of water resource plans under Queensland's *Water Act 2000* will centre on greater on 2 m drawdown for unconsolidated aquifers (e.g. in alluvial sands) and greater than 5 m of drawdown in consolidated rock aquifers (e.g. confined sandstone aquifers of the GAB).

These hydrological response variables are based on the maximum difference between the CRDP and the baseline for the full 90-year simulation period (2013 to 2102).

5.2.3.2.1 Example: groundwater economic assets in the Maranoa-Balonne-Condamine subregion

Unlike other landscape classes and assets, where potential hydrological changes to the regional watertable are most relevant, it is important to determine the source aquifer of each individual bore for the impact and risk analysis (Figure 18). This is achieved by comparison with available datasets that contain aquifer information for each bore, and is commonly presented in product 1.5 (current water accounts and water quality). Where this information is not available, the Assessment team can assume that these bores access the shallowest hydrogeological layer in that assessment unit (i.e. the regional watertable). Any potential hydrological changes to surface water economic assets are assumed to be related to the regional watertable in the absence of surface water modelling.

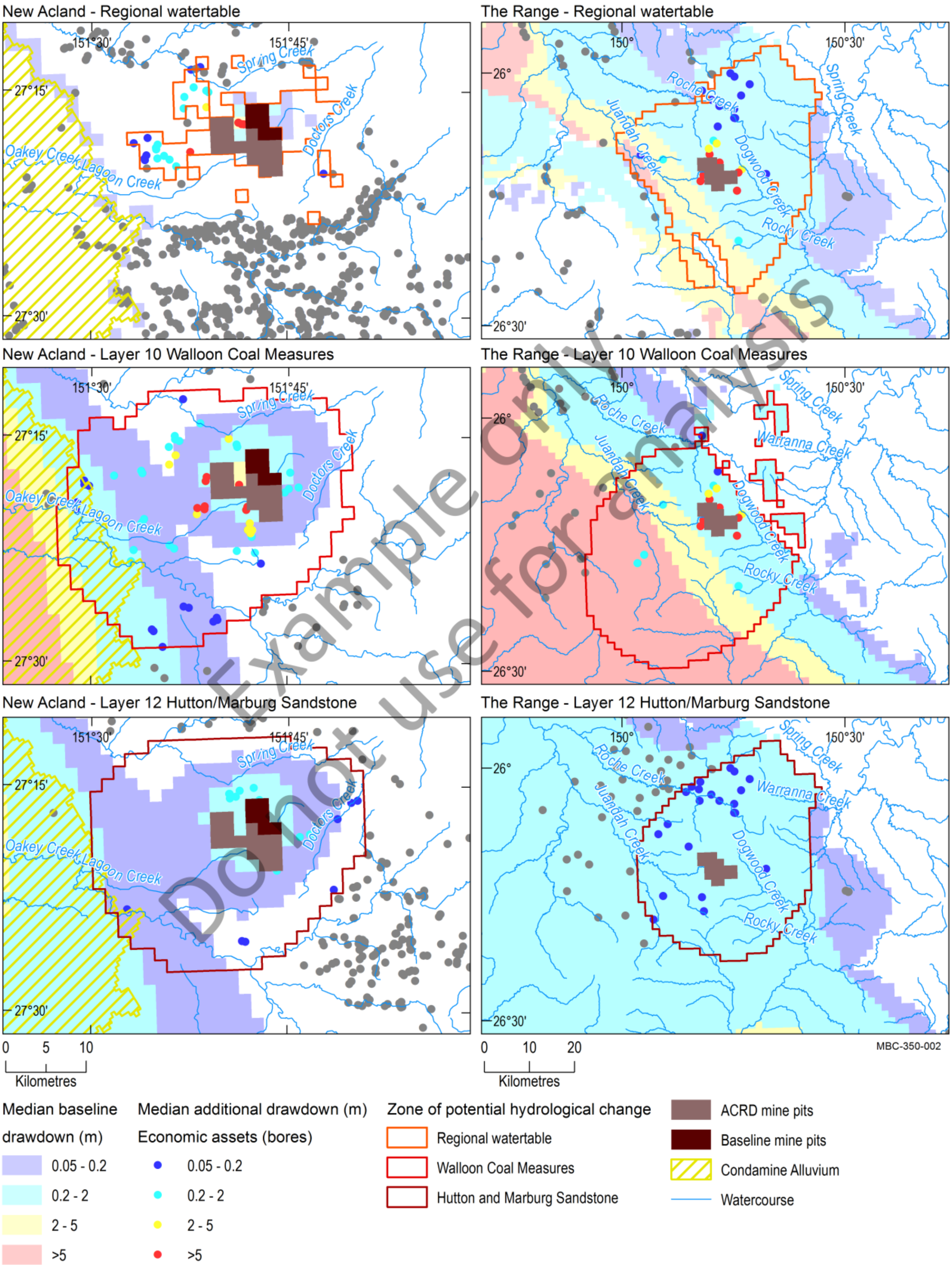

Figure 18 Median baseline drawdown and additional drawdown for economic bores in the zone of potential hydrological change in the relevant aquifer in the vicinity of New Acland Coal Mine and The Range coal mine

Example only; do not use for analysis. This is an early draft of a figure published in companion product 3-4 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2017). See Holland et al. (2017) for full explanation and interpretation of the final results, which might vary from that shown here.
Baseline drawdown is the maximum difference in drawdown (*dmax*) under the baseline relative to no coal resource development. Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development (ACRD).

For groundwater, potential impacts due to additional coal resource development are assessed by considering the overlap of the spatial extent of individual asset elements with the zone of potential hydrological change for each aquifer or model layer (e.g. regional watertable, deeper aquifers). Where there is no overlap, potential impacts are considered *very unlikely* and are not analysed further.

The overlay analysis is summarised by the number of individual groundwater bores that overlie the zone of potential hydrological change. This may be reported through a series of maps, figures and tables. The specific presentation options for economic assets is an Assessment team choice. As an example, Figure 19 presents the distribution of exceedance probabilities of two important drawdown thresholds (0.2 m and 5 m) for four groundwater resource management groups in the Maranoa-Balonne-Condamine subregion. This enables the reader to identify how many bores may exceed either of those thresholds for a given level of certainty. For instance, for the Condamine and Balonne Water Resource Management Plan (top left plot) it is almost certain (chance of exceedance greater than 0.95) that five bores will exceed 5 m of additional drawdown. The locations of these bores may then be examined through map products (not shown here).

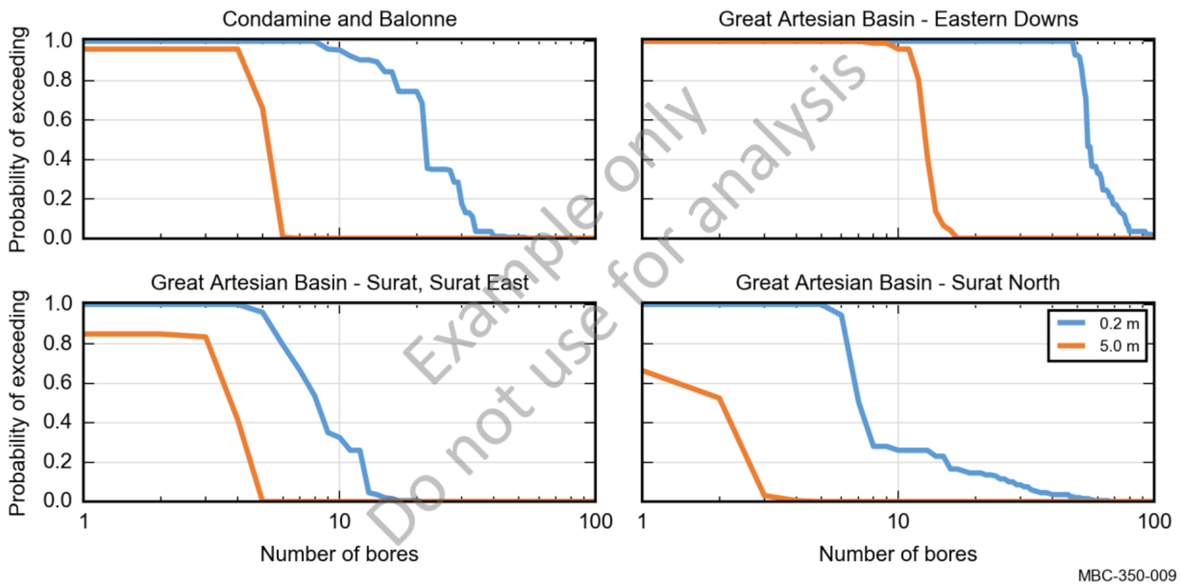

Figure 19 Probability of exceeding 0.2 and 5 m additional drawdown in the relevant aquifer for economic bores in each water resource management group for the Maranoa-Balonne-Condamine subregion

Example only; do not use for analysis. This is an early draft of a figure published in companion product 3-4 for the Maranoa-Balonne-Condamine subregion (Holland et al., 2017). See Holland et al. (2017) for full explanation and interpretation of the final results, which might vary from that shown here.
Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, due to additional coal resource development.

5.2.3.3 Sociocultural assets

Sociocultural assets are classified into 'Heritage site', 'Indigenous site' or 'Recreation area' classes. The water-dependent asset register considers sociocultural assets to be water dependent based on the presence of floodplain and wetland areas and shallow groundwater within their spatial extent.

In the absence of being able to undertake any more detailed appraisal of why Indigenous people have nominated individual assets, the criteria for water dependency for Indigenous assets is simply to assume that all are water dependent.

The overlay analysis is used to determine whether sociocultural assets are considered either ruled out or subject to further investigation. Water-dependent assets that do not partially or fully intersect the zone of potential hydrological change are ruled out from potential impacts and are not analysed further. The overlay analysis is summarised by the extent (area, length or number of points) of each subgroup that overlies the zone of potential hydrological change as per ecological assets and landscape classes. The specific maps, figures and table presentations used are in product 3-4 (impact and risk analysis).

For Indigenous assets that are aspatial it is not possible in BAs to undertake any type of overlay analysis, and the analysis is more limited because it is not even clear if those assets are within the zone of potential hydrological change.

In some cases, sociocultural assets, particularly Indigenous or recreation areas that are ecological in character, relate directly to ecological assets. Where that is the case, the assessment of impact and risks for that ecological asset is highly relevant to that sociocultural asset and that connection should be made.

5.3 Summary of impacts and risks for a bioregion or subregion

The three impact profiles provide a structured way to interrogate the large and complex information base that is generated through a BA.

The hydrological changes profiles summarise the broader hydrological changes across the bioregion or subregion, and introduce the zone of potential hydrological change as the focal point for assessing potential impacts (and non-impacts). The landscape classes profile provides a natural aggregation to meaningful biophysical ecosystems, and is the most appropriate resolution to consider any changes in receptor impact variables given they are selected as indicators of those ecosystems. The qualitative mathematical modelling for a landscape class provides the opportunity to consider potential direct and indirect impacts for that landscape. The assets profile is important because a water-dependent asset speaks to the values contributed by the community. The choice of meaningful subgroups of assets allows the assessment to synthesise potential asset impacts and address the large number of assets. Individual asset profiles, and their split into changes within contributing landscape classes for each asset, provide the ability to see potential hydrological and ecosystem changes that an asset may experience. While the information from individual asset profiles is only presented in a limited way in product 3-4 (impact and risk analysis) due to the large of number of assets, each of those individual asset profiles are available as part of the BA Explorer (see www.bioregionalassessments.gov.au/explorer/XXX/assets where XXX is a three-letter code for a bioregion or subregion (e.g. ‘MBC’ for the Maranoa-Balonne-Condamine subregion)). This provides additional functionality to identify individual assets and which assets are assessed as experiencing no potential impacts, which may be restricted such as some Indigenous assets, and those that fall within the zone of potential hydrological change and therefore may experience some change. The direct communication of results from the product 3-4 (impact and risk analysis) and BA Explorer (www.bioregionalassessments.gov.au/explorer) with interested groups, such as during impact and risk workshops and any subsequent community-level consultation, provides the opportunity to refine the presentation of outputs.

The impact and risk analysis needs to flag where future efforts of regulators and proponents should be directed, and where further attention is not necessary for the CRDP considered in the BA. This is emphasised through the 'rule out' process, which progressively seeks to prioritise this analysis by focusing on the areas where hydrological changes are predicted (Figure 20). In doing so it identifies areas, and consequently water resources and water-dependent assets, that are *very unlikely* to experience any hydrological change or impact due to additional coal resource development.

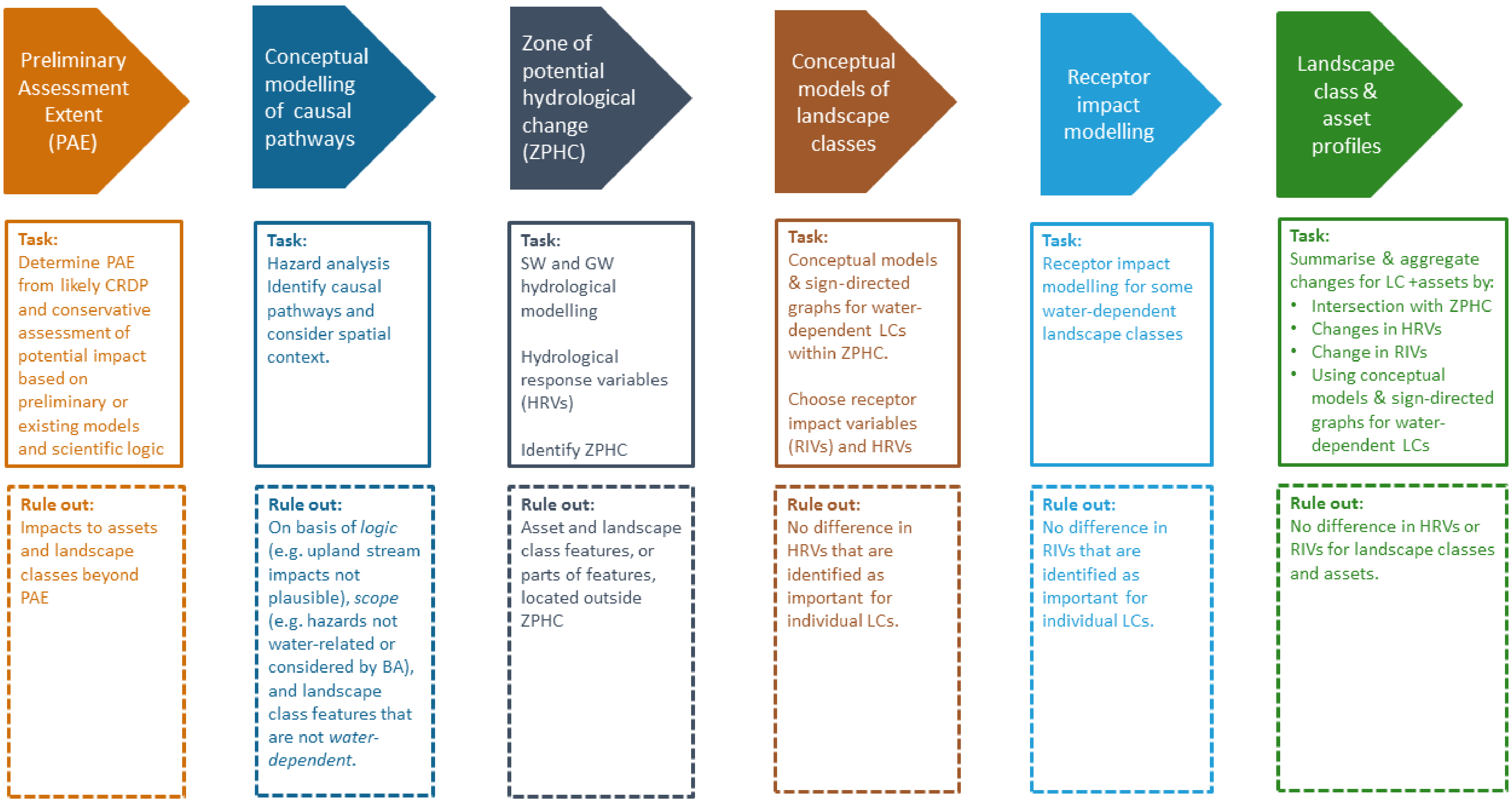

Figure 20 Illustration of the 'rule-out' process within bioregional assessments

CRDP = coal resource development pathway; GW = groundwater; HRV = hydrological response variable; LC = landscape class; PAE = preliminary assessment extent; RIV = receptor impact variable; sign-directed graph = signed digraph; SW = surface water; ZPHC = zone of potential hydrological change

Spatial areas, and water resources and water-dependent assets, that are ruled out are something that can typically be communicated strongly due to the high level of confidence in the ability of the assessment process to rule out areas of hydrological change. The confidence in modelled predictions is directly related to the strengths of the regional hydrological models, their ability to reflect broad-scale hydrological changes related to impacts that may accumulate from multiple sites and styles of coal resource development, and the wide range of parameter distributions and combinations (e.g. aquifer hydraulic conductivities are assessed across several orders of magnitude) propagated through the models. Where there are changes predicted, and particularly close to the mine or CSG operations, the assessments are confident in asserting that hydrological changes are likely to occur, but less confident in the precise magnitude or extent of propagation of those changes from depth to the surface. This is because the regional-scale groundwater model or surface water model apply simplified conceptualisations that are appropriate for regional-scale analysis but may not be unable to adequately reflect known local-scale structures, stratigraphy and operations. There is consequently much greater confidence in the ability of a BA to identify areas where potential impacts may occur, rather than quantify the precise magnitude of those impacts.

The development and evaluation of hydrological models and receptor impact models, underpinned by conceptual models, will provide a coherent and principled basis for describing potential impacts in a bioregion or subregion, however, they are only a component of the analysis. There will be a broader knowledge and expert opinion base that cannot be represented in the modelling components. The Assessment team needs to ensure that this broader knowledge is incorporated into the assessment wherever possible. For example, while salinity is not modelled in BAs, it is possible to make qualitative statements about potential impacts based on the knowledge and modelling information that is available. This should also discuss the uncertainty in the final analysis and comment on its source as well as discuss how additional information and knowledge could improve the analysis.

The assessment of impacts may not be possible at all locations, for example, because the model does not provide an adequate outcome. Where the assessment of impacts is not possible, this will be identified as a gap and reported in the impact assessment.

While these impact profiles provide important structure and summaries for the impact and risk analysis, they still contain a substantial amount of information given the numbers for features such as water-dependent assets, landscape classes, hydrological response variables, and receptor impact variables that need to be considered across the different futures and time points. Information from those profiles needs to be complemented by descriptions of what those changes may mean wherever possible because it is that ‘so what’ that will resonate with the reader. The overall intent of that narrative should be on the big picture, describe what is unlikely to happen, what might happen, and what is considered *very likely* to happen, under baseline and CRDP in a bioregion or subregion. That synthesis and narrative should underpin many of the key findings in a BA.

5.4 Content for product 3-4 (impact and risk analysis)

The content presented in product 3-4 (impact and risk analysis) for a bioregion or subregion follows the structure outlined in Table 8. The core of product 3-4 comprises the three profiles (summarised in Figure 8) through this information, namely the impact and risk profiles related to the hydrology, landscape classes and water-dependent assets. Details on the gaps, limitations and opportunities of the assessment are important in identifying a set of factors that assist in determining confidence in predicted risk outcomes and how the assessment may be built upon.

Table 8 Outline for product 3-4 (impact and risk analysis), and brief description of suggested content

Section number	Title
3.1	**••Overview**
3.2	**••Methods**
3.3	**••Potential hydrological impacts**
3.3.1	•••Defining the zone of potential hydrological change
3.3.2	•••Potential impacts on groundwater
3.3.3	•••Potential impacts on surface water
3.3.4	•••Potential impacts on water quality
3.4	**••Impacts on and risks to landscape classes**
3.4.1	•••Overview
3.4.2	•••Landscape classes that are unlikely to be impacted
3.4.3	•••Landscape group #1 (or landscape class if required)
3.4.3.1	••••Description
3.4.3.2	••••Potential hydrological impacts
3.4.3.3	••••Potential ecosystem impacts
3.4.4	•••Landscape group #2 (or landscape class if required)
3.4.4.1	••••Description
3.4.4.2	••••Potential hydrological impacts
3.4.4.3	••••Potential ecosystem impacts
3.4.5	(Add more landscape groups as required)
3.5	**••Impacts on and risks to water-dependent assets**
3.5.1	•••Overview
3.5.2	•••Ecological assets
3.5.2.1	••••Description
3.5.2.2	••••Subset 1 <insert name of subset>
3.5.2.3	••••Subset 2 <insert name of subset>
3.5.2.4	(Add more ecological asset subsets as required)
3.5.3	•••Economic assets

Section number	Title
3.5.3.1	••••Assets in the zone of potential hydrological change
3.5.3.2	••••Potential impacts on surface water assets
3.5.3.3	••••Potential impacts on groundwater assets
3.5.4	•••Sociocultural assets
3.5.4.1	••••Description
3.5.4.2	••••Subset 1 <insert name of subset>
3.5.4.3	••••Subset 2 <insert name of subset>
3.5.4.4	(Add more sociocultural asset subsets as required)
3.6	**••Commentary for coal resource developments that are not modelled**
3.7	**••Conclusion**
3.7.1	•••Key findings
3.7.2	•••Gaps, limitations and opportunities

6 Building on the impact and risk analysis

6.1 Overview

Bioregional assessments (BAs) seek to help governments, industry and the community make better-informed regulatory, water management and planning decisions.

A BA is an analysis at a particular point in time. Those components that are most likely to change are the human parts, particularly decisions around the coal resource development and around the list of community assets.

The coal resource development pathway (CRDP) is verified during the BA as the most likely future at the time of analysis, even though it may ultimately be implemented in different ways, such as changes to the timing and scale of some proposed developments. Additionally, particular coal resource developments may become more or less likely in response to a range of external economic, social or political factors. Despite the potential for the CRDP to change with time, it still provides a valuable indicative scenario as the basis for highlighting potential regional-scale changes to water resources and water-dependent assets. These may need to be considered further as part of local-scale assessments by proponents, or through future regulatory approval processes and government decision making at both national and state levels for particular coal resource developments. Equally as important, the impact and risk analysis indicates where impacts to water resources and water-dependent assets are unlikely to occur, which may help in ensuring that both regulators and proponents concentrate their focus on those aspects and areas that have greater potential to change.

The water-dependent assets are identified as features of ecological, economic or sociocultural value by the community and supplemented by key Commonwealth and state databases. The assets identified may change over time as values change and additional assets are included and others lessen in importance.

While the CRDP and asset register are date-stamped, BAs have been conceived and implemented in a modular fashion. This means that future updates or iterations to a BA do not have to revisit each component of work to the same level and intensity as done during the implementation. For example, if the CRDP were to change, adjustments to some components of work may be needed (e.g. incorporating new coal resource developments in the groundwater model) but may not affect many other components (e.g. the landscape classification). BAs have certainly been undertaken with the clear intention of updating the assessment at some future stage. While there is effort and expertise required in any update, the modular nature of the assessment means that effort is greatly reduced by the way a BA has been implemented.

It will be essential to identify gaps or opportunities to improve those components in the future. Given prediction is at the heart of the impact and risk analysis, focusing on those components that may reduce the predictive uncertainty should take priority. For example, that might include new data requirements to better characterise the hydraulic properties of important geological layers (e.g. coal-bearing units and water supply aquifers) and tighten the plausible range of associated parameters used in the groundwater models. It could include improved spatial resolution of groundwater-dependent ecosystem (GDE) mapping to reduce the spatial uncertainty and tighten the link between hydrological modelling and the ecosystem modelling; or it might involve additional expert elicitations to focus on ecosystem indicators that tie more directly to specific decision making and reduce some of the management uncertainty.

One of the key challenges for a BA is scale. BAs focus on regional cumulative analyses. These reflect the broad-scale hydrological and ecosystem changes related to impacts that may accumulate from multiple sites and types of coal resource development. Where changes are predicted, and particularly close to the mine or coal seam gas (CSG) operations, the Assessment team is confident in asserting that hydrological changes may occur, but less confident in the precise magnitude or extent of propagation of those changes from depth to the surface because of the dependence on local processes and operations. BAs are not a substitute for careful assessment of proposed coal mine or CSG extraction projects under Australian or state environmental law. Such assessments may use finer-scale surface water and groundwater models and consider impacts on matters other than water resources. However, the results from a BA should help inform the advice on proposed coal resource development projects from the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (IESC), a federal government statutory authority established in 2012 under the Commonwealth's *Environment Protection and Biodiversity Conservation Act 1999,* and state government regulators.

There is also a limited ability to isolate the impact of individual developments from the regional cumulative analyses. The baseline and CRDP may each consider a suite of developments, the potential impacts of which may overlap to varying degrees in both time and space. This allows an assessment to predict and understand the cumulative hydrological changes and potential impacts of those developments on surface water, groundwater and water-dependent assets. However, it does not, in general, allow the attribution of these effects to individual developments. In some cases the spatial or temporal alignment of certain coal resource developments may allow for some attribution, but that is the exception rather than the norm. To accurately isolate the contribution of any particular coal resource development would require the comparison of two futures – one with that coal resource development and one without it. The hydrological models are available as part of the Programme focus on transparency so it is possible with sufficient expertise to make an adjustment (e.g. remove a coal mine) to these models and re-run the analysis.

A BA provides important context to identify potential issues that may need to be addressed in local-scale environmental impact assessments of new coal resource developments. It should help project proponents to meet legislative requirements to describe the environmental values that may be affected by the exercise of underground water rights, and to adopt strategies to avoid, mitigate or manage the predicted impacts. These assessments do not investigate the broader social, economic or human health impacts of coal resource development, nor do they consider risks of fugitive gases and non-water-related impacts.

In comparing results under two different futures, factors such as climate change or land use are held constant through an assessment. Future assessments could look to include these and other stressors to more fully predict cumulative impacts on a landscape scale. Within any bioregion or subregion there will may be interest in building on the BA for particular assets or areas of interest. In such cases the BA outputs could feed into additional and focused impact and risk assessments surrounding that asset or area. For instance, this might occur by using the individual asset profile for the asset of interest, examining the range of hydrological changes that asset may experience and bringing additional knowledge about changes or thresholds that may be important to protecting values that derive from that asset.

A number of design choices have been made for the impact and risk analysis to achieve this objective while addressing the constraints imposed by the BA methodology (Barrett et al., 2013), complexity of the task and good practice in risk assessment. Ultimately these design choices need to be scrutinised, and particularly when considering if the BA outputs are seen to meet the needs of decision makers and the scientific quality criteria.

6.2 Data and information

The impact and risk analysis, and the companion products that underpin it, will produce a vast amount of data and analysis output. Only some of this is able to be summarised in product 3-4 (impact and risk analysis). The full suite of information, including information for individual assets, will be provided on www.bioregionalassessments.gov.au. A subset of that will be displayed on the BA Explorer interactive web mapping tool on www.bioregionalassessments.gov.au/explorer. For example, for the Gloucester subregion, users can explore detailed results for:

- the entire subregion at www.bioregionalassessments.gov.au/explorer/GLO
- hydrological changes at www.bioregionalassessments.gov.au/explorer/GLO/hydrologicalchanges
- impacts on landscape classes at www.bioregionalassessments.gov.au/explorer/GLO/landscapes
- impacts on assets at www.bioregionalassessments.gov.au/explorer/GLO/assets.

Much more information is provided as datasets at data.gov.au.

These underpinning datasets, including shapefiles of geographic data and modelling results, can assist decision makers at all levels to review the work undertaken to date, and to extend or update a BA if new models or data become available. This access also allows others to use those same data layers as part of tailored risk assessments about individual assets or areas of concern within the bioregion or subregion. In doing so, people are able to choose thresholds of impact that may threaten the specific values they are trying to protect and calculate the corresponding likelihood of occurrence.

The Bioregional Assessment Programme has adopted an extensive and rigorous approach to the management and publication of data. This is part of a commitment to making sure there is a clear understanding of the scientific process and that the data used and created along the way are accessible to the community. This approach is consistent with the Australian Government's principles of providing publicly accessible, transparent and responsibly managed public sector information.

6.3 Monitoring

6.3.1 Objectives and motivation

Most risk assessment frameworks identify the need for, and emphasise the importance of, post-assessment monitoring designed to test and (in)validate the predictions of the risk assessment (Hayes, 1997). Post-assessment monitoring is essential to complete the scientific method loop: hypothesis, prediction and observation. In the context of a risk assessment, and BAs more particularly, the hypothesis step is embodied within the conceptual modelling stages of the assessment, and the prediction step is embodied within the outputs of the surface water, groundwater and receptor impact models. A post-assessment monitoring strategy embodies the observation step. Without it the risk assessment is incomplete because it does not close the scientific loop of hypothesis, prediction and observation.

All monitoring programmes should begin with clear operational objectives, both for scientific and practical reasons. In this context, the objectives of the programme are to test and (invalidate) all of the risk assessment predictions. This includes surface water, groundwater and receptor impact model predictions. Monitoring may also be able to confirm or 'rule out' the existence of particular causal pathways and influence mitigation options.

The objectives of a post-risk assessment monitoring programme must speak directly to the predictions of the risk assessment and the management objectives that motivated the risk assessment. They should also provide additional details about what the monitoring programme and sampling protocol will do, and identify boundaries or limits of the monitoring programme by specifying particular areas, species or measures. An effective set of monitoring objectives should meet the test of being realistic, specific and measurable. The US National Park Service (2012) suggests the use of the following checklist of questions to determine if monitoring objectives meet the test:

- Are each of the monitoring objectives measurable?
- Are they achievable?
- Is the location and spatial bounds of the monitoring specified?
- Is the species or asset being monitored specified?
- Will the reader be able to anticipate and understand what the data will look like?

Alternative lines of evidence (e.g. from existing risk assessments and local analyses) may also complement the monitoring in validating (or invalidating) the predicted risk outcomes.

6.3.2 Design and implementation

Figure 21 provides a basic flow chart that illustrates the steps in designing and implementing a monitoring programme, beginning with a clear specification of the objectives, and ending with an analysis of the data that, in this context, is used to compare risk predictions with actual outcomes.

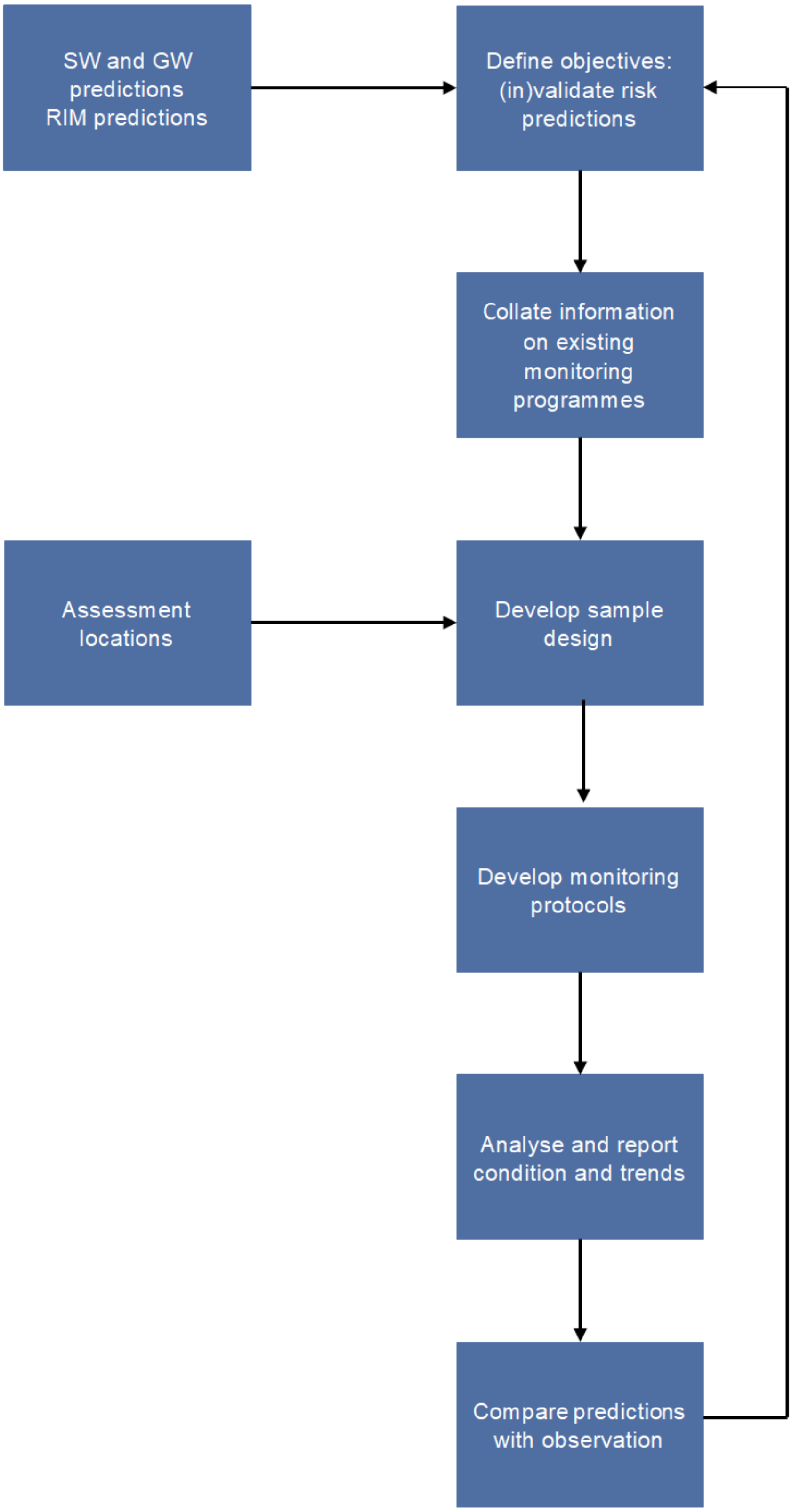

Figure 21 Flow chart summarising the steps in the design and implementation of a post-risk assessment monitoring programme

GW = groundwater; RIM = receptor impact model; SW = surface water

6.3.3 Existing monitoring programmes

Once the Programme objectives have been clearly enunciated, the next step in the process is to collate information on any existing monitoring programmes. There are a number of ways to go about compiling information on existing monitoring programmes. In some cases there may be existing reviews of monitoring programmes that could provide a sound basis to start this work. Another approach is to search metadata within institutional, or ideally national, data centres, such as the Australian Ocean Data Network (AODN, n.d.), *Atlas of living Australia* (ALA, n.d.) and the Terrestrial Ecosystem Research Network (TERN, 2009). Searches can be performed using keywords and/or by providing a bounding box around the assessment area to retrieve all records that intersect with this box.

Completing this step requires very little time and expertise if relevant metadata records are provided to central data repositories. Considerably more time and effort will be required to complete this work if there are no existing reviews of monitoring programmes and if existing monitoring programs do not publish metadata records for their monitoring data. If this is the case, the discovery, summary and analysis in these circumstances will need to rely on internet searches, supported by the experience, tenacity and networking skills of the analyst concerned.

6.3.4 Sample design considerations

Developing the overall sampling design for a post-risk assessment monitoring programme comprises two inter-related functions: (i) selecting variables to monitor and (ii) developing sampling design. A third integration step in this stage is necessary if there are existing monitoring programmes already in place. This third step must include an evaluation of the existing programmes and, if necessary, selection and integration of existing programmes outputs in the post-assessment programme.

In this context the monitoring variables are specified in advance by the previous steps in the risk assessment, specifically:

- the hydrological response variables used in the receptor impact models – targeting the associated predictions from the surface water and groundwater models
- the ecological receptor impact variables chosen through the qualitative mathematical modelling steps – targeting the associated predictions from the receptor impact models.

It is important that the monitoring programme seeks to measure hydrological response variables and receptor impact variables. In the event that the post-assessment observations do not agree with the risk assessment predictions it is important to distinguish between the situation where the hydrological response variables do not behave as predicted (indicative of surface water or groundwater modelling errors) and the situation where the receptor impact variables do not behave as predicted (indicative of incomplete system understanding and/or errors in the receptor impact models).

The sampling design for a post-assessment monitoring programme is shaped by a variety of factors including the monitoring variables; the existing monitoring legacy; advice from experts in sampling design and the constraints of budgets, resources and logistics.

The adequacy of sampling design for the selected monitoring programmes (i.e. existing, refined or proposed monitoring programmes) should be assessed before they are incorporated into the post-assessment programme. Opportunities to integrate sampling designs across monitoring programmes (e.g. co-location of sample sites for pressure and value monitoring, or complementary site selection of monitoring sites for the same type of monitoring to generate better insights from the collective monitoring effort) can also be considered at this point; this can produce benefits in both cost savings and data analysis.

The sampling design phase of a monitoring programme must address three critical questions: (i) what is an appropriate level of statistical power to inform decisions in a timely manner, (ii) how are sample sites to be selected, and (iii) how often should measurements be taken at these sites or subsets of sites? These three questions address the fundamental issues of where, and how often, samples should be collected.

Informally, statistical power is the probability of making the right decision when it matters most. Environmental managers face two options when presented with data from a monitoring programme: act upon the information or do nothing; this entails the possibility of two types of errors. The first (Type I error, with probability α) occurs if the manager acts in the belief that a significant trend or change is occurring, when in fact no such change is or has occurred. The second error (Type II error, with probability β) occurs when the manager fails to act in the erroneous belief that no significant change is occurring when in fact a change has or is occurring.

The question of appropriate statistical power has been traditionally approached using the '5-80' convention, which fixes the Type I error rate to be 5% and seeks a sample size such that statistical power (1- β) is 80% (i.e. the Type II error rate is 20%). This approach, however, places the burden of proof disproportionately on those trying to demonstrate environmental change, and undermines the fundamental aim of many monitoring programmes, which is to ensure that real change is detected and acted upon as early as possible (Field et al., 2007).

Mapstone (1995) recommends that the relative weighting of the two error rates are set according to the costs associated with each, and in the absence of this information the two error rates should simply be set equal to each other. This is a sensible proposition. Importantly the selection, and desired ratio, of the two error rates provides a means to tailor the monitoring design to the priorities of management objectives, for example, selecting lower Type II error rates for higher priority objectives, and vice-versa.

There are two important challenges that must be met in order to answer the second critical question in the context of BAs:

- BAs take a regional, whole-of-system, perspective, which implies inference must be made at greater spatial scales and higher levels of ecological organisation (i.e. regional populations and communities), than that typically associated with impact assessments for individual coal resource developments.
- Large-scale monitoring programmes must try to integrate the existing monitoring legacy with any new initiatives in order to be cost efficient and generate the long time series of observations that are typically necessary to detect changes in ecological systems.

Stevens (1994) identifies two distinct approaches when deciding where to locate sample sites for the purposes of regional-scale evaluation of environmental status or trends. The first approach is judgmental sampling wherein sites are selected by their anticipated ability to reflect regional characteristics. The second approach is probability sampling characterised by three distinguishing features: (i) the population being sampled is explicitly described, (ii) every element of the population has some opportunity of actually being sampled, and (iii) the sample selection procedure includes an explicit random element.

Judgmental sampling has been applied for many decades to environmental and social problems, and has demonstrably failed on many occasions (Edwards, 1998). Although recent modelling approaches have been developed to help account for this complication, this requires additional effort and modelling assumptions. It is strongly recommended that this approach is avoided in a post-assessment monitoring programme. It is also important that existing monitoring programmes are evaluated to identify the basis for site selection and transparently clarify any assumptions of existing monitoring programmes based on judgmental sampling.

Examples of probability-based approaches to survey design include systematic sampling, simple random sampling, two-stage sampling, stratified random sampling (Gilbert, 1987), spatially balanced Quasi-Monte Carlo sampling and Generalised Random Tessellation Stratified (GRTS) sampling (Stevens and Olsen, 2003).

Monitoring programmes designed to meet the needs of a strategic assessment will typically seek to identify trends and change points in regional (rather than local) populations. This type of monitoring objective implies that sites will be re-surveyed with a specified periodicity that depends on the defined management need. In this context it is important to recognise that the ability to detect trends in regional populations is influenced by variability in populations, space, time and the way data are collected (Larsen et al., 1995; Urquhart et al., 1998).

The main sources of uncertainty that will be encountered in this context, and that will affect the ability of a monitoring programme to detect trends are:

- population variance – differences in observations across the members of a regional population or sub-populations (such as a receptor impact variable in a landscape class across the northern half of a large bioregion)
- temporal variance – the amount by which observation across all members of a population or sub-population are high or low in a particular time period (e.g. a year). Over time, the value of any observation will fluctuate around a trend, or in the absence of a trend, around a central value. This variance component measures the amount by which all members of the population are above or below a long-term trend line or curve, or central value. Larsen et al. (1995) call this a 'year effect'
- space-time interaction (random) effects – the amount by which observations taken on an individual member of a population (e.g. at a single forest) fluctuate over time around a trend line, trend curve or central value. These fluctuations are caused by localised factors that operate at small scales, such as individual forest, or a localised group of forests

- index variation – a composite of several sources of variation, some natural and some introduced by the differences in the way data are collected. It includes sources such as differences caused by imprecise measuring devices and differences between survey teams. Standard operating procedures outlined in monitoring protocols are typically designed to minimise this source of variance
- spatial temporal dependence – objects near to each other in time and space will exhibit more similar responses than objects that are far apart.

In designing a post-assessment monitoring programme it is important to consider the effect of each of these sources of uncertainty on the analysis and the power of the program to detect trends at local and regional scales.

6.3.5 Monitoring protocols

In its minimalist form a monitoring protocol is a detailed document that provides operational instructions about how data are to be collected. It should provide operational instructions for the entire 'data life cycle' including how to collect, manage, analyse and report data in a consistent and comparable fashion over space and time. Monitoring protocols must be sufficiently well documented so that different people, or new programmes, can complete these procedures in exactly the same way.

Monitoring protocols are important for ensuring monitoring data are robust to changes in personnel, technology and management needs. They set minimum standards for issues such as observer training, data collection and storage, and are therefore a key component of quality assurance and quality control for integrated monitoring to support strategic assessment.

Oakley et al. (2003) provide generic guidance on developing monitoring protocols, and recommend that protocols include:

- a narrative that gives background information on why a particular component or process of the ecosystem was selected for monitoring, together with an overview of the various components of the monitoring protocol, including the objectives, the sampling design, field methodology, data analysis, data archival and reporting, personnel requirements, training procedures and operational requirements
- a set of standard operating procedures (SOPs) that provide detailed, step-by-step instructions on how each component of the protocol is to be completed, including instructions for how any of the SOPs are to be amended
- supplementary materials that provide additional guidance and support, and can include items such as reports, photographs and data analysis examples
- a conceptual model without too much detail that can guide monitoring programmes and provide a graphical narrative that can be updated with improved scientific understanding (Lindenmayer and Likens, 2010).

6.3.6 Data management

Australia has an established and developing national data infrastructure with the supporting processes and standards that could be used to meet the needs of regional monitoring programmes to support strategic assessments in terrestrial, coastal and marine regions. This includes national data stores and metadata stores to access data (e.g. Australian Ocean Data Network, *Atlas of living Australia* and the Terrestrial Ecosystem Research Network) and national standards for data management (e.g. ISO Standard and metadata profiles). Data standards are very important for discovery, storage and accessibility of data, particularly in decentralised systems where differences in vocabularies can create problems for discovery and access to data.

Data management for monitoring programmes all too often receives insufficient attention and support (Caughlan and Oakley, 2001; Lindenmayer and Likens, 2010). The costs of adequate data management systems to support monitoring are typically underestimated and can be expected to be about 20% to 30% of the total monitoring programme budget (Fancy et al., 2009; Lindenmayer and Likens, 2010).

Another important focus for data management is identifying the preferred model for discovering, storing and accessing monitoring data (i.e. the primary asset) generated from the selected programmes. A decentralised model may be attractive if selected monitoring programmes involve numerous institutions. It is also important to identify the existing data management infrastructure, processes and standards, and opportunities to establish the preferred model for data management. Acknowledgement and consideration should also be given to the relationship between data management processes and standards and monitoring protocols. Guidance on data management processes and standards needs to be embedded in monitoring protocols to ensure data are discoverable, stored securely and made accessible.

Appendix A Methods for structuring and processing data for bioregional assessment impact and risk analysis purposes

A.1 Context

There are a very large number of multi-dimensional and multi-scaled datasets that are used in the impact analysis for each bioregional assessment (BA) including model outputs, and ecological, economic and sociocultural data from a wide range of sources. Part of the approach used to manage these multiple dimensions and produce meaningful results is to adopt a clear spatial framework as an organising principle. While the inherently spatial character of every BA is important and must be addressed, it is also essential that the temporal and other dimensions of the analysis do not lose resolution during data processing. For example, knowing where a potential impact may take place is obviously important, but so is knowing what kind and level of impact and which assets may be affected.

A.2 Overview and purpose

The data are organised into *impact and risk analysis databases* to enable efficient management. The purpose of the databases is to produce result datasets that integrate the available modelling and other evidence across the assessment extent of the BA. The result datasets are required to support three types of BA analyses: hydrological change analysis, landscape impact profiles and asset impact profiles. These outputs are used in product 3-4 (impact and risk analysis) and displayed on the BA Explorer (a spatial data viewer available at www.bioregionalassessments.gov.au/explorer). They are also available as datasets at data.gov.au.

Given the context and purpose, the impact and risk analysis databases must achieve the following outcomes:

- The bulk of analysis queries are run in a professionally managed relational database environment.
- The result datasets are delivered in a format suitable for use by the Assessment teams.
- Queries are rapidly refined for the Assessment teams.
- Automation of queries by pre-running whenever possible to generate a 'bank' of queries.
- Continuity of provenance is maintained from the repository through the impact and risk analysis databases and the BA Explorer (www.bioregionalassessments.gov.au/explorer).
- Result datasets are available for rapid viewing across multiple media including via web feature services (WFS) and the BA Explorer web interface.

A.3 Data structures

The spatial framework underpinning the impact and risk analysis databases requires knowledge about the:

- structure of the attributes and tables to enable secure, efficient querying in a relational database environment
- characteristics of the impact analysis spatial datasets
- characteristics of the technical geoprocessing datasets needed to underpin the spatial framework for the impact analysis
- standards for the spatial framework (e.g. coordinate system and naming conventions).

Each of these is addressed in turn in the following sections.

A.4 Data structures for efficient geoprocessing

The data are structured to overcome the slow geoprocessing operations typical of complex queries of very large spatial datasets, such as those required for a BA. This structuring is achieved by (i) loading as many attributes as possible in relational tables, including some spatial information such as area and length data and (ii) simplifying and partitioning the remaining spatial data using 1 km x 1 km *assessment units* while, importantly, retaining spatial geometries below the resolution of the assessment units. An *assessment unit* is a geographic area represented by a square polygon with a unique identifier. The assessment units are non-overlapping and form a grid that completely covers each assessment extent. The spatial resolution of the assessment units is closely related to that of the BA groundwater modelling and is, typically, 1 km x 1 km. Assessment units are used to spatially partition asset and landscape class spatial data for impact analysis purposes. The partitioned data, including the model results, may be combined and recombined into any aggregation supported by the conceptual modelling, causal pathways and model data. The assessment units are used to summarise and present potential changes in the hydrological response variables and the receptor impact variables.

The assessment units enable fast querying and display of the spatial data as most of the querying is completed in the relational database rather than through geoprocessing operations.

A.5 Impact analysis datasets

The impact analysis datasets are outlined in Table 9, which describes their relevant characteristics.

Table 9 Impact analysis datasets

Datasets	Data characteristics
Landscape classes	Usually a dataset of non-overlapping polygons that cover the entire assessment extent. Each landscape class has a unique identifier. The entire layer is 'split'.
Assets (and Elements)	Assets are provided to the analysis collected from a wide variety of sources as part of creating product 1.3 (description of the water-dependent asset register) and maintained in the bioregion or subregion assets database. Not all attribute information of the assets database is required for the impact and risk analysis. The entire layer is 'split' against the assessment units of the bioregion or subregion.
Groundwater modelling	• A regular assessment unit grid, which is nominally 1000 x 1000 m (exceptions for GLO 500 m and MBC 1500 m). • SW HRV attributes interpolated from source models are 'joined' (linked) to the regular grid cell geometry. • Each BA has a regional watertable drawdown layer and some have additional model layers at other depths. • The resolution is estimated to incorporate the uncertainties in the modelling.
Surface water modelling	• A link-node (line and point) spatial structure interpolated from source models and, typically, based on the Geofabric Network streamlines. • SW HRV attributes are 'joined' (linked) to the link-node geometry. • There are nine 'standard' HRVs and six to ten additional HRVs specifically produced to support the receptor impact modelling (RIM).
Coal resource development footprints	The spatial locations of mining activity considered in the bioregional assessment. The entire layer is 'split' against the assessment units of the bioregion or subregion.
Boundaries	Assessment boundaries of the bioregion including subregion boundary, preliminary assessment extent, assessment extent and analysis domain
Zone of potential hydrological change	The zone of potential hydrological change allocates a one-to-one mapping between assessment units, reporting regions and surface water modelling links. The mapping contained within the zone provides the assessment connection between all datasets used by the impact and risk analysis database.

BA = bioregional assessment; GLO = Gloucester subregion; HRV = hydrological response variable; MBC = Maranoa-Balonne-Condamine subregion; SW = surface water

A.6 Geoprocessing datasets

The geoprocessing BA datasets, including their relevant characteristics and rationale for inclusion as a geoprocessing dataset, are outlined in Table 10.

Table 10 Geoprocessing datasets

Datasets	Data characteristics	Rationale
Assessment units (AU)	• Regular grid cells at nominally 1000 x 1000 m (exceptions for GLO 500 m and MBC 1500 m) • Precisely aligned to the groundwater model grid cells (see below) • Unique identifier for each assessment unit.	The assessment units enable a common spatial structure for all datasets at the resolution of the regional-scale groundwater modelling. The assessment units enable the efficient linkage and transfer of data between the analysis datasets.
Blue line links and nodes	• A link-node (line and point) spatial structure interpolated from source models and, typically, based on the Geofabric Network streamlines • Precisely aligned to the surface water link-node dataset.	The blue line links and nodes enable linkages between the surface water modelling and the receptor impact modelling with other analysis datasets.

A.7 Spatial framework standards

The standard projected coordinate system for the *impact and risk analysis databases* is the standard Australian Albers (i.e. using the 132 meridian, EPSG 3577) and for the geographical coordinate system (where required), use GDA94 (EPSG 4283). The other BA standard coordinate systems (i.e. the Albers ones based on the 140 and 151 meridians) are for map making and are not affected by this decision.

Table and field naming conventions are an essential part of achieving efficient automation of geoprocessing and other database transactions. Key information that must be captured in the names are: the futures (baseline or CRDP), the hydrological response variables, the receptor impact variables, time periods and variable characteristics (absolute, relative). The naming conventions are detailed in Dataset 1 (Bioregional Assessment Programme, Dataset 1).

A.8 Geoprocessing workflow

1. The fundamental and impact analysis datasets are prepared for ingestion into *impact and risk analysis databases* as follows:
    a. The assessment unit (AU) unique identifiers and spatial geometry are stamped through the asset and landscape class datasets, effectively 'splitting' the central impact analysis datasets into pieces of data that are 1 km x 1 km. The exceptions are for the Gloucester (500 m) and Maranoa-Balonne-Condamine (1500 m) subregions for reasons explained in the relevant product 3-4 methods sections (in companion product 3-4 for the Gloucester subregion (Post et al., 2018) and for the Maranoa-Balonne-Condamine subregion (Holland et al., 2017) respectively).
    b. The area, length or count of individual ‘split’ polygons, lines and points respectively are calculated and added to the datasets.
    c. The modelling results are interpolated and summarised, then formatted to a consistent structure including consistent field and table names.

2. The data must meet certain requirements before it can be loaded into the *impact and risk analysis database.*
   a. The data must meet database schema requirements.
   b. The data must be already registered as datasets in data.gov.au to meet provenance requirements.
3. The data are loaded into the *impact and risk analysis database* as follows:
   a. A preliminary step is to load the data using a method that allows the data to be reloaded if necessary. The method also maintains a record of the loading procedure for provenance purposes.
   b. Queries are run to produce views of the data attributes and geometries that are then loaded into the *impact and risk analysis database* for each BA bioregion or subregion.
4. Once loaded into the *impact and risk analysis database* the data are used as follows:
   a. They are tracked and attributed to maintain the chain of provenance.
   b. They are served to the Assessment teams so they can conduct the impact analysis in their respective GIS environments.

Refinement is made with further queries as required.

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

aquifer: rock or sediment in a formation, group of formations, or part of a formation that is saturated and sufficiently permeable to transmit quantities of water to bores and springs

assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed. The assessment extent is created by revising the preliminary assessment extent on the basis of information from Component 1: Contextual information and Component 2: Model-data analysis.

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

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

asset element: individual spatial features – points, lines and polygons – that describe an asset spatially

at minimal risk of ecological and hydrological changes: assessment units that overlap a landscape class are considered 'at minimal risk of ecological and hydrological changes' relative to other assessment units if modelled hydrological changes result in ecological changes that do not exceed the lower thresholds of risk. These bioregion-specific thresholds are based on expert opinion and are defined using receptor impact variables. Categorisation assists the rule-out process and in identifying where further local-scale assessment is warranted.

at some risk of ecological and hydrological changes: assessment units that overlap a landscape class are considered 'at some risk of ecological and hydrological changes' relative to other assessment units if modelled hydrological changes result in ecological changes that exceed the lower thresholds of risk but do not exceed the upper thresholds of risk. These bioregion-specific thresholds are based on expert opinion and are defined using receptor impact variables. Categorisation assists the rule-out process and in identifying where further local-scale assessment is warranted.

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

baseline drawdown: the maximum difference in drawdown (dmax) under the baseline relative to no coal resource development

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

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).

depressurisation: in the context of coal seam gas operations, depressurisation is the process whereby the hydrostatic (water) pressure within a coal seam is reduced (through pumping) such that natural gas desorbs from within the coal matrix, enabling the gas (and associated water) to flow to surface

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

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

discharge: water that moves from a groundwater body to the ground surface or surface water body (e.g. a river or lake) 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 asset: an ecosystem that may provide benefits to humanity. It is a spatial area comprising a combination of biotic and abiotic components and other elements which function together.

effect: for the purposes of Impact Modes and Effects Analysis (IMEA), change in the quantity and/or quality of surface water or groundwater. An effect is a specific type of an impact (any change resulting from prior events).

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

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

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 (from 2013 to 2102). The threshold for high-flow days is the 90th percentile from the simulated 90-year period. In some early products, this was referred to as 'flood days'.

hydrogeology: the study of groundwater, including flow in aquifers, groundwater resource evaluation, and the chemistry of interactions between water and rock

hydrological response variable: a hydrological characteristic of the system that potentially changes due to coal resource development (for example, drawdown or the annual flow volume)

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

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

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

indirect impact: for the purposes of bioregional assessments, a change in water resources and water-dependent assets resulting from coal seam gas and coal mining developments with one or more intervening agents or pathways

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

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

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

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

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

likelihood: probability that something might happen

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

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

Maranoa-Balonne-Condamine subregion: The Maranoa-Balonne-Condamine subregion is mainly within the Queensland part of the Murray–Darling Basin, with a small area in New South Wales. It includes the headwaters of the Condamine River and the Maranoa River as well as the floodplains of the Upper Darling Plains. The main cities and towns are Toowoomba, Warwick, Dalby, Chinchilla, Roma, St George and Goondiwindi. Most of the land is used for agriculture. Groundwater use varies across the subregion, but is commonly extracted for stock and domestic purposes, as well as for town water supply, agriculture and coal seam gas production. Wetlands in the subregion include seasonal, semi-permanent and permanent wetlands and lagoons. Some of these wetlands are nationally significant. The Culgoa River Floodplains and the Narran Lakes system are downstream of the subregion. The northern part of the Narran Lakes system is an internationally recognised and protected wetland. Two significant cultural sites are also downstream of the subregion and could be impacted by activities in the subregion. The subregion is home to a number of water-dependent ecological communities, animals and plants which are listed as threatened under Queensland and Commonwealth legislation.

material: pertinent or relevant

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

more at risk of ecological and hydrological changes: assessment units that overlap a landscape class are considered ‘more at risk of ecological and hydrological changes’ relative to other assessment units if modelled hydrological changes result in ecological changes that exceed the upper thresholds of risk. These bioregion-specific thresholds are based on expert opinion and are defined using receptor impact variables. Categorisation assists the rule-out process and in identifying where further local-scale assessment is warranted.

Namoi subregion: The Namoi subregion is located within the Murray–Darling Basin in central New South Wales. The subregion lies within the Namoi river basin, which includes the Namoi, Peel and Manilla rivers. However, the subregion being assessed is smaller than the Namoi river basin because the eastern part of the river basin does not overlie a coal-bearing geological basin. The largest towns in the subregion are Gunnedah, Narrabri and Walgett. The main surface water resource of the Namoi subregion is the Namoi River. There are three large dams that supply water to the subregion, of which Keepit Dam is the main water storage. More than half of the water released from Keepit Dam and river inflow may be extracted for use for agriculture, towns and households. Of this, the great majority is used for agricultural irrigation. The landscape has been considerably altered since European settlement for agriculture. Significant volumes of groundwater are also used for agriculture (cropping). Across the subregion there are a number of water-dependent ecological communities, and plant and animal species that are listed as threatened under either Commonwealth or New South Wales legislation. The subregion also contains Lake Goran, a wetland of national importance, and sites of international importance for bird conservation.

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.

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

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

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)

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

severity: magnitude of an impact

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

spring: a naturally occurring discharge of groundwater flowing out of the ground, often forming a small stream or pool of water. Typically, it represents the point at which the watertable intersects ground level.

stratigraphy: stratified (layered) rocks

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

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

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

surface water zone of potential hydrological change: outside this extent, changes in surface water hydrological response variables due to additional coal resource development (and hence potential impacts) are very unlikely (less than 5% chance). The area contains those river reaches where a change in any one of nine surface water hydrological response variables exceeds the specified thresholds. 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.

transparency: a key requirement for the Bioregional Assessment Programme, achieved by providing the methods and unencumbered models, data and software to the public so that experts outside of the Assessment team can understand how a bioregional assessment was undertaken and update it using different models, data or software 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.

very likely: greater than 95% chance

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

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

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’.

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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