Australian Government

BIOREGIONAL ASSESSMENTS

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

Surface water modelling

Submethodology M06 from the Bioregional Assessment Technical Programme

10 November 2016

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 Office of Water Science, within 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 978-1-925315-46-2

Citation

Viney N (2016) Surface water modelling. Submethodology M06 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/M06..

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Cover photograph

Wards River, NSW, 10 December 2013

Credit: Heinz Buettikofer, CSIRO

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Executive summary

The surface water modelling provides key information for bioregional assessments (BAs), including estimates of the future surface water regime within the subregion or bioregion, and, in particular, those aspects of the regime subject to changes due to coal resource development.

This submethodology summarises the approaches taken in surface water modelling in BAs. It outlines options for modelling, makes recommendations on modelling tools that are fit for purpose, and highlights linkages with other components of the BAs.

Surface water modelling in the BAs is a two-stage process. Firstly, fluxes from the landscape (predominantly surface runoff, interflow and baseflow) are modelled using a streamflow model. These fluxes are then accumulated and routed through the river network using a river system model. It is recommended that, where possible, numerical modelling should use Australian Water Resources Assessment (AWRA) models: AWRA landscape model (AWRA-L) for streamflow modelling and AWRA river model (AWRA-R) for river system modelling. While other models have relatively similar prediction performance, AWRA is readily available and couples readily with the groundwater models used in BAs.

The surface water modelling outputs *hydrological response variables*, the hydrological characteristics of the system or landscape class that potentially change due to coal resource development. The following are examples of hydrological response variables:

- P01 – the daily streamflow rate at the 1st percentile (ML/day)
- ZFD – the number of zero-flow days per year. Zero streamflow is identified using the minimum detectable flow. For ease of applicability, a threshold of 0.01 ML/day is set for determining the ZFD for all surface water model nodes
- P99 – the daily streamflow rate at the 99th percentile (ML/day)
- FD – flood (high-flow) days, the number of days per year with streamflow greater than the 90th percentile from the simulated 90-year period (2013 to 2102)
- AF – the annual flow volume (GL/year)
- IQR – the interquartile range in daily streamflow (ML/day); that is, the difference between the daily streamflow rate at the 75th percentile and at the 25th percentile.

For each of the hydrological response variables, a time series of annual values is constructed.

The surface water model results are used to refine the groundwater models, particularly for surface water – groundwater interactions. The surface water model provides inputs to the boundary conditions of the groundwater model and the groundwater model provides inputs to the surface water model as changes in baseflow generation. The surface water modelling also interacts with the BA process for placing model nodes across the landscape, including on the stream network.

A sensitivity analysis is conducted to identify the parameters that affect the hydrological response variables the most. The uncertainty due to the most important parameters is then quantified.

Results from the surface water modelling are reported in product 2.6.1 (surface water numerical modelling) and in product 2.5 (water balance assessment).

These results are used in subsequent receptor impact modelling and the impact and risk analysis in the BA.

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Acknowledgements

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The author acknowledges the significant contributions of Jorge Peña Arancibia and Luk Peeters.

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 will be 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, will undertake 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.

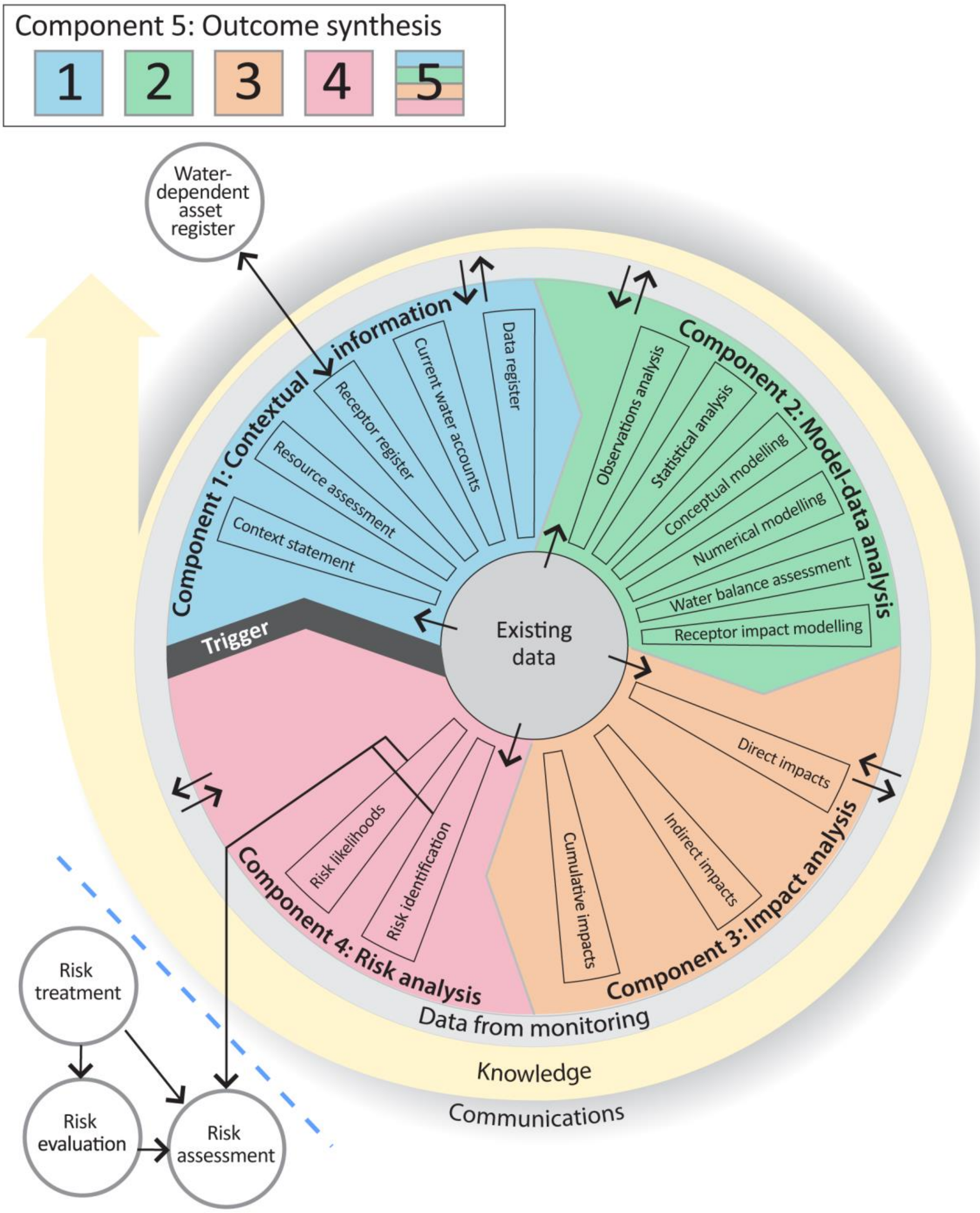

Figure 1 Schematic diagram of the bioregional assessment methodology

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 – in this case an explanation will be supplied in the technical products of that BA. Ultimately the Programme anticipates publishing a consolidated 'operational BA methodology' with fully worked examples based on the experience and lessons learned through applying the methods to 13 bioregions and subregions.

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. The copyright owners of the following figures, however, did not grant permission to do so: Figure 8. It should be assumed that third parties are not entitled to use this material without permission from the copyright owner.
- Visit http://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

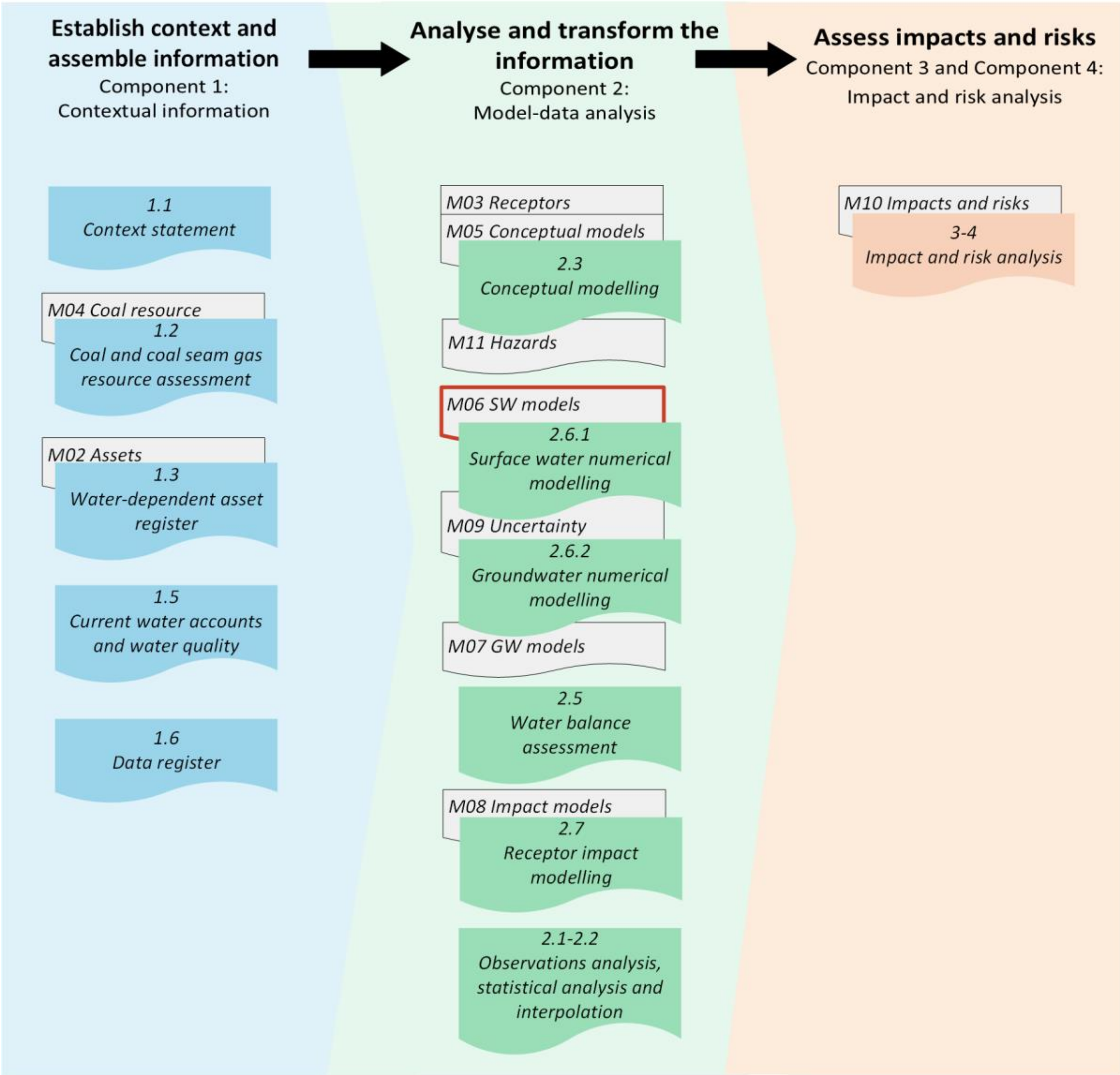

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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)

References

Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 22 June 2017, 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 22 June 2017, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

1 Background and context

A *bioregional assessment* (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 coal resource development on water and water-dependent assets. 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) provides the scientific and intellectual basis for undertaking BAs. It is further supported by a series of submethodologies of which this is one. Together, the submethodologies ensure consistency in approach across the BAs and document how the BA methodology has been implemented. Any deviations from the approach described in the BA methodology and submethodologies are to be noted in any technical products based upon its application.

A critical part of a BA is implementing a surface water model that models fluxes of water from the landscape (predominantly surface water runoff, interflow and baseflow) and, in turn, the accumulated flow through the river network. The surface water model must integrate with other BA models and processes, particularly the groundwater modelling, uncertainty analysis and receptor impact modelling. This submethodology applies overarching principles outlined in the BA methodology to the specifics of developing and running surface water models and writing product 2.6.1 (surface water numerical modelling) and product 2.5 (w*ater balance assessment)* (see Table 2 for details of BA products).

To provide context for this submethodology, Section 1.1 provides an overview of an entire BA from end to end, and the key concepts and relationships between activities within components. See Figure 3 for a simple diagram of the BA components. See Figure 4 for a more detailed diagram of the BA process that includes all the submethodologies, supporting workshops and technical products.

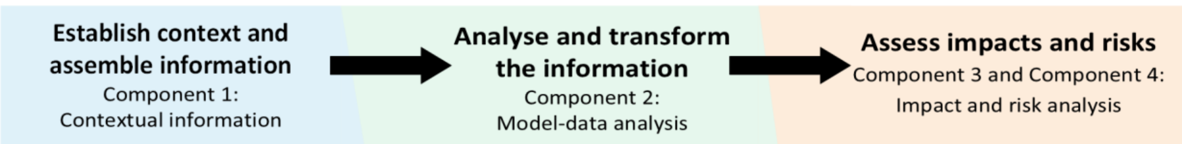

Figure 3 The components in a bioregional assessment

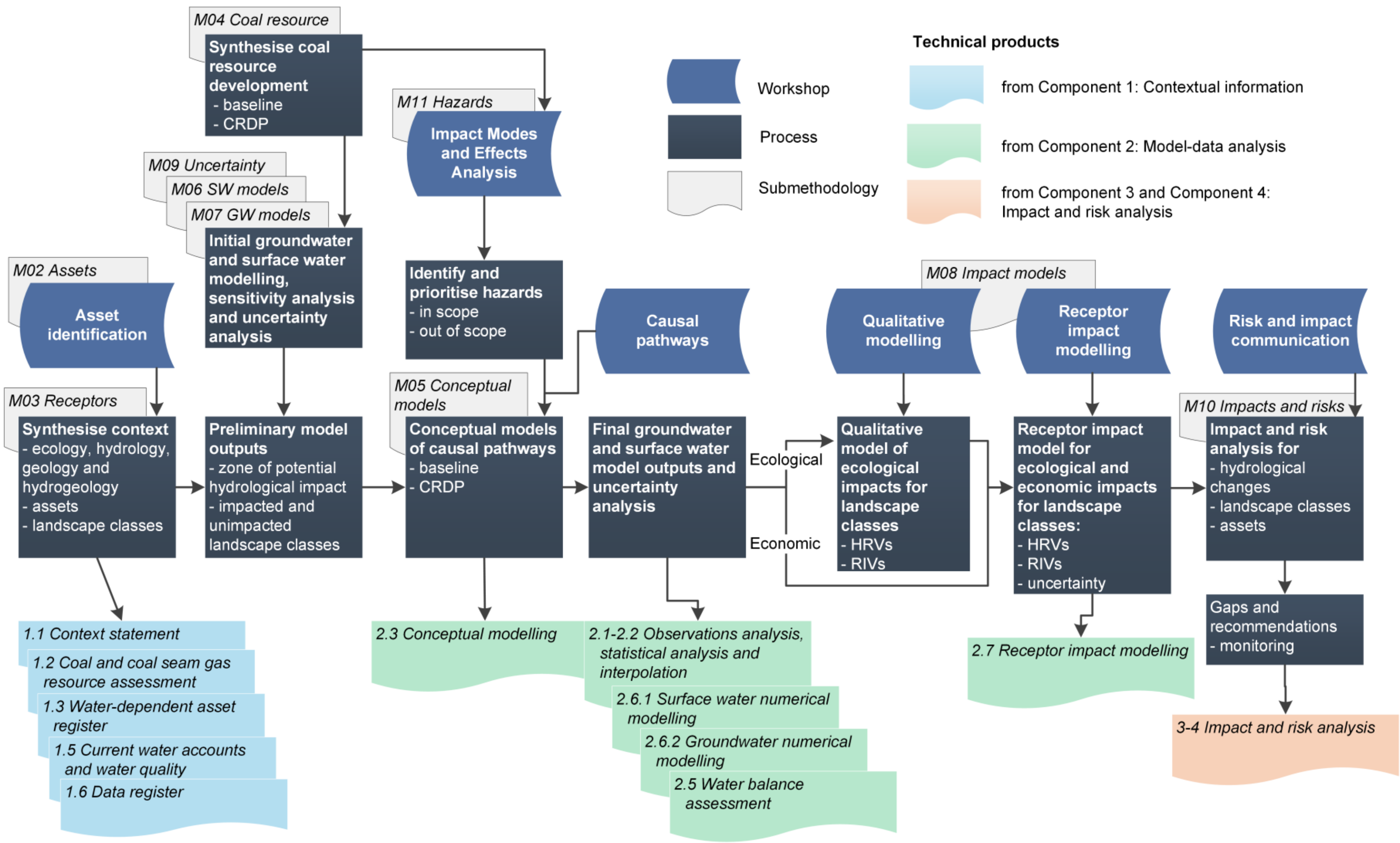

Figure 4 A bioregional assessment from end to end, showing the relationship between the workflow, technical products, submethodologies and workshops

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

1.1 A bioregional assessment from end to end

1.1.1 Component 1: Contextual information

In Component 1: Contextual information, the context for the BA is established and all the relevant information is assembled. This includes defining the extent of the subregion or bioregion, then compiling information about its ecology, hydrology, geology and hydrogeology, as well as water-dependent assets, coal resources and coal resource development.

An *asset* is an entity having value to the community and, for BA 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.

A *bioregion* is 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 BAs are conducted. A *subregion* is an identified area wholly contained within a bioregion that enables convenient presentation of outputs of a BA.

A *water-dependent asset* has a particular meaning for BAs; it is an asset potentially impacted, either positively or negatively, by changes in the groundwater and/or surface water regime due to coal resource development. Some assets are solely dependent on incident rainfall and will not be considered as water dependent if evidence does not support a linkage to groundwater or surface water.

The *water-dependent asset register* is a simple and authoritative listing of the assets within the *preliminary assessment extent* (PAE) that are potentially subject to water-related impacts. A PAE is 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 compiling of the asset register is the first step to identifying and analysing potentially impacted assets.

Given the potential for very large numbers of assets within a subregion or bioregion, and the many possible ways that they could interact with the potential impacts, a *landscape classification* approach is used to group together areas to reduce complexity. For BA purposes, a *landscape class* is 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. The rule set for defining the landscape classes is underpinned by an understanding of the ecology, hydrology (both surface water and groundwater), geology and hydrogeology of the subregion or bioregion.

Most assets can be assigned to one or more landscape classes. Each receptor belongs to one landscape class. Different subregions and bioregions might use different landscape classes. Conceptually landscape classes can be considered as types of *ecosystem assets*, which are ecosystems that may provide benefits to humanity. The landscape classes provide a systematic approach to linking ecosystem and hydrological characteristics with a wide range of BA-defined water-dependent assets including sociocultural and economic assets. Ecosystems are defined to include human ecosystems, such as rural and urban ecosystems.

Two potential futures are considered in BAs:

- *baseline coal resource development* (baseline), a future that includes all coal mines and CSG fields that are commercially producing as of December 2012
- *coal resource development pathway* (CRDP), a future that includes all coal mines and CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in results between CRDP and baseline is the change that is primarily reported in a BA. This change is due to the additional coal resource development (ACRD) – all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012.

Highlighting the potential impacts due to the additional coal resource development, and the comparison of these futures, is the fundamental focus of a BA, as illustrated in Figure 5, with the baseline in the top half of the figure and the CRDP in the bottom half of the figure. In BAs, changes in hydrological response variables and particular receptor impact variables are compared at *receptors* (points in the landscape where water-related impacts on assets are assessed).

Hydrological response variables are defined as the hydrological characteristics of the system that potentially change due to coal resource development (for example, drawdown or the annual streamflow volume). *Receptor impact variables* are the characteristics of the system that, according to the conceptual modelling, potentially change due to changes in hydrological response variables (for example, condition of the breeding habitat for a given species, or biomass of river red gums). Each landscape class and/or asset may be associated with one or more hydrological response variables and one or more particular receptor impact variables.

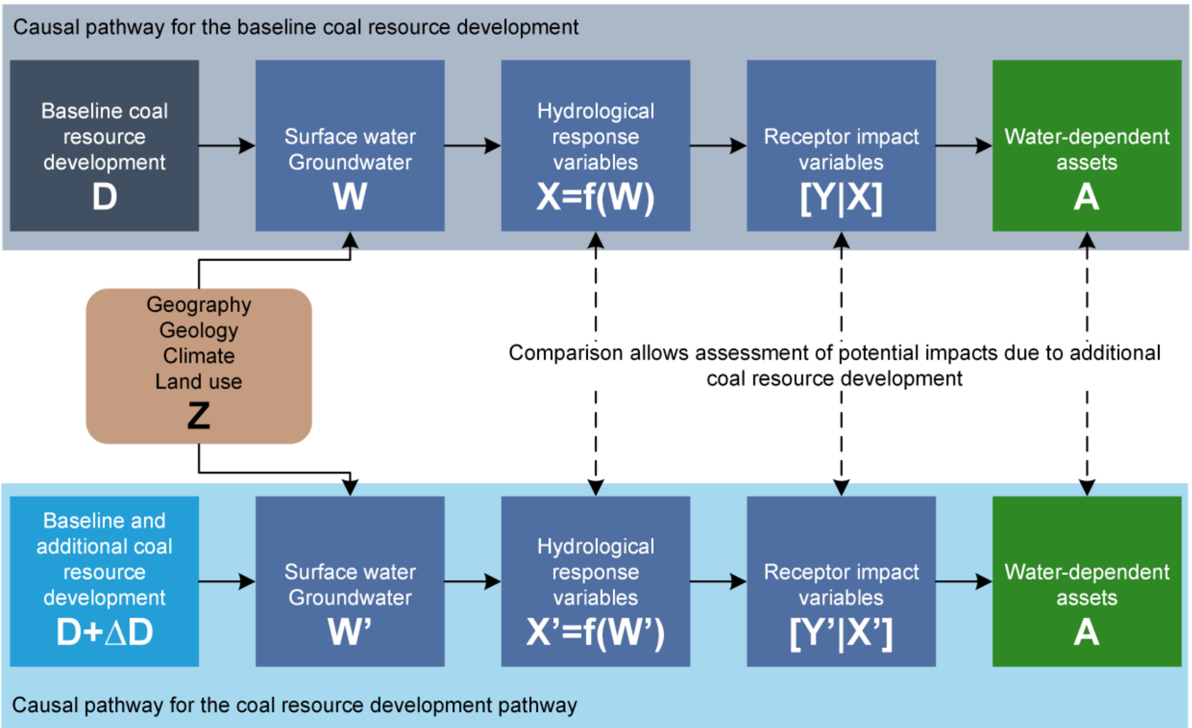

Figure 5 The difference in results for the coal resource development pathway (CRDP) and the baseline coal resource development (baseline) provides the potential impacts due to the additional coal resource development (ACRD)

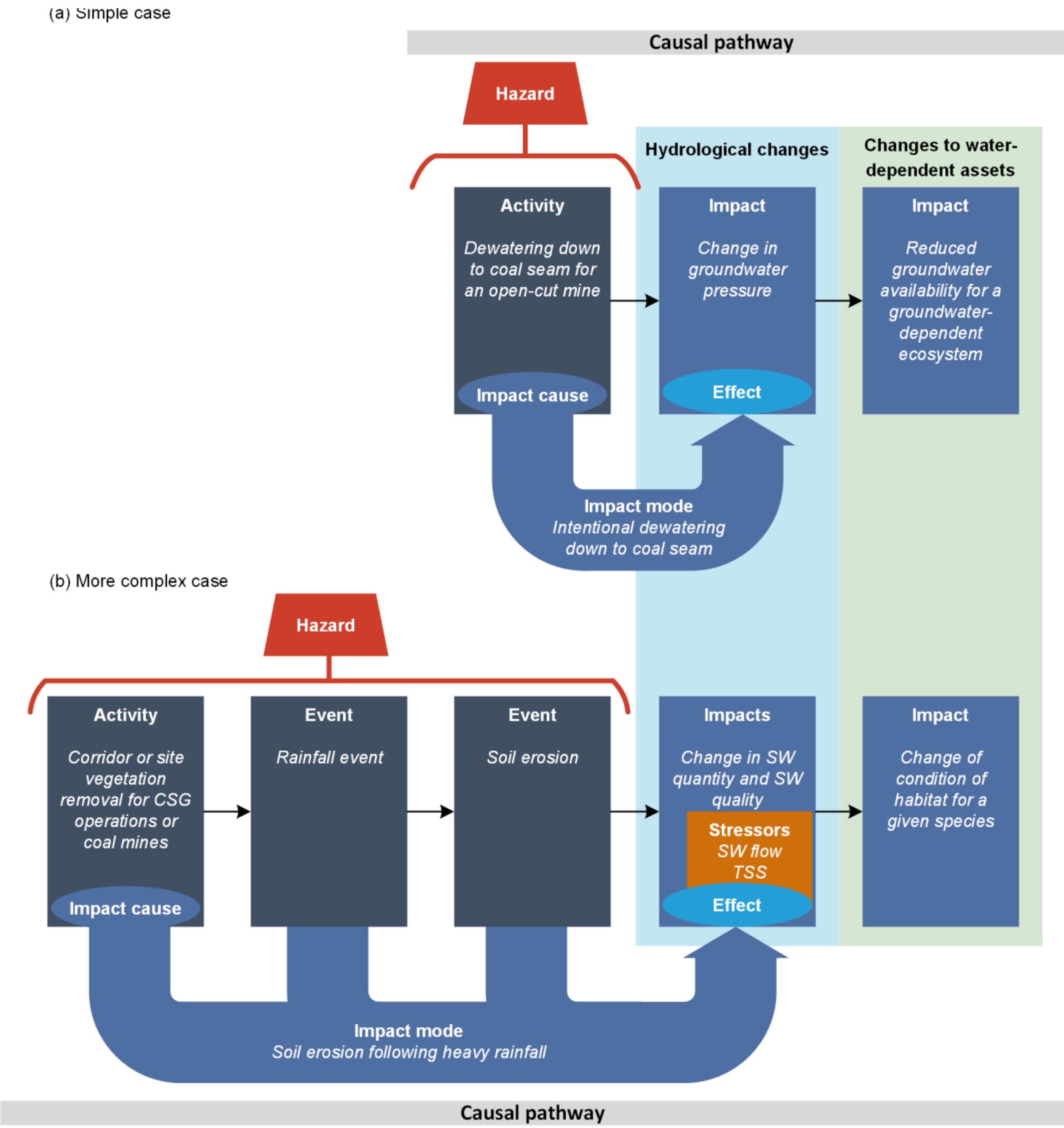

Figure 6 Hazard analysis using the Impact Modes and Effects Analysis (IMEA). This figure shows how hazards identified using IMEA are linked to changes in hydrology and water-dependent assets via causal pathways

The italicised text is an example of a specified element in the Impact Modes and Effects Analysis. (a) In the simple case, an activity related to coal resource development directly causes a hydrological change which in turn causes an ecological change. The hazard is just the initial activity that directly leads to the effect (change in the quality or quantity of surface water or groundwater). (b) In the more complex case, an activity related to coal resource development initiates a chain of events. This chain of events, along with the stressor(s) (for example, surface water (SW) flow and total suspended solids (TSS)), causes a hydrological change which in turn causes an ecological change. The hazard is the initial activity plus the subsequent chain of events that lead to the effect.

The hazards arising from coal resource development are assessed using *Impact Modes and Effects Analysis* (IMEA). A *hazard* is an event, or chain of events, that might result in an *effect* (change in the quality and/or quantity of surface water or groundwater). In turn, an *impact* (*consequence*) is a change resulting from prior events, at any stage in a chain of events or a causal pathway (see more on *causal pathways* below). An impact might be equivalent to an effect, or it might be a change resulting from those effects (for example, ecological changes that result from hydrological changes).

Using IMEA, the hazards are firstly identified for all the *activities* (*impact causes*) and *components* in each of the five *life-cycle stages*. For CSG operations the stages are exploration and appraisal, construction, production, work-over and decommissioning. For coal mines the stages are exploration and appraisal, development, production, closure and rehabilitation. The hazards are scored on the following basis, defined specifically for the purposes of the IMEA:

- *severity score*: the magnitude of the impact resulting from a hazard, which is scored so that an increase (or decrease) in score indicates an increase (or decrease) in the magnitude of the impact
- *likelihood score*: the annual probability of a hazard occurring, which is scored so that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the probability of occurrence
- *detection score*: the expected time to discover a hazard, scored in such a way that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the expected time (measured in days) to discover it.

Impact modes and *stressors* are identified as they will help to define the causal pathways in Component 2: Model-data analysis. An *impact mode* is 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. A *stressor* is a chemical or biological agent, environmental condition or external stimulus that might contribute to an impact mode.

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.

1.1.2 Component 2: Model-data analysis

Once all of the relevant contextual information about a subregion or bioregion is assembled (Component 1), the focus of Component 2: Model-data analysis is to analyse and transform the information 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 retain as many variables in play until they can be positively ruled out of contention. Further, estimates of the certainty, or confidence, of the decisions are provided where possible; again to assist the user of the BA to evaluate the strength of the evidence.

The analysis and transformation in Component 2 depends on a succinct and clear synthesis of the knowledge and information about each subregion or bioregion; this is achieved and documented through *conceptual models* (abstractions or simplifications of reality). A number of conceptual models are developed for each BA, including regional-scale conceptual models that synthesise the geology, groundwater and surface water. *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 the BA on the 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 subregion or bioregion. The causal pathways also underpin the construction of groundwater and surface water models, and frame how the model results are used to determine the severity and likelihood of impacts on water and water-dependent assets.

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). 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 latter is only used in a subset of subregions or bioregions 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 subregion or bioregion depending on data availability and the characteristics of the coal resource development in the area.

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* that 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 varying the values of the input parameters through a precisely defined and randomised range of values. 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 uncertainty framework is quantitative and coherent. The models are developed so that probabilities can be chained throughout the sequence of modelling to produce results with interpretable uncertainty bounds. Consistent and explicit spatial and temporal scales are used and different uncertainties in the analysis are explicitly discussed. The numerical and uncertainty model results are produced at specific locations known as *model nodes*. Results can be subsequently interpolated to other locations, such as landscape classes and/or assets.

The values for the hydrological response variables estimated by the numerical modelling are critical to assessing the types and severity of the potential impacts on water and water-dependent assets. This is achieved through a staged *receptor impact modelling*.

First, information and estimates are *elicited* from experts with relevant domain knowledge about the important ecosystem components, interactions and dependencies, including water dependency, for specific landscape classes. The experts have complete access to the assembled BA information, including preliminary results from the hydrological numerical modelling. The results are *qualitative ecosystem models* of the landscape classes (or assets) constructed using signed directed graphs.

Based on these qualitative models, the second stage is producing quantitative *receptor impact models* where experts, drawing on their knowledge and the extensive peer-reviewed literature, estimate the relationships between meaningful hydrological response variables and the resulting measurable change in a key characteristic of the landscape class or asset (i.e. receptor impact variables). For example, a receptor impact model could be elicited for the relationship between reduced surface water quality and the change in condition of habitat of a given species (as per Figure 6(b)). As only a small number of receptor impact variables (at least one and no more than three) will be identified for each potentially impacted landscape class, the particular receptor impact variables selected for the receptor impact modelling should be considered to be a measure of a critical ecosystem function (e.g. the base of complex food webs) and/or be indicative of the response of the ecosystem to hydrological change more broadly.

The receptor impact models are, where available, evaluated for each landscape class; this links the numerical hydrological modelling results (hydrological changes due to coal resource development) with ecological changes in water and water-dependent assets of the subregion or bioregion. Therefore, the output of Component 2 is a suite of information of hydrological and ecological changes that can be linked to the assets and landscape classes.

1.1.3 Component 3 and Component 4: Impact and risk analysis

Once all of the relevant contextual information about a subregion or bioregion is assembled (Component 1), and the hydrological and receptor impact modelling is completed (Component 2), then the impact and risk is analysed in Component 3 and Component 4 (respectively).

These components are undertaken within the context of all of the information available about the subregion or bioregion and a series of conceptual models that provide the logic and reasoning for the impact and risk analysis. Coal resource development and potential impacts are sometimes linked directly to assets (e.g. for water sharing plans); however, more often, the impacts are assessed for landscape classes which are linked to assets using conceptual models. Impacts for assets or landscape classes are assessed by aggregating impacts across those assets or landscape classes.

Results can be reported in a number of ways and for a variety of spatial and temporal scales and levels of aggregation. While all the information will be provided in order for users to aggregate to their own scale of interest, BAs report the impact and risk analysis via at least three slices (*impact profiles*) through the full suite of information.

Firstly, the hazards and causal pathways that describe the potential impacts from coal resource development are reported and represented spatially. These show the potential hydrological changes that might occur and might underpin subsequent flow-on impacts that could be considered outside BA. The emphasis on rigorous uncertainty analyses throughout BA will underpin any assessment about the likelihood of those hydrological changes. All hazards identified through the IMEA should be considered and addressed through modelling, informed narrative, considerations of scope, or otherwise noted as gaps.

Secondly, the impacts on and risks to landscape classes are reported. These are assessed quantitatively using receptor impact models, supported by conceptual models at the level of landscape classes. This analysis provides an aggregation of potential impacts at the level of landscape classes, and importantly emphasises those landscape classes that are not impacted.

Finally, the impacts on and risks to selected individual water-dependent assets are reported. These are assessed quantitatively using receptor impact models at assets or landscape classes, supported by the conceptual models. This analysis provides an aggregation of potential impacts at the level of assets, and importantly emphasises those assets that are not impacted. Given the large number of assets, only a few key assets are described in the technical product, but the full suite of information for all assets is provided on http://www.bioregionalassessments.gov.au. Across both landscape classes and assets the focus is on reporting impacts and risks for two time periods: a time related to peak production in that subregion or bioregion, and a time reflecting more enduring impacts and risk at 2102.

The causal pathways are reported as a series of impact statements for those landscape classes and assets that are subject to potential hydrological impacts, where there is evidence from the surface water and groundwater numerical modelling. Where numerical modelling results are not available, impact statements will be qualitative and rely on informed narrative. If signed directed graphs of landscape classes are produced, it might be possible to extend impact statements beyond those related to specific receptor impact variables, to separate direct and indirect impacts, and to predict the direction, but not magnitude, of change.

In subregions or bioregions without relevant modelled or empirical data, the 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 in or out.

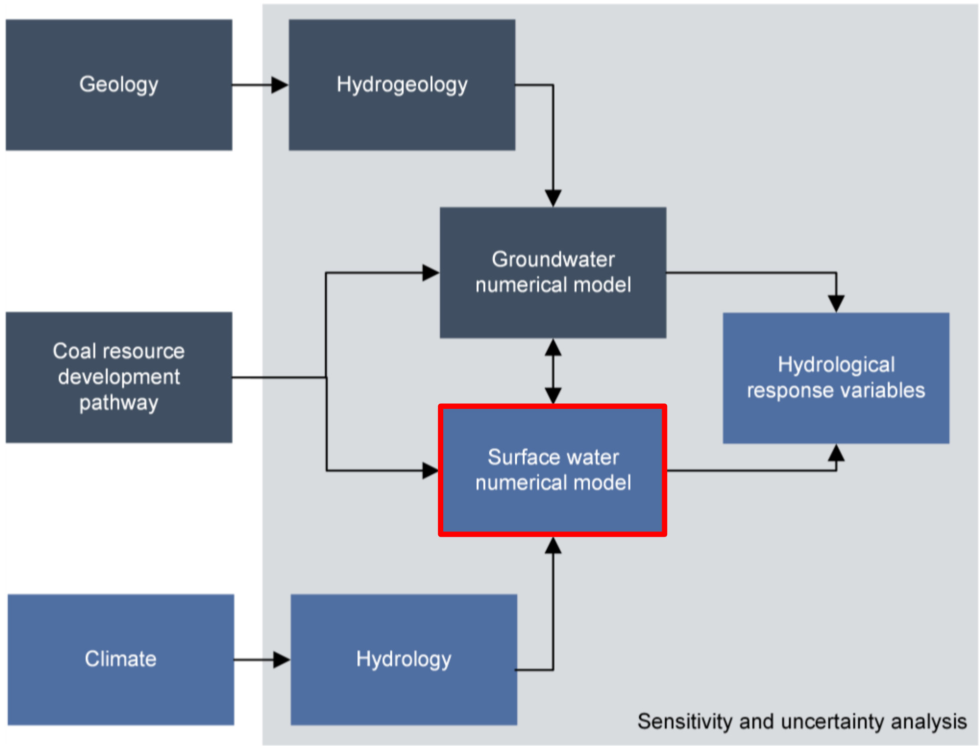

Figure 7 Data flows for surface water modelling (red outline) showing connections to closely related bioregional assessment activities including the sensitivity and uncertainty analysis (light grey box)

Conceptual representation of the data flows to and from the groundwater and surface water models, including the sensitivity and uncertainty analysis (light grey box), which considers uncertainties in input parameters and carries them through to hydrological response variables. Surface water modelling uses the Australian Water Resources Assessment (AWRA) model suite, while the groundwater model varies between subregions and bioregions.

1.2 Role of this submethodology in a bioregional assessment

This submethodology (M06) is intended to assist those conducting a BA to model surface water flows, in particular landscape (streamflow) modelling, river system modelling and constituent (salt) modelling. It provides the basis for identifying areas of a subregion or bioregion where the hydrological impact of coal resource development occurs due to changes in surface water flows. The model delivers spatially explicit model outputs that are used as inputs to other BA models and processes, including groundwater modelling, uncertainty analysis and receptor impact modelling, and directly to evaluate impact on water resources. Interactions between several processes in a BA are involved in surface water modelling (Figure 7).

Results from the surface water modelling are reported in product 2.6.1 (*surface water numerical modelling)* and in product 2.5 (*water balance assessment).*

The development of the surface water model relies on input from:

- the context statement (product 1.1)
- the coal and coal seam gas resource assessment (product 1.2)
- the hazard analysis (product 2.3)
- the conceptual model of causal pathways (product 2.3)
- groundwater modelling (product 2.6.2).

Readers should consider this submethodology in the *context* of the complete suite of methodologies and submethodologies from the Bioregional Assessment Programme (see Table 1), particularly 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), which remains the foundation reference that describes, at a high level, how BAs should be undertaken. Submethodology M06 is most strongly linked to the following submethodologies:

- submethodology M04 for developing a coal resource development pathway (Lewis, 2014)
- submethodology M05 for developing a conceptual model of causal pathways (Henderson et al., 2016)
- submethodology M07 for groundwater modelling (Crosbie et al., 2016)
- submethodology M08 for receptor impact modelling (as listed in Table 1)
- *submethodology M09 for propagating uncertainty through models (Peeters et al., 2016)*
- submethodology M11 for hazard analysis (Ford et al., 2016).

2 Components of surface water modelling

2.1 Aims of surface water modelling

The aim of surface water modelling in bioregional assessments (BAs) is to provide information on flow characteristics at locations in the stream networks that are relevant for key water-dependent assets. In particular, the modelling needs to account for changes in flow regime that relate directly to the impacts of future coal mining and coal seam gas extraction. This modelling forms the basis for product 2.5 (water balance assessment) and product 2.6.1 (surface water numerical modelling).

2.2 Components of surface water modelling

In most subregions and bioregions, surface water modelling is done in a two-stage process. Firstly fluxes from the landscape (predominantly surface runoff, interflow and baseflow) are modelled using a streamflow model (also called a landscape model or a rainfall-runoff model). These fluxes are then accumulated and routed through the river network using a river system model.

There are several modelling options available for each of these stages. These options, together with recommended models, are discussed in Chapter 3 and Chapter 4.

Given the operational constraints for modelling in BAs, it is clearly desirable to adopt any pre-existing models where possible. If no existing model is suitable, then efforts should be next directed towards adapting an existing model by making appropriate and necessary changes to its algorithms or mode of operation. Only as a last resort should resources be directed towards building new models.

3 Streamflow modelling

3.1 Considerations in streamflow modelling

Streamflow modelling (also called rainfall-runoff modelling) takes input from meteorological data (primarily rainfall and potential evaporation) and produces inflows to the stream network. Almost all streamflow models contain parameters with unknown values, which must be estimated by calibration. This calibration is usually done by comparing predicted streamflows with those observed at streamflow gauging stations (Viney et al., 2014).

The major challenge in streamflow modelling is to produce credible predictions of streamflow in ungauged parts of the modelling domain. This usually involves the estimation of appropriate model parameters to use in those parts of the landscape. This process of parameter estimation in the absence of direct calibration is called regionalisation (Viney et al., 2014).

There are two broad categories of regionalisation. One involves using parameter values from a gauged catchment that is considered to share similar characteristics (climate, soils, vegetation, geomorphology) to the ungauged area. Often, it is found that the simple expedient of using parameters from the nearest gauged catchment is among the best regionalisation methods. Implicit in this nearest-neighbour approach is the assumption that catchments in proximity are likely to share similar physical and hydrological characteristics and that therefore, optimal models of each of them will also share similar parameter values. However, there is a significant degradation in model performance with this type of regionalisation as regionalisation distance increases (Viney et al., 2014).

The second regionalisation approach involves simultaneous calibration of a model using observations from several nearby gauging stations. In this approach, the calibration procedure uses a single objective function that combines the prediction responses in all gauged catchments and results in a single set of model parameter values that provide best fit to the streamflow observations from all gauges. The key assumption here is that if a single set of parameter values provides good predictions in the gauged catchments it might also be expected to provide good predictions in adjacent ungauged areas. This regionalisation approach is called regional calibration (Viney et al., 2014). Unlike nearest-neighbour calibration, the performance of regionally calibrated models does not degrade with distance from the calibration catchments and is likely to lead to more stable predictions in ungauged parts of the modelling domain.

The temporal and spatial scales of streamflow modelling are dictated largely by the temporal and spatial scales of the available meteorological input data. The bioregional assessments (BAs) use meteorological data from the dataset of the Bureau of Meteorology's Australian Water Availability Project (Bureau of Meteorology, 2016a). These data use a daily time step and are presented on a grid with spacing of 0.05 degrees of latitude and longitude (approximately 5 km). Thus, it follows that the smallest temporal element in the raw streamflow modelling is one day and the smallest spatial element is 0.05 degrees. Note that this raw spatial scale does not preclude modelling at finer spatial scales through interpolation, and nor does it preclude the assessment of the impacts of coal resource developments with sub-pixel extents.

3.2 Modelling options

A large number of streamflow models exist in the literature and many of them have been applied widely in Australia. These include:

- GR4J (Perrin et al., 2003)
- Sacramento (Burnash et al., 1973)
- Simhyd (Chiew et al., 2002)
- IHACRES (Croke et al., 2006)
- SMAR-G (Goswami et al., 2002)
- AWBM (Boughton, 2004)
- AWRA-L (Viney et al., 2015)
- LASCAM (Sivapalan et al., 2002).

The first six of these models are typical rainfall-runoff models. Most are relatively parsimonious in their parameterisation. They are amenable to both nearest-neighbour regionalisation and regional calibration. Studies comparing their prediction quality in Australia (e.g. Viney et al., 2014) generally indicate that these models have relatively similar prediction performances. Sacramento is the model usually adopted to provide tributary inflows in state agency river system models (e.g. IQQM and Source Rivers; see Chapter 4).

AWRA-L (Viney et al., 2015) is designed for use in a regional calibration setting using gridded input. This regional calibration approach is assisted by the model's explicit inclusion of vegetation density as a factor controlling streamflow generation. AWRA-L is typically calibrated Australia-wide to yield a single continental parameter set. A recent comparison study by Viney et al. (2014) shows that AWRA-L provides streamflow predictions with an improved fit to observations relative to the Sacramento and GR4J models whether the latter are implemented using either nearest-neighbour regionalisation or regional calibration. AWRA-L is part of a suite of models in the AWRA (Australian Water Resources Assessment) system (Bureau of Meteorology, 2016b) which also includes a river routing module (AWRA-R). At present, these two components operate together in an uncoupled fashion, but work is underway in CSIRO to develop a fully coupled AWRA model. This fully coupled model is not available for use in the current round of BAs, but may be available for future BAs.

LASCAM has been designed for use at the large catchment scale. Like AWRA-L, LASCAM explicitly includes the effects of vegetation density and has been designed for use in a regionally-calibrated context. LASCAM also includes an embedded routing scheme, thus meaning that it can also replicate many of the functions of a river system model. LASCAM has recently been used in a study in the Namoi subregion by Schlumberger Water Services (2012), but has not been applied in any of the other subregions. This application in the Namoi subregion appears to have been done with limited calibration. Unlike the other candidate models, LASCAM has not yet been implemented using gridded input, although this could be readily done. It also requires more input data and can be difficult and time-consuming to calibrate properly.

3.3 Recommended modelling approach

It is desirable – although by no means requisite – that a consistent modelling approach be adopted across all the bioregions in the Bioregional Assessment Programme. Since the adopted model will be used for both futures (baseline and coal resource development pathway (CRDP)), it is also desirable that a common set of model parameters be used in each subregion or at least in each major river basin in a subregion. This is not just for practical reasons, but also to ensure that the true spatial heterogeneity of runoff generation is represented across the modelling domain, with no significant spatial discontinuities that might arise as artefacts of regionalisation. This rules out the use of nearest-neighbour regionalisation, although all candidate models are capable of being deployed in a regional calibration mode.

Given its adoption for the Bureau of Meteorology's water accounts and assessments (Bureau of Meteorology, 2016b), its prediction performance relative to other rainfall-runoff models, its ready availability to the BA modelling team, and the ability to make the code and executables publicly available, it is recommended that AWRA-L be the streamflow model adopted for BAs. Furthermore, it is recommended that AWRA-L be implemented using regional calibration.

In the main – and modelling of impacts of coal resource development notwithstanding – this approach falls somewhere between the adopt and adapt strategies canvassed in Section 2.2.

There is a requirement that the models used in the BAs, including their code, executables, data and parameters, be made publicly available. All open access data used in the AWRA-L model will be made available through data.gov.au as well as all output data from the model. The metadata for the model will direct users to where the model can be downloaded.

3.4 Streamflow modelling methodology

3.4.1 Spatial and temporal resolution

AWRA-L operates on a daily time step using gridded input. It is applied in a modelling domain that includes not just the subregion itself, but also extends upstream of the subregion boundaries to include all upstream tributaries, and downstream of the subregion boundaries to include all of the preliminary assessment extent and all of its tributaries. Raw output is gridded at the same spatial scale as the input data.

Each spatial unit (grid cell) in AWRA-L is divided into a number of hydrological response units (HRUs) representing different landscape components. Hydrological processes are modelled separately for each HRU before the resulting fluxes are combined to give cell outputs. The current version of AWRA-L includes two HRUs which notionally represent (i) tall, deep-rooted vegetation (i.e. forest), and (ii) short, shallow-rooted vegetation (i.e. non-forest). Hydrologically, these two HRUs differ in their aerodynamic control of evaporation, in their interception capacities and in their degree of access to different soil layers.

3.4.2 Data requirements

AWRA-L requires the following data:

- gridded daily rainfall
- gridded daily potential evaporation (or the raw data from which to estimate it – e.g. gridded daily maximum and minimum temperature, vapour pressure, wind speed, etc.)
- proportion of deep-rooted vegetation in each grid cell
- time series of remotely sensed leaf area index for each grid cell
- daily streamflow at multiple sites
- catchment boundaries for each streamflow measurement site.

The meteorological and vegetation datasets are readily available to modellers in the Bioregional Assessment Programme and are ready to use immediately. Streamflow records are available from the Bureau of Meteorology. However, there are substantial variations in the quality of observed streamflow records (Zhang et al., 2013), so there is likely to be a role for programme staff to vet data from individual streamflow gauges before it can be used in model calibration. Catchment boundaries can be extracted from the Australian Hydrological Geospatial Fabric (Geofabric) dataset (Bureau of Meteorology, 2016c) using the best available digital elevation and gauge location information.

3.4.3 Calibration

Because of the nature of the BA application – in particular that it is mostly focused on the differences between model runs, rather than on absolute predictions, and that its results are presented in an uncertainty framework – the importance of model calibration is less than it is in most other surface water modelling applications. Nonetheless, model calibration still forms part of the methodology.

The streamflow model is calibrated separately in each subregion using streamflow observations from gauging sites in and near the subregion. Selection criteria for calibration gauges include that the gauges, where possible, should:

- have catchment areas greater than 50 km^2
- have at least ten years of observed streamflow data since 1983
- have no significant flow regulation (e.g. upstream reservoirs, irrigation withdrawals, mining)
- be non-nested (i.e. not directly upstream or downstream of another selected gauge).

Since the objective of this calibration is to obtain a single set of model parameters, there should be no impediment to using nearby observations even if they are from catchments outside the modelling domain. Indeed, some subregions contain few, if any, streamflow gauges, so it is necessary to use data from further afield or to relax one or more of the selection criteria. Observations from at least two gauges, and preferably more, should be used in the calibration process. The prediction performance in these calibration catchments should be summarised statistically and combined into a single objective function for optimisation.

In most subregions, the parameters to be calibrated are those designated by Viney et al. (2015) as the parameters that are typically and routinely calibrated in AWRA-L applications.

Two calibration runs are performed, one with an objective function biased towards high flows and one with an objective function biased towards low flows. This is because streamflow at both ends of the hydrograph spectrum are likely to be important for receptor impact modelling and for water balance estimation.

The objective functions used in calibration should seek to optimise the joint prediction of temporal variability in the streamflow hydrographs and the overall bias in model prediction. This can be achieved by basing calibration on the methodology of Viney et al. (2009). In the case of the high flow calibration, a function *F*, which characterises prediction quality, is evaluated for each catchment. This function is given by:

$$F = \frac{E_d(1.0) + E_m}{2} - 5|\ln(1 + B)|^{2.5} \tag{1}$$

where $E_d(1.0)$ is the daily Nash-Sutcliffe efficiency with a Box-Cox lambda value of 1.0, E_m is the monthly Nash-Sutcliffe efficiency and *B* is the bias (prediction error divided by sum of observations). The optimiser then maximises an objective function that is given by:

$$OF = \frac{F_{25} + F_{50} + F_{75} + F_{100}}{4} \tag{2}$$

where F_n is the *n*th percentile of the *F* values in the calibration catchments.

In the case of the low flow calibration, *F* is given by:

$$F = E_d(0.1) - 5|\ln(1 + B)|^{2.5} \tag{3}$$

where $E_d(0.1)$ is the Nash-Sutcliffe efficiency with a Box-Cox lambda value of 0.1. These *F* values are used along with the same functional form for the objective function as for the high flow calibration.

Although the two resulting deterministic model predictions are not used directly in reporting BA outcomes, they are used in BAs to:

- inform prior parameter distributions for the uncertainty analysis
- provide recharge estimates for surface water – groundwater modelling
- populate water balance estimation.

The calibration period used will depend in part on the temporal coverage of the available streamflow observations. Ideally, the calibration period should cover at least 20 years – preferably in recent decades – and should be preceded by at least 10 years of spin-up to allow water stores to equilibrate. In subregions or river basins where 20 years of observational data are not available, consideration should be given to including streamflow observations from farther afield into the response dataset.

Previous applications and assessments of AWRA-L (Viney et al., 2014) have indicated that there is little difference in model performance between the catchments used in calibration and those used in independent validation. For this reason, it is recommended that no independent validation be done on AWRA-L modelling in the Bioregional Assessment Programme. This frees up all the available streamflow data to be used in calibration to better constrain model parameters. It also means that the quality of the model's performance in the calibration catchments will provide a strong indication of its performance in other parts of the modelling domain. There will, however, be validation of model performance during the uncertainty analysis against observations of several metrics of streamflow.

3.4.4 Modelling impacts of coal resource development

Coal resource development is defined with two potential futures:

- *baseline coal resource development* (baseline), a future that includes all coal mines and coal seam gas (CSG) fields that are commercially producing as of December 2012
- *coal resource development pathway* (CRDP), a future that includes all coal mines and coal seam gas (CSG) fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in development between CRDP and baseline is defined as the *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.

Highlighting the potential impacts due to the additional coal resource development, and the comparison of these futures, is the fundamental focus of a BA.

In order to assess the impacts due to the additional coal resource development, the surface water modelling undertaken in the BAs must produce and compare outputs from two simulations: a baseline simulation without the additional coal resource development and a CRDP simulation with the additional coal resource development.

The starting date for the two simulations is January 2013.

Any pre-existing coal resource developments (i.e. those that were commercially producing before 2013) are included in both simulations. The modelling outputs report the changes in surface water availability between the baseline and CRDP.

Some proposals for coal resource developments contain insufficient information to allow meaningful modelling. For example, they may be lacking in groundwater pumping rate information or detailed development footprint information. Such proposals will be dealt with through commentary only. Only those proposals that do have sufficient information will be modelled and it is those developments that are considered here and are of relevance to the modelling outcomes in product 2.5 (water balance assessment) and product 2.6.1 (surface water numerical modelling).

3.4.5 Climate input

The key outcome of the BAs is in determining how the additional coal resource development leads to changes in flow regime and risks to water-dependent assets. In reality, this can be achieved using any (consistent) climate input signal for the two simulation runs. Nonetheless, it is possible that the magnitudes of these changes could be different when the coal resource developments are superimposed over different baseline climates. It is therefore ideal – though not crucial – that the projections into the future for both simulations use climate input that reflects likely climate change trends. To be consistent with the philosophy of the CRDP, a single 'mid-range' future climate time series will be constructed.

It is important to recognise that the BA is not a climate change study. The main focus is on the impacts of coal resource development activities on water resources and water-dependent assets. Both the baseline and CRDP simulations will use the same climate input; BA is interested in the differences between the two simulations caused by the coal resource development, not the impact of climate change on streamflow characteristics.

3.4.5.1 Construction of future climate input

As the future climate is unlikely to be stationary, it is desirable to incorporate a trajectory of likely climate change in the future climate time series from January 2013 to December 2102. To avoid a climate change signal being present in the donor time series used for creating a future climate time series, and to ensure the donor series has the highest notional data quality, a shorter 30-year period will be used as the basis for generating the future climate time series. A recent 30-year period (January 1983 to December 2012) will be assumed short enough that a changing climate trend is not significant and assumed to be long enough to be representative of the climate variability (i.e. contains the millennium drought in southern Australia and the floods of 2011 in some subregions). The 30-year historical climate time series will be repeated three times to create a 90-year time series.

Global climate model (GCM) outputs will be downscaled separately for each 30-year period using the 'seasonal scaling' approach described by Chiew et al. (2009). This is neither the most sophisticated nor the simplest method of downscaling, but has been proven to be effective and the method will require little development to be adapted for use in BA. The three 30-year periods will be modelled as step changes in climate, nominally representing 2030, 2060 and 2090. The seasonal scaling method modifies the historical time series using seasonal scaling factors and then modifies the daily rainfall according to the projected change in temperature and the GCM-predicted change in rainfall per degree of climate change.

The very simplistic representation of the future climate time series and ignoring of the uncertainty in the future climate are justified as the BA projects are not investigating the impact of climate change upon the assets and receptors. The only two forward modelling runs that will be conducted are the baseline and the CRDP. The future climate time series will be used for both runs and so it will not be possible to disentangle the impact of the future climate from the impact of the future coal resource development upon the assets and receptors.

The landscape modelling will be conducted using the 90-year future climate time series on a daily basis to create the input time series for the river and groundwater modelling (runoff and recharge, respectively). The river modelling will be conducted using the entire 90-year future climate time series. The groundwater modelling will be conducted on a monthly time step for the 90-year period until 2102 to enable the surface water – groundwater interactions to be accounted for in the river modelling.

3.4.5.2 Choice of climate change signal

In each subregion, the future climate series will be based on the projections of a single global climate model (GCM) and a single emissions scenario. This choice of GCM and emissions scenario must be transparent and defensible. There is considerable uncertainty in future climate projections so a desktop study will be conducted of previous comparison studies to determine an appropriate GCM for each subregion.

In all bioregions, climate projections from 15 GCMs[1] are available. Associated with each GCM are local scaling factors which give the change in rainfall expected per degree of global warming. We will use scaling factors for the AR4 emissions scenario A1B (IPCC, 2007). Depending on GCM, the scaling factors may be seasonal or monthly. Together with seasonal or monthly trends in historical rainfall, it is possible to use these scaling factors to assess the change in mean annual rainfall associated with each GCM. In each subregion, we will choose the scaling factors from the GCM that produces the median change in mean annual rainfall.

3.4.6 Methodological variations among the bioregions

It is expected that in all subregions where new modelling is being undertaken, the application of the landscape model will closely follow the methodology outlined in Section 3.4.

The most likely scope for variation is in the selection of a suitable objective function for calibration of the low flow parameter set. This choice might be dictated at the local level by two factors: the nature of the flow characteristics and the required hydrological response variables. An objective function for a low flow calibration, for example, might include a metric describing the degree of intermittency in streamflows. Such a metric, however, might be redundant in a subregion where streams are typically permanent.

In subregions where analysis will be based on existing model results – which are likely to come from models other than AWRA-L – it is likely that these results will have been generated from a single set of model parameters, most likely one that is predicated largely on high flows. This means that projected impacts on low flow characteristics may be more uncertain in these subregions.

1These 15 AR4 model runs that underpinned the 2007 Climate Change in Australia Projections were used as these were what was available at the time.

4 River system modelling

4.1 Modelling options

There are three existing models that could potentially be used for river system modelling. They are:

- IQQM (Simons et al., 1996)
- Source Rivers (Welsh et al., 2013)
- AWRA-R (Dutta et al., 2015).

IQQM (Integrated Quantity and Quality Model) is the model that forms the basis of most state agency river models in NSW and Queensland. It has been developed to aid the development and assessment of water sharing plans and river management rules. IQQM models have been developed for all river basins in the Northern Inland Catchments bioregion and for some of the coastal river basins in the remaining bioregions.

Source Rivers is a recent extension of IQQM that also includes some of the functionality of river system models used in other jurisdictions (e.g. Victoria).

AWRA-R has been developed as the river modelling component of the AWRA modelling system. It is a simplified version of Source Rivers that includes most, but not all, of the functionality of the latter. However, it additionally includes explicit representation of surface water – groundwater interactions and a floodplain modelling algorithm, as well as having a more robust calibration methodology. AWRA-R has been applied widely throughout the Murray–Darling Basin and in many other river basins in eastern Australia. The two components of the AWRA modelling system are currently operated uncoupled, but work is underway on coupled operation.

The option of adopting pre-existing models is not viable for the river system modelling in bioregional assessments (BAs). In general, it will be necessary to modify existing models to account for changes in flow associated with the baseline and coal resource development pathway (CRDP). This, in turn, will dictate that the river system models will require recalibration in every basin. Indeed, the need for recalibration of IQQM and Source Rivers models is also dictated by the use of different runoff inputs to those with which the models were originally calibrated.

4.2 Recommended modelling approach

As with the streamflow modelling component of the surface water modelling in BAs, it is desirable that, as far as possible, the river system modelling component be conducted using a consistent methodology and modelling platform. There is also a requirement that the models used, including their code, executables, data and parameters, be made publicly available.

In the light of access and publication difficulties with IQQM and Source Rivers, AWRA-R appears to be the best option for river system modelling in the Bioregional Assessment Programme.

Apart from the accessibility of its code, AWRA-R offers several other advantages for BA modelling. It is relatively easy to set up and calibrate and there is ready access to local expertise. Secondly, AWRA-R explicitly accounts for surface water – groundwater interactions, includes a floodplain modelling component and does not include unaccounted losses and gains. Thirdly, the robustness and rigour of AWRA-R's automated single-step calibration procedure is particularly appropriate for the purposes of BA modelling. Finally, although AWRA-L and AWRA-R will be used in an uncoupled fashion during the BAs, ongoing work to fully couple the two models means that future incarnations of BAs can easily transition to this coupled model.

AWRA-R is under active development by partners within the Bioregional Assessment Technical Programme, including by some members of the Bioregional Assessment Programme. During the course of the Bioregional Assessment Programme, new functionality has been added to AWRA-R to account for simple management rules, dam releases and irrigation demand (see Appendix A). There is agreement on cooperation between the developers of AWRA-R and the Bioregional Assessment Programme on further mutually beneficial development, user training and ongoing assistance.

In the main – and modelling of impacts of coal resource development notwithstanding – the use of AWRA-R in BA falls somewhere between the adopt and adapt strategies canvassed in Section 2.2.

4.3 River system modelling methodology

4.3.1 Overview of AWRA-R

A brief model overview of AWRA-R is presented in this section. A complete technical description, governing equations and justifications of structure and specific parameter values are reported in Dutta et al. (2015). New components of AWRA-R that have been added specifically for BA are described in Appendix A.

The AWRA-R model uses a node-link concept, where a river system is schematised into a simplified river network using a node-link structure. The river network begins and ends with a node, and all nodes are interconnected by links. A link is used for transfer of flow between two nodes with routing. Runoff from gauged or ungauged tributaries or local contributing area between two nodes is fed into the connecting link as an inflow at the relevant location; all other physical processes (such as diversions, groundwater fluxes, overbank flow) occurring between the two nodes are incorporated in the link (Dutta et al., 2015). AWRA-R includes the following modules that are used to compute different parts of the water balance (Figure 8):

- rainfall and runoff
- a routing scheme that also includes the estimation of the volume in the river bed and associated fluxes
- irrigation modelling, calibrated outside AWRA-R using crop modelling based on Food and Agriculture Organization of the United Nations crop factors and soil moisture accounting, and on-farm storage and variable source allocation (Hughes et al., 2014)
- floodplain dynamics using empirical relations between flood height and floodplain volume

- interactions between surface water and groundwater with simple conceptual models describing connected and unconnected systems
- a storage component relating storage outflow to the storage water balance.

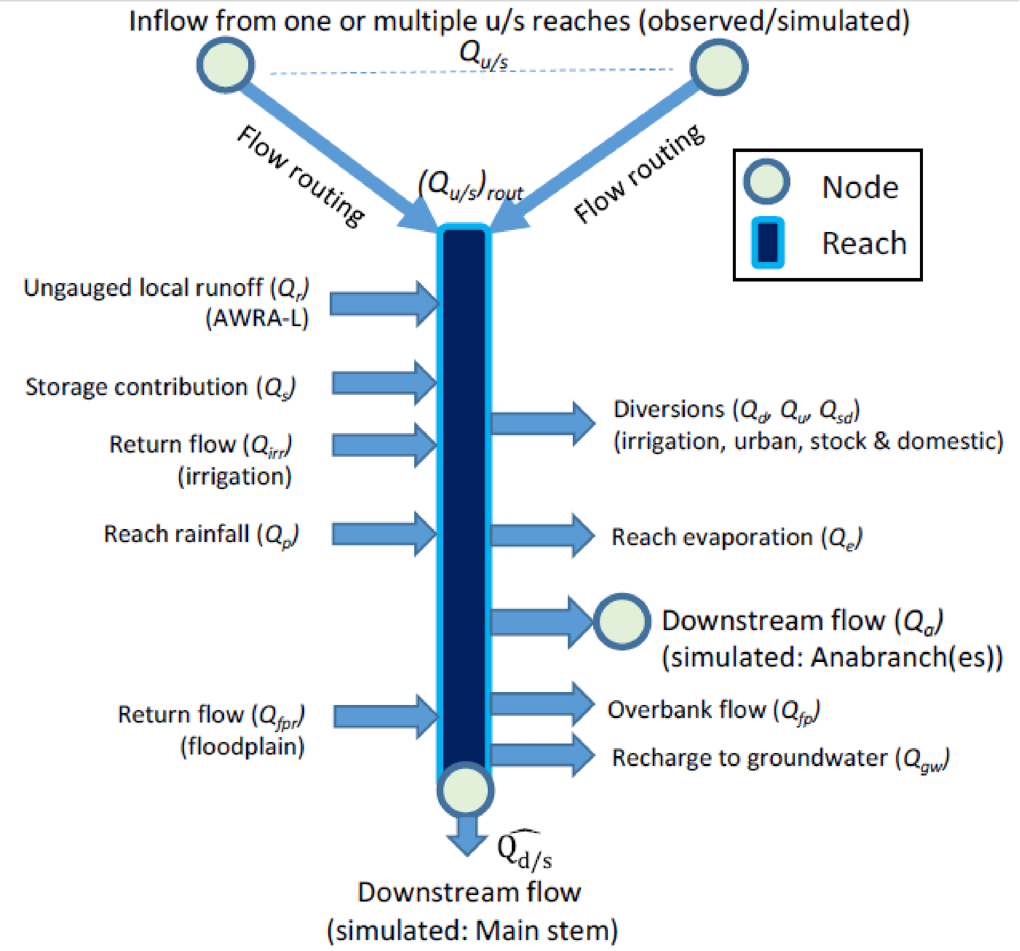

Figure 8 Schematics of AWRA-R with the different modelling components

Source: Figure 2.2 in Dutta et al. (2015). This figure is not covered by a Creative Commons licence. It has been reproduced with the permission of the CSIRO Land and Water.

4.3.2 Data requirements

AWRA-R requires the following data:

- gridded daily rainfall
- gridded daily potential evaporation (or the raw data from which to estimate it – e.g. gridded daily maximum and minimum temperature, vapour pressure, wind speed, etc.)
- daily streamflow at multiple sites
- rating curve information at stream gauging sites
- catchment boundaries for each streamflow measurement site
- historical reservoir release fluxes.

The meteorological datasets are readily available to modellers in the Bioregional Assessment Programme and are ready to use immediately. Streamflow records are available from the Bureau of Meteorology. However, there are substantial variations in the quality of observed streamflow records (Zhang et al., 2013), so there is likely to be a role for programme staff to vet data from individual streamflow gauges before it can be used in model calibration. Catchment boundaries can be extracted from the Geofabric dataset (Bureau of Meteorology, 2016c) using the best available digital elevation and gauge location information. Fluxes of reservoir release are available from state agencies.

4.3.3 New functionality in AWRA-R

AWRA-R was originally developed to provide daily retrospective estimates of water fluxes and stores in both regulated and unregulated river systems. The original model does not include management rules to determine allocations nor control of dam releases. In order to model river flow in regulated reaches, the AWRA-R model needs to determine allocations to compute the dam releases needed as inflow into the river system. To this end, new functionality was developed for BAs that performs a resource assessment and simulates downstream water demand (for irrigation, mining, industry, town water) and concurrent releases from major dams.

Details of the newly developed components of AWRA-R do not appear in the current version of the AWRA-R technical documentation (Dutta et al., 2015). They are presented instead in Appendix A.

These new components in AWRA-R provide a simplistic representation of river management that are relatively easy to run for multiple simulations and are sufficient for the modelling of BA impacts. It should be noted that AWRA-R as used here should not be used in place of the more complex river system models such as IQQM or Source Rivers for detailed river operations or management.

4.3.4 Model preparation

To apply AWRA-R in a river basin, the modeller must first define a link-node network describing the surface water flow network in the basin. Nodes are typically assigned to streamflow gauging locations, reservoir release points and major stream confluences and bifurcations. Nodes may also need to be defined at locations of important assets or coal resource developments. Next, catchment boundaries must be delineated around each of the links that join the nodes. This allows tributary inflows from the streamflow model to be allocated to the correct link.

4.3.5 Calibration

Calibration of AWRA-R is done against daily streamflow observations at a number of gauging stations within the basin. It is recommended that the calibration period be at least 20 years. It is preferable, but not crucial, that this calibration period coincide with that used for calibration of the streamflow model.

The AWRA-R model has 11 calibration parameters: three for river routing; two for floodplain modelling; two for surface water – groundwater interaction modelling; three for irrigation diversion modelling; and one for scaling locally produced runoff. The conceptualisation of AWRA-R and the parameterisations are described in detail in Dutta et al. (2015), Lerat et al. (2013) and Hughes et al. (2014).

Depending on the subregion, AWRA-R is calibrated using either an automated, single-step approach or a reach-by-reach approach, in which each reach is independently calibrated starting from the headwater catchments in a cascading manner from upstream to downstream reaches (Lerat et al., 2013). When calibrating a reach, the upstream inflows are set to the observed streamflow data. Outside of this period, or during periods with no streamflow data, upstream modelled inflows are used instead (Lerat et al., 2013). The parameters are optimised to best reproduce the observed streamflow at the downstream nodes to minimise the objective function defined by the combination of sum of square errors of the square root transform of streamflow and bias in total flow volume (Dutta et al., 2015):

$$OF = \left(1 + \frac{\sum_{j=1}^{n}\left(\sqrt{sim_j} - \sqrt{obs_{ij}}\right)^2}{\sum_{j=1}^{n}\left(\sqrt{obs_j} - \overline{\sqrt{obs}}\right)^2}\right) \times \left(1 + \left|\frac{\sum_{j=1}^{n} sim_j - \sum_{j=1}^{n} obs_j}{\sum_{j=1}^{n} obs_i}\right|\right) \tag{4}$$

where *j* is the current time-step (day), *sim* is the simulated streamflow (ML/day), *obs* is the observed streamflow (ML/day) and *n* is the number of days.

4.3.6 Modelling development impacts

Changes in hydrological regime associated with coal mining and coal seam gas development will be modelled either through changes in groundwater levels, through direct discharge to or extraction from the streams or through mediation of local surface runoff. Changes in groundwater levels will come from groundwater modelling or expert elicitation of changes in groundwater. These changes will then feed back in to the river model and result in changed river flow. Any direct discharge to, or extraction from, the stream will be modelled in the river system model as a direct flux.

4.3.7 Methodological variations among the bioregions

Despite the desirability of having a consistent methodology across the bioregions, in practice this cannot be easily achieved. It is inevitable that in some subregions or river basins, some variations to the recommended methodology will be necessary. Any such variations will be reported in the relevant subregional products.

In some river basins, river system modelling might be constrained by the lack of suitable observed streamflow data. In particular, streamflow observations are likely to be sparse or of poor quality in some parts of the Lake Eyre Basin bioregion. Similarly, there may well be some small river basins (e.g. those in the Gloucester subregion) where streamflow data are limited. Fortunately, in these areas, there is unlikely to be significant regulation or consumptive use of flow. This means that a simple accumulation of runoff fluxes from the streamflow model is likely to provide an adequate approximation of river flow. In the absence of a river system model, the development-mediated changes in groundwater levels and associated baseflow discharges will be applied to the predicted streamflows in a post-processing step.

5 Constituent modelling

Constituent modelling concerns the modelling of the concentrations or discharge loads of water quality variables. These might include particulate (e.g. sediment, particulate nutrients) or soluble (e.g. salt, dissolved nutrients) components, or physical characteristics of the water (e.g. temperature, acidity). In BA, constituent modelling is likely to be required only in cases where water quality variables form an integral part of any receptor impact models.

The water quality constituent most likely to be required is salt. Any saltload modelling is likely to take place as a post-processing step (i.e. after landscape and river modelling) using fixed-source concentrations routed conservatively.

Prediction of salt loads in the streamflow requires concentration information for inflows from the groundwater system and the availability of observed load (or concentration) data to validate any mixing assumptions.

6 Modelling the impacts of coal resource development

Coal resource developments may include open-cut and underground coal mining and coal seam gas extraction. There are many similarities in how these different types of extractive industries manage water and how this affects streamflow generation (see product 2.3 (conceptual modelling) for details). The water management processes that will be considered in the surface water modelling are outlined below.

6.1 Groundwater pumping

The dewatering of coal mines and depressurisation of CSG fields will lead to the development of drawdown cones in groundwater levels. These reductions in groundwater levels have the potential to reduce the discharge of baseflow from the groundwater to the stream. This reduction will be modelled in the surface water – groundwater modelling. The impact on baseflow predicted there will then be applied to reduce river flows in a post-processing step in the surface water modelling.

6.2 Interception of surface runoff

An open-cut coal mine is likely to change surface runoff conditions considerably. The disturbed area may be converted from deep-rooted forest to bare soil or short-rooted vegetation. This will necessitate a transition within AWRA from the deep-rooted hydrological response unit (HRU) to the shallow-rooted HRU. This, in turn, is likely to lead to reductions in canopy interception of rainfall. While surface runoff from outside the footprint of the disturbed area is likely to be diverted around and past the tenement, any surface runoff generated on site is likely to be retained on site, with some of it used for dust suppression or coal washing. Thus, the presence of an open-cut mine is likely to reduce natural surface runoff to the stream network. Furthermore, the amount of interception (i.e. the size of the footprint) is likely to change considerably over time.

6.3 Extraction of water from streams

Where there is a proposal for a mine or CSG field to extract water directly from the stream network, we will need a time series of extracted volumes. We will not model the decision-making processes that lead to variations in the timing and volume of extractions. Any such extractions can be deducted from modelled flow in that stream.

Note that there may be some subregions or jurisdictions where direct extraction is only allowed through the purchase of licences from existing water users. Extraction through this mechanism might not substantially change the total extraction from the stream, but it might alter its timing.

6.4 Discharge of mine water and co-produced water

Water sourced from groundwater pumping, interception of surface runoff or extraction from streams may be temporarily stored on site. There are a number of potential fates for this water. Some of it is likely to be used on site for washing coal, damping roads, etc. In some developments, the water may be used for irrigation of on-site or nearby crops. In some developments it may be left indefinitely in storage to evaporate or may be trucked off site. Some developments may be licensed to discharge water directly to the stream. In the latter case, this discharge may be strictly regulated and only allowed during favourable conditions. Such conditions might be when natural river flows are high and the discharge is not likely to affect the quality of the river flows.

Depending on the fate of stored or produced water, the surface water modelling in some regions may require the explicit modelling of storage volumes. In some subregions (e.g. Hunter) the discharge of stored water is regulated by a permit system in which mining companies buy discharge permits at auction and are allowed to trade permits with other producers. We will not directly model this water-trading system since it is governed by human decision-making. Nonetheless, the surface water modelling will allow automatic discharges to the stream when flow condition triggers are met.

6.5 Subsidence

Subsidence of material above a longwall coal mine has the potential to change the surface landscape to such an extent that the generation of surface runoff or its flow paths are altered. These changes may, in turn, alter the hydrology of nearby wetlands. Subsidence may also result in increased surface ponding, which will, in turn, mean that some runoff water could evaporate or recharge rather than reach the natural drainage network. Any changes to surface runoff can be accounted for in surface water modelling.

7 Linkages with other modelling components

7.1 Linkages with groundwater modelling

7.1.1 Spatial domain

Since various aspects of model output need to be passed between surface water, groundwater and surface water – groundwater models, it is imperative that their spatial modelling domains be complementary. In general, it will not be possible to make predictions of impacts due to the additional coal resource development using the full suite of numerical models at locations where one or more of these components are missing. Ideally, these models should also be developed concurrently and have compatible time domains.

7.1.2 Interactions with groundwater models

The principal coupling points between surface water and groundwater models are:

- River stage heights generated by the surface water model are used to provide boundary conditions to a groundwater model.
- The exchange fluxes between groundwater and the river are calculated in the groundwater model and passed back to the surface water model as changes in baseflow generation.

In general, at the surface water modelling stage, these interactions will take place via the river system model. However, in subregions without a river model, a similar level of coupling can be achieved by accumulating grid-scale landscape model outputs to an appropriate scale.

AWRA-L has a simplified integrated groundwater modelling capability which can model lateral groundwater flows between grid cells. For application in BA, the algorithms controlling such processes are not active.

The BA groundwater modelling methodology is described in more detail by Crosbie et al. (2016).

7.1.3 Model sequencing

The groundwater models (possibly including both a regional model and an alluvial model) and the surface water models (possibly including both a landscape model and a river system model) need to pass information between each other. Considerable care is required in designing how this is achieved. This is particularly true when considering the need to run models for different levels of coal resource development and the need to accommodate the various post-processing steps.

In general there will be significant differences between subregions in terms of the types of model used. The groundwater modelling in some subregions will be done using only a regional groundwater model, while in others there will also be an adjunct alluvium model. The surface water modelling will be done in some subregions using a combination of landscape and river models, while in other subregions there will be a landscape model only. Given these regional differences, it is not possible to prescribe a universal model sequencing plan. Such plans will be detailed in product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling) for each subregion or bioregion. However, a simplified coupling scheme for the case where there is a river model but no alluvium model is as depicted in Figure 9.

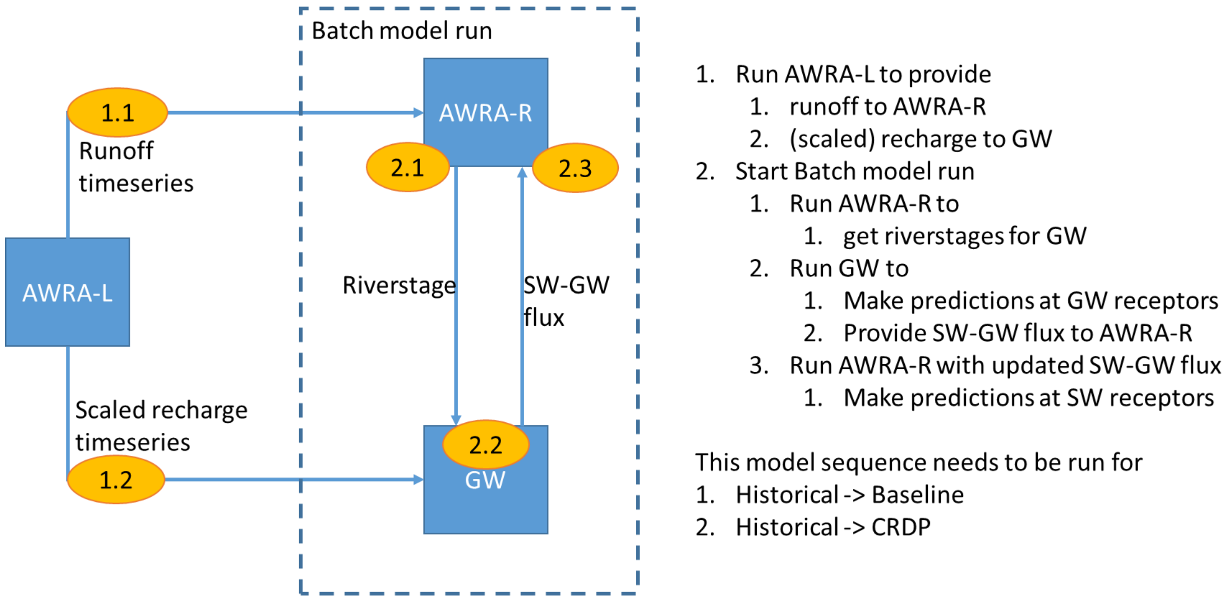

Figure 9 Example diagram: schematic of model run sequencing between the landscape (AWRA-L), river (AWRA-R) and groundwater models

SW = surface water; GW = groundwater; CRDP = coal resource development pathway; AWRA = Australian Water Resources Assessment system

7.2 Linkages with model node allocation

The model nodes associated with surface water provide the key output locations for surface water modelling. However, it is also important to note that streamflow will often change only slowly with distance down a river. This is particularly true in reaches with little lateral tributary inflow. This means that predicted streamflow at a single model node can often provide appropriate predictions for a range of locations along a river reach. In particular, this single set of streamflow predictions may be well within the uncertainty limits of the surface water modelling. In such environments, a single model node may prove adequate, even in quite long river reaches. It is recommended, therefore, that expert input from the surface water team be considered in allocating model nodes. In places where the density of model nodes is insufficient for receptor impact modelling, it is a reasonably trivial task to interpolate streamflows to any new model node.

7.3 Linkages with uncertainty analysis

A sensitivity analysis is conducted to assess the sensitivity of model output to variations in each of the model parameters. The most sensitive of these parameters is included in an uncertainty analysis. The uncertainty analysis is conducted using plausible ranges of values for each of the sensitive parameters using (a) a Monte Carlo procedure if there are no constraining data available or (b) a Markov chain Monte Carlo procedure when there are data to constrain the prediction.

From the surface water model, the uncertainty analysis requires estimates of the probability density function (the prior distribution) of each important model parameter. These distributions are refined from an analysis of the calibration logs for both high-flow and low-flow calibrations.

The uncertainty analysis involves the linked execution of 10,000 replicates of the groundwater and surface water models. For the surface water models, these 10,000 simulations are run on the assumption that there is no coal mining or CSG extraction in the modelling domain. The model output is modified in post-processing to account for coal resource developments in the baseline and CRDP.

The BA uncertainty analysis is described in more detail in Peeters et al. (2016).

8 Outputs from surface water modelling

8.1 Outputs for product 2.6.1 (surface water numerical modelling)

8.1.1 Hydrological response variables

8.1.1.1 Routine set of nine hydrological response variables

Product 2.6.1 (surface water numerical modelling) reports the potential impacts of coal resource development on water resources at the selected model nodes within the surface water modelling domain. This is done by comparing model simulations of the CRDP with those of the baseline. See Appendix B for recommended content to be included in product 2.6.1 (surface water numerical modelling).

Nine hydrological response variables have been chosen by BA ecological experts to characterise the impacts of coal resource development. These variables are intended to be representative of the flow characteristics that are important for assessing impacts on economic and ecological assets. To a large extent they are selected from the list of ecologically relevant streamflow metrics presented by Kennard et al. (2010). Five of the hydrological response variables characterise low streamflow, two characterise high streamflow, and two characterise long-term flow variability.

The low-streamflow hydrological response variables are:

- **P01:** the daily streamflow rate at the 1st percentile (ML/day)
- **ZFD:** the number of zero-flow days per year. Zero flow is identified using the minimum detectable flow. For ease of applicability, a threshold of 0.01 ML/day is set for determining the number of zero-flow days for all surface water nodes
- **LFD:** the number of low-flow days per year. The threshold for low-flow days is the 10th percentile from the simulated 90-year period (2013 to 2102)
- **LFS:** the number of low-flow spells per year (perennial streams only). A spell is defined as a period of contiguous days of streamflow below the 10th percentile threshold
- **LLFS:** the length (days) of the longest low-flow spell each year.

The high-streamflow hydrological response variables are:

- **P99:** the daily streamflow rate at the 99th percentile (ML/day)
- **FD:** flood (high-flow) days, the number of days with streamflow greater than the 90th percentile from the simulated 90-year period (2013 to 2102).

In addition, two hydrological response variables that represent streamflow volume and variability are:

- **AF:** the annual flow volume (GL/year)
- **IQR:** the interquartile range in daily streamflow (ML/day); that is, the difference between the daily streamflow rate at the 75th percentile and at the 25th percentile.

For each of these hydrological response variables a time series of annual values is constructed.

Some of these hydrological response variables are mutually exclusive. For example, a location with many zero-flow days is likely to have a P01 value of 0 ML/day. In general for a particular location, one or the other of these metrics is likely to produce useful information, but not both.

While the selection of these hydrological response variables for characterising important surface water impacts considers economic and ecological assets and spans the potential hydrological changes, the expert input into the receptor impact modelling (through qualitative models of potentially impacted landscape classes) might identify the system's dependency on other key hydrological response variables which will be considered at that time. The priority in product 2.6.1 (surface water numerical modelling) is to routinely estimate a set of hydrological response variables that summarise the potential hydrological changes.

8.1.1.2 Additional hydrological response variables for receptor impact modelling

Any extra hydrological response variables identified through further expert input will not be described in product 2.6.1 (surface water numerical modelling) but will be carried forward to the analysis reported in product 2.7 (receptor impact modelling). In general, different additional hydrological response variables might be selected in different subregions. These additional hydrological response variables are likely to be presented as 30-year averages of occurrence frequencies. Examples of additional hydrological response variables might include:

- **R0.3:** the peak daily flow in flood events with a return period of 0.3 years is defined from modelled baseline flow in the reference period (1983 to 2012). In the future 30-year periods, we report the mean annual number of events with a peak daily streamflow exceeding this reference R0.3 value. This metric is designed to be approximately representative of over-bench flow events.
- **R3.0:** the peak daily flow in flood events with a return period of 3 years is defined from modelled baseline flow in the reference period (1983 to 2012). In the future 30-year periods, we report the mean annual number of events with a peak daily streamflow exceeding this reference R3.0 value. This metric is designed to be approximately representative of over-bank flow events.

- **Qzero:** the mean number of days per year with zero streamflow during a 30-year period. For practical and numerical reasons, zero streamflow is defined as any modelled streamflow below 10 ML/day. Note that its flow threshold is much higher than that used for the zero streamflow metric (ZFD) described in Section 8.1.1. This Qzero metric is designed to be approximately representative of the flow rate at which all river pools will join up and form a continuously flowing reach.

Justification for these and any other additional metrics will be provided in product 2.7 (receptor impact modelling).

8.1.2 Criteria for analysing the impacts on hydrological response variables

Three criteria are selected to evaluate the change in each hydrological response variable. These three criteria are calculated for each of the 10,000 model run replicates of the uncertainty analysis. Each criterion is obtained from the annual time series of the relevant hydrological response variable.

The first criterion is the maximum absolute change in the hydrological response variable and is defined as:

$$\Delta A_{max} = \max(A_c(t) - A_b(t)) \tag{5}$$

where A is the variable (hydrological response variable), t represents the tth prediction year, and the subscripts c and b represent the CRDP and the baseline, respectively.

Equation (5) describes the case where the additional coal resource development is expected to lead to increases in the value of A (e.g. the number of low flow days). In cases where the additional coal resource development is expected to lead to decreases in the value of A (e.g. the annual flow volume), the criterion ΔA_{max} is negative and is given by:

$$\Delta A_{max} = \min(A_c(t) - A_b(t)) \tag{6}$$

The second criterion is the maximum percentage change in hydrological response variable and is defined as:

$$\Delta A_{pc} = 100\Delta A_{max} / A_b(t_{max}) \tag{7}$$

where t_{max} is the year of maximum difference between A_c and A_b. This criterion is applicable for volumetric hydrological response variables (e.g. P01, P99, annual streamflow and interquartile range), but will not always be applicable for the other five hydrological response variables with days as units. This is because the five hydrological response variables under the baseline are likely to be equal to zero for many hydrological nodes (see Section 2.6.1.4.3) which makes Equation (7) invalid.

The third criterion is t_{max}, the year of maximum change (the year when ΔA_{max} is observed).

Each of these criteria will be reported in product 2.6.1 (surface water numerical modelling) for each model node. They will be presented in the form of boxplots representing the range of responses from the 10,000 model replicates. The output will follow this format regardless of whether it is derived from AWRA-L or a combination of AWRA-L and AWRA-R.

Figure 10 and Figure 11 provide examples of these boxplots for two hydrological response variables for 30 surface hydrological model nodes in the Gloucester subregion. In these figures ΔA_{max} is denoted as amax, ΔA_{pc} is denoted as pmax and t_{max} is denoted as tmax.

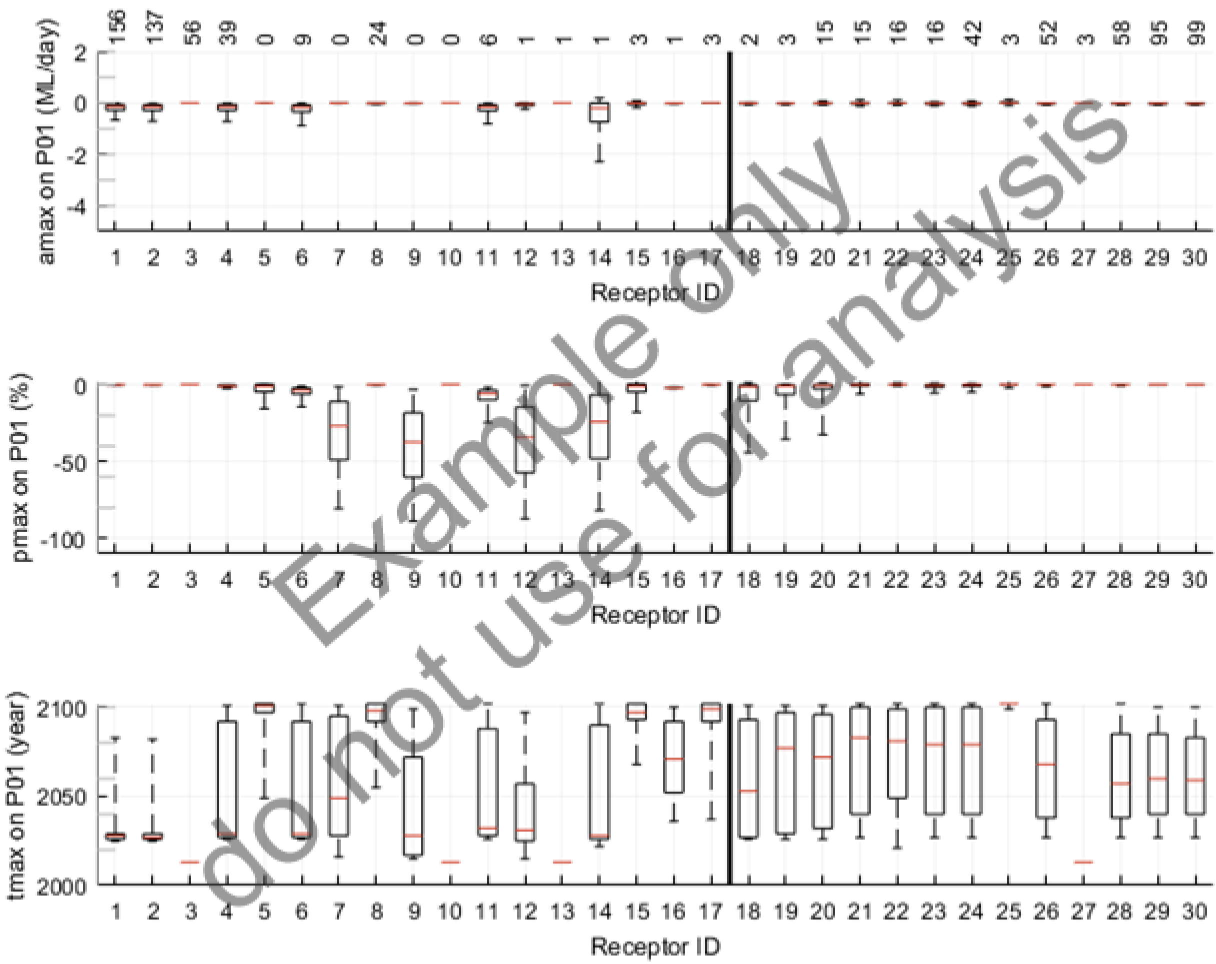

Figure 10 Example boxplot: the impact of additional coal resource development on streamflow at the 1st percentile (P01) at the 30 model nodes within the Gloucester subregion

Example only; do not use for analysis. This is an early draft of a figure published in Zhang et al. (2016). See Zhang et al. (2016) for full explanation and interpretation of the final results, which might vary from that shown here.
Numbers above the top panel are the median of the 10,000 replicates under the baseline for the year corresponding to the median *tmax*. In each boxplot, the bottom, middle and top of the box are the 25th, 50th and 75th percentiles, and the bottom and top whiskers are the 5th and 95th percentiles. The thick black line divides northern model nodes (1–17) and southern model nodes (18–30). The *amax*, *pmax* and *tmax* refer to the maximum absolute impacts, maximum percentage impacts and year of maximum change, respectively.
Receptor ID = model node ID

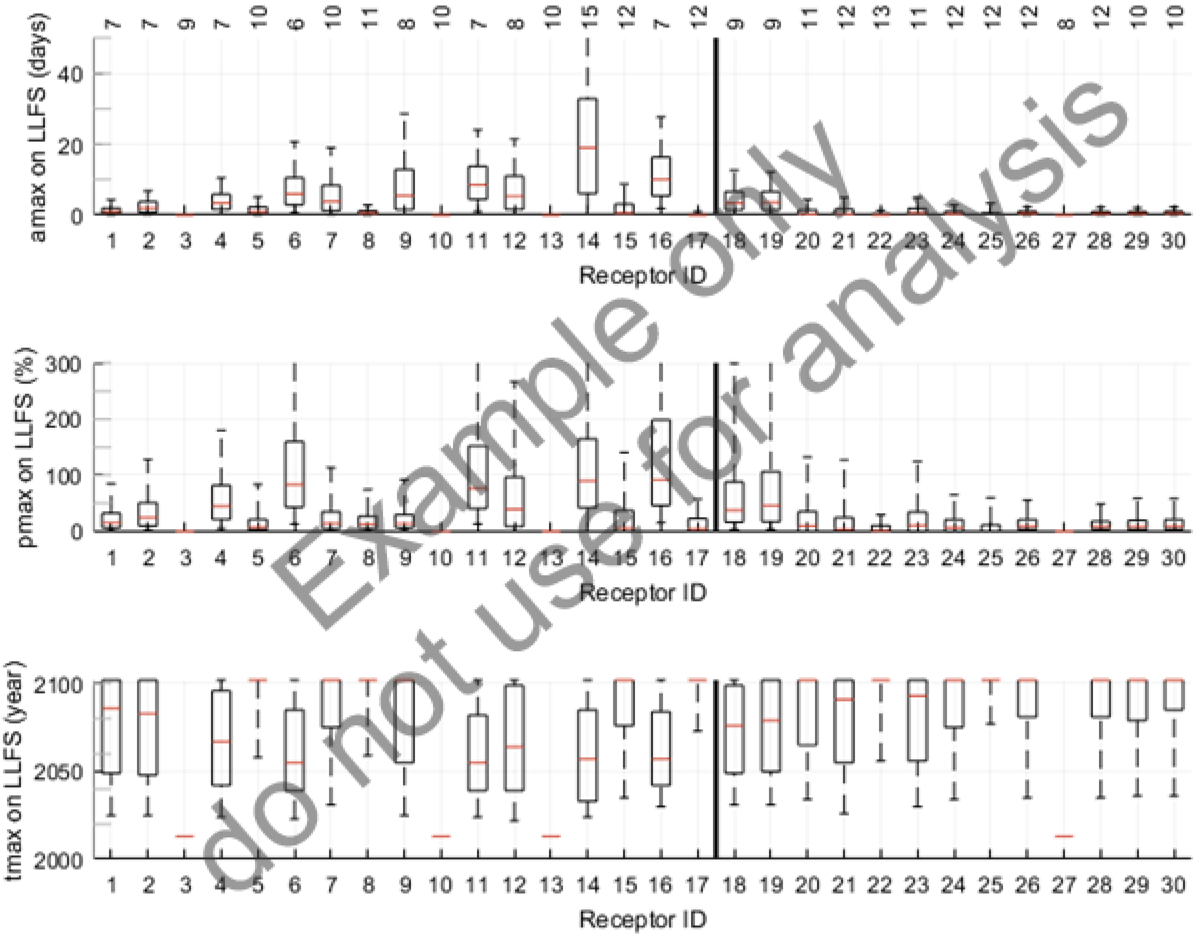

Figure 11 Example boxplot: the impact of additional coal resource development on the length of longest low-flow spell (LLFS) at the 30 model nodes within the Gloucester subregion

Example only; do not use for analysis. This is an early draft of a figure published in Zhang et al. (2016). See Zhang et al. (2016) for full explanation and interpretation of the final results, which might vary from that shown here.
Numbers above the top panel are the median of the 10,000 replicates under the baseline for the year corresponding to the median *tmax*. In each boxplot, the bottom, middle and top of the box are the 25th, 50th and 75th percentiles, and the bottom and top whiskers are the 5th and 95th percentiles. The thick black line divides northern model nodes (1–17) and southern model nodes (18–30). The *amax*, *pmax* and *tmax* refer to the maximum absolute impacts, maximum percentage impacts and year of maximum change, respectively.

8.1.3 Interpolation of hydrological changes

The predictions of streamflow from the landscape and river models are for specific locations in the stream network. These are termed the model nodes. It is at these model nodes that the hydrological response variables are derived.

For some applications in BA, particularly in relation to the river impact modelling, it may become necessary to provide hydrological response variable predictions for locations on the stream network that are not at model nodes. In other words, some degree of spatial interpolation or extrapolation will be required. Such an interpolation or extrapolation will allow entire stretches of particular riverine landscape classes to be associated with one or more streamflow regimes.

The simplest interpolation strategy is to simply adopt the flow volume (and associated hydrological response variables) from a nearby model node on the same streamline. Since model nodes are typically placed immediately upstream of major confluences, it is not unreasonable to expect that flow predictions at such a node will be representative of the flow for some distance along the reach upstream of the node. The distance along the reach over which this translation of flow prediction would be safe is dictated by the topology of the network and by proximity to additional coal resource development.

In some instances it may be appropriate to interpolate along part, but not all, of a reach. For example, it may be appropriate to interpolate upstream from a model node as far as the next significant inflow point. Alternatively, it may be appropriate to interpolate upstream from a node as far as an inflow point associated with a mining development.

This direct interpolation scheme may be inappropriate in some circumstances. In such cases, consideration could be given to implementing alternative interpolation strategies such as areal weighting of streamflows.

8.1.4 Zone of potential hydrological change

Product 2.6.1 (surface water numerical modelling) reports on the maximum differences between CRDP and baseline projections of the annual time series of nine hydrological response variables. Each of these variables are produced at every model node. Using the interpolation schemes outlined in Section 8.1.3, these projections can give estimates of the maximum hydrological change at any point along a reach.

It is important to recognise that the predicted hydrological changes represent the largest annual departure between the baseline and CRDP predictions for the respective hydrological response variables. As such, they represent extreme responses. They do not necessarily represent the magnitudes of responses that would be expected to occur every year.

However, they do provide a convenient means of discriminating between parts of the landscape that are potentially affected by additional coal resource development and those parts of the landscape that are almost certainly unaffected and can be ruled out from further analysis. The river reaches that are potentially affected – that is, those reaches where changes in one or more hydrological response variables exceed the specified thresholds – are within the zone of potential hydrological change (which includes the extent of potential changes in both surface water and groundwater).

For the flux-based hydrological response variables (AF, P99, IQR and P01), the threshold for inclusion in the surface water zone of potential hydrological change is a greater than 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 (FD, LFD, LLFS and ZFD), the threshold is a greater than 5% chance of there being a change in the variable of at least 3 days in any year. For the final frequency-based metric (LFS), the threshold is a greater than 5% chance of there being a change in the variable of at least 2 spells in any year.

A node and its associated reach are considered potentially impacted if changes in any one of these nine hydrological response variables exceed the specified thresholds. Otherwise, the node and its associated reach are deemed to be outside the zone of potential hydrological change.

In reaches where interpolation of streamflow from adjacent model nodes is not possible, the reach may be judged in or out of the surface water zone of potential hydrological change depending on its proximity to additional coal resource development and whether it is in the groundwater zone of potential hydrological change (the area with a greater than 5% chance of exceeding 0.2 m drawdown due to additional coal resource development). In general, a reach is outside the zone of potential hydrological change when it is not downstream of a mine footprint and where groundwater drawdown does not exceed the specified threshold.

8.2 Outputs required for product 2.5 (water balance assessment)

Product 2.5 (water balance assessment) presents a quantitative water balance for the subregion; see Appendix B for recommended content to be included in this product. The surface water components of this water balance will be derived from the outputs of the surface water modelling.

The water balance will represent a defined control volume. The nature of this control volume may vary between subregions. However, it is likely to involve a subarea of the surface water modelling domain. It may represent a hydrologically intact catchment area (or areas) draining to a particular point (or points) in the river network, or it may exclude external tributary inflows. Since there will be a groundwater component to the water balance, the extent of the control volume may be constrained by the spatial extent of the groundwater model. In other words, it is likely that the control volume will be a subarea of the intersection between the spatial domains of the surface and groundwater models.

The surface water components that are reported in the water balance may vary from subregion to subregion, but will include some or all of:

- precipitation
- streamflow discharge
- tributary inflow
- evapotranspiration
- change in storage (i.e. water in soil and artificial reservoirs).

An exemplar for a water balance table for part of the Gloucester subregion is shown in Table 3.

Table 3 Example water balance table: mean annual surface water balance at node 6 on the Avon River for 2013 to 2042 in the Gloucester subregion (ML/year)

	Water balance term	Under the baseline	Under the coal resource development pathway	Difference
Surface water	Rainfall	281,966	281,966	0
	Surface water outflow	63,312 (59,175; 67,586)	62,207 (58,129; 66,386)	–1105
	Licensed extractions	NM	NM	NM
	Residual (e.g. ET, leakage, change in storage)	218,654 (214,380; 222,791)	219,759 (215,580; 223,837)	1105

Example only; do not use for analysis. This is an early draft of a figure published in Herron et al. (2016). See Herron et al. (2016) and Zhang et al. (2016) for full explanation and interpretation of the final results, which might vary from that shown here.
For some (but not all) terms, three numbers are provided. The first number is the median, and the 10th and 90th percentile numbers follow in brackets. NM = data not modelled

Appendix A Modifications to AWRA-R

A.1 Background

AWRA-R was originally developed to provide daily retrospective estimates of water fluxes and stores in both regulated and unregulated river systems. The original model does not include management rules to determine allocations nor control of dam releases. In order to model river flow in regulated reaches, the AWRA-R model needs to determine allocations to compute the dam releases needed as inflow into the river system. To this end, new functionality was developed that performs a resource assessment and simulates downstream water demand (for irrigation, mining, industry, town water) and concurrent releases from major dams.

This new functionality was largely based on existing management rules, which were informed by data and management rules from IQQM (Simons et al., 1996).

Four components were developed to represent the new functionality described above:

1. a water resource assessment to determine allocations
2. dam storage volumes based on inflows and releases
3. dam releases based on downstream demand
4. rules to simulate coal industry water discharges.

These model components are jointly calibrated using both observed data and simulated data from IQQM. They have been developed as a stand-alone model run independently of AWRA-R. Outputs from these components are used as input to the AWRA-R model, which enables it to run more efficiently.

A.2 Modifications

A.2.1 Resource assessment and allocation

A water resource assessment component was developed to estimate the allocation, which is the percentage of the licensed volume for irrigation permitted to be extracted in a water year in the regulated section of the river system. This differs from the IQQM resource assessment which includes all general security licences, whereas all irrigation licences are lumped in AWRA-R. Allocations are computed on 15 August each year and are kept at that level for the remainder of the water year. Again, this differs from IQQM as allocations are computed on 1 July and updated based on resource assessments conducted approximately every fortnight. Allocations cannot go below the level estimated at the previous resource assessment.

To determine the allocation in AWRA-R, the assessment adds the volume of available water in supply dams and subtracts the essential water requirements and losses for the entire river system. The percentage allocation from 15 August onwards is computed as:

$$Alloc = \min\left(1, \max\left(0, \frac{S \times (Irr_{min} \times S_{tot})}{\overline{Rel}_{irr} + \overline{Rel}_{mine} + \overline{Rel}_{other} + \overline{Rel}_{env} + (\bar{P}_S - \bar{E}_S) \times A_{S,max} + S_{dead}}\right)\right) \times 100 \quad (8)$$

where S is the storage on August 14 (m^3), Irr_{min} is a calibrated parameter that represents the minimum proportion of maximum storage capacity below which there are no irrigation allocations, S_{tot} is the total storage volume for the supply dams (m^3), $\overline{Rel}_{irr}$ is the mean annual irrigation release (m^3), $\overline{Rel}_{mine}$ is the mean annual mine release (m^3), $\overline{Rel}_{other}$ is the mean annual other release (m^3), $\overline{Rel}_{env}$ is the mean annual environmental release (m^3) which includes minimum flows and an environmental contingency allowance, $\bar{P}_S$ is mean annual rainfall on the reservoir (m), $\bar{E}_S$ is mean annual potential evapotranspiration (m), $A_{S,max}$ is the maximum storage surface area (m^2) and S_{dead} is the dead storage volume (m^3).

A.2.2 Dam storage volumes

The volume of water stored in a dam at a given time-step is a function of the water stored in the dam in the previous time-step, plus the inflows and outflows for the given time-step. Inflows to the storage include rainfall on the reservoir and contributing catchment runoff. Outflows include losses to evaporation, releases from the dam or dam spills. Thus the storage volume of a reservoir on day *j* can be expressed in the form of a water balance as:

$$S_j = S_{j-1} + kQ_{S,j} \times A_{cat} + (P_{S,j} - E_{S,j}) \times A_{S,j} - Q_{rel,t} \quad (9)$$

where S_{j-1} is storage on the previous day (m^3), k is a calibrated scaling parameter, $Q_{S,j}$ (m/day) is AWRA-L runoff depth, A_{cat} is the catchment area (m^2) contributing to the storage, $P_{S,j}$ is the rainfall depth on the storage (m/d), $E_{S,j}$ is potential evaporation depth from the storage (m/d), $A_{S,j}$ is the surface area (m^2) of the reservoir in day *j* and $Q_{rel,t}$ is storage release (m^3/day).

Leakage from the dam is not explicitly considered in Equation 9 since these data are not available.

Because a dam has a finite storage capacity, there is a volume beyond which the dam will spill because it cannot contain all the inflows. Thus a limit based on dam characteristics is imposed upon the stored volume as:

$$S_j = \min(S_j, S_{full}) \quad (10)$$

When $S_j > S_{full}$, spillway discharge occurs and is calculated as $Q_{spill} = S_j - S_{full}$. At all other times for $S_j \leq S_{full}$, $Q_{spill} = 0$.

During dry periods when the storage is below a calibrated critical threshold (S_{min}, in m^3), but above the dead storage volume, dam releases are reduced in day *j* by a factor (R_j, which varies between 0 and 1) depending on the storage level and S_{min} by:

$$R_j = \frac{S_{j-1} - S_{dead}}{S_{min} - S_{dead}} \qquad (11)$$

where R_j is the reduction factor (varying between 0 and 1) and S_{min}>S_{dead}. Dead storage (S_{dead}) is water stored in the reservoir below the lowest offtake point, which means that this water cannot be released from the dam.

A.2.3 Dam releases

Dam releases are computed as volumes that satisfy downstream demand for irrigation and industry (including mining, power stations and town water supply). In addition, dam releases are made to meet minimum flow requirements and other environmental flows. Thus, the dam release on day *j* is the sum of the releases (*Rel*) to all users along all reaches and is given by:

$$Q_{rel,j} = \sum_{i=1}^{n} (Rel_{irr,i,j} + Rel_{mine,i,j} + Rel_{ind,i,j} + Rel_{env,i,j} + Rel_{other,i,j}) \qquad (12)$$

where for reach *i* and day *j*, $Rel_{irr,i,j}$ is the volume to satisfy irrigation demand, $Rel_{mine,i,j}$ is the volume to satisfy mining demand, $Rel_{ind,i,j}$ is the volume to satisfy industry demand, $Rel_{env,i,j}$ is the environmental release and $Rel_{other,i,j}$ is other unaccounted releases. All variables are in m^3/day.

The daily irrigation release ($Rel_{irr,i,j}$) is the amount of water needed to balance a soil moisture deficit, resulting from the difference in precipitation inputs and potential evapotranspiration outputs. Irrigation releases are constrained by: a minimum threshold deficit ($\Theta_{irr,min}$) below which soil moisture is sufficient to meet crop water requirements and a dam release is not required; allocation (*alloc*) which limits the amount of water permitted to be extracted for irrigation from the regulated river reaches; maximum irrigable area ($A_{irrimax}$) which limits the volume of soil moisture deficit; utilisation in the irrigated reach (I_u), which is the proportion of $A_{irrimax}$ effectively used; and irrigation system efficiency (I_e), which is the ratio of the volume of water supplied for irrigation to the volume of water consumed by the crop. The daily irrigation release is calculated as:

$$Rel_{irr,i,j} = \max\left(0, \left(\theta_j - \theta_{irr,min}\right) \times alloc_j \times A_{irrimax} \times I_u \times I_e\right) \qquad (13)$$

where Θ_j is the moisture deficit (m) is calculated using a 30-day moving average of daily precipitation P_j (m/day) minus potential evapotranspiration ET_i (m/day) to reflect soil moisture fluctuations, $\Theta_{irr,min}$ is the minimum threshold deficit (m), a surrogate of soil wilting point and a calibrated parameter, $alloc_j$ is estimated allocation (dimensionless), $A_{irrimax}$ is the maximum irrigable area (m^2), I_u is utilisation in the irrigated reach and is a calibrated parameter which varies from 0 to 1, and I_e is irrigation system efficiency which is assumed to be 2, which means that half the water extracted from the river is lost through conveyance.

Daily mining releases for each reach are calibrated against modelled monthly mining diversions (DPI Water, Dataset 1) and given by:

$$Rel_{mine,i,j} = \max\left(Rel_{mine,min}, \left(\theta_j - \theta_{mine,min}\right) \times A_{minemax,j}\right) \quad (14)$$

where $Rel_{mine,min}$ is the minimum mine release, Θ_j is the mine water deficit (m) computed similarly as the irrigation moisture deficit, $\Theta_{mine,min}$ is the minimum threshold deficit (m) a calibrated parameter above which mines require water, and $A_{minemax}$ is the maximum mine 'area' in all reaches used as a proxy for water demand, and is calibrated independently using daily mining diversion data for all reaches against simulated mine water demand using a similar approach as for irrigation calibration in AWRA-R (Hughes et al., 2014).

$Rel_{ind,i,j}$ and $Rel_{env,i,j}$ are taken directly from the industry and environmental diversions and used as inputs in the calibration. $Rel_{ind,i,j}$ follows a summer dominated pattern and is estimated manually during calibration.

$Rel_{other,i,j}$ is an additional release included during testing to improve calibration. It acts as a compensating factor for details not included in the model that were difficult to capture without a more detailed representation. $Rel_{other,i,j}$ is conceptualised as:

$$Rel_{other,i,j} = \theta_j \times A_{othermax,j} \quad (15)$$

where $A_{othermax,j}$ is a calibrated parameter.

Table A.1 provides details of the six calibrated parameters in the additional model components for AWRA-R, including units, admissible range and relevance of the parameter.

Table A.1 Optimisable parameters of the four components developed in AWRA-R

Parameter	Unit	Admissible range	Comment
S_{min}	m^3	0 to less than 0.30 of total dam storage but higher than dead volume S_{dead}	Controls the rate of reduction in releases (other than irrigation)
Irr_{min}	dimensionless	0 to 1	Proportion of dam storage below which irrigation allocation is zero
I_u	dimensionless	0 to 1	Proportion of total area irrigated
$A_{othermax,j}$	m^2	0 to 1x106	Maximum area of irrigation not accounted elsewhere
k1 and *k2*	dimensionless	0.5 to 2	Scaling factor applied to AWRA-L runoff

Allocation and volumes are calibrated against observed volumes and IQQM releases, in a joint fashion and with the aim of reducing the error and overall bias by optimising the following objective function (*OF*):

$$OF = \frac{\sum_{j=1}^{n}\left(simvol_j - obsvol_{ij}\right)^2}{\sum_{j=1}^{n}\left(obsvol_j - \overline{obsvol}\right)^2} + \left|\frac{\overline{simrel} - \overline{obsrel}}{\overline{obsrel}}\right| \tag{16}$$

where $simvol$ is the simulated volume time series, *obsvol* is the observed total dam volume time series, $\overline{simrel}$ is the mean daily simulated irrigation release time series and $\overline{obsrel}$ is the mean observed daily irrigation release value for the entire system.

The function *OF* is minimised during optimisation. The optimiser used is the differential evolution algorithm implemented in the R package 'DEoptim' (Ardia et al., 2011). This calibration objective function was intended to obtain a parameter set that can simulate dam storage and irrigation release with acceptable accuracy.

The storage volume, releases and allocations are calibrated in the following order:

1. Volumes, release and allocations are calibrated for the whole system (all dams).
2. The computed allocation is then used to simulate releases for each dam separately. The release volumes for individual dams are split by proportion for each dam based on irrigated areas, mining, industry and environmental releases for each dam, all informed by diversion data.

A.2.4 Rules to simulate industry water discharge

This section refers to a change in AWRA-R that is only applicable to the Hunter subregion.

A simple set of rules to simulate industry water discharge within the Hunter River Salinity Trading Scheme was developed based on the analysis reported in Section 2.1.4.2.4 in companion product 2.1-2.2 (observations analysis, statistical analysis and interpolation) for the Hunter subregion. Table A.2 summarises the streamflow thresholds above which discharges are permitted as a fixed ratio of streamflow, the mean annual discharge volume by Hunter River Salinity Trading Scheme participants during the period 2006 to 2012 and the discharge to streamflow ratio assumed in the AWRA-R model for each reach of the Hunter River Salinity Trading Scheme. Thus when flow reaches 1000 ML/day at stream gauge 210055 on the Hunter River at Denman, the model assumes that the daily discharge from mines in this reach is 0.006*1000 ML/day or 6 ML/day.

Table A.2 Streamflow thresholds and mean industry annual discharge volumes and maximum discharges used in the simplified industry discharge scheme

Gauge	Name	Streamflow threshold (ML/d)	Mean industry annual discharge volume (ML/y)	Discharge/streamflow ratio
210055	Hunter R at Denman	1000	750	0.006
210127	Hunter R U/S Glennies Ck	1800	1000	0.009
210001	Hunter R at Singleton	2000	100	0.009

Data: NSW EPA (Dataset 2)

Appendix B Proposed structure of product 2.6.1 (surface water numerical modelling) and product 2.5 (water balance assessment)

Table B.1 Recommended content for product 2.6.1 (surface water numerical modelling)

Section number	Title of section	Main content to include in section
2.6.1.1	Methods	This will be mostly generic text. Overarching information about how the groundwater and surface water models are linked is included here.
2.6.1.2	Review of existing models	Discussion of any models that have been used for regional coal resource development modelling.
2.6.1.3	Model development	If there is more than one model, include level 5 headings as follows. Not required if just one model. 2.6.1.3.1 Model #1 2.6.1.3.2 Model #2
2.6.1.4	Calibration	If there is more than one model, include level 5 headings as follows. Not required if just one model. 2.6.1.4.1 Model #1 2.6.1.4.2 Model #2
2.6.1.5	Uncertainty	
2.6.1.6	Prediction	

Table B.2 Recommended content for product 2.5 (water balance assessment)

Section number	Title of section	Main content to include in section
2.5.1	Methods	
2.5.1.1	Spatial and temporal extent of the water balances	Temporal resolution: The water balance is reported over three 30-year periods, namely 2013 to 2042, 2043 to 2072 and 2073 to 2102, which align with the three global warming scenarios of 1.0, 1.5 and 2.0 °C. Spatial resolution: This will vary by subregion, but a general principle is to report the water balance over the minimum possible area which incorporates all hydrologically connected cumulative impacts. Thus more than one might be required per subregion or bioregion.
2.5.2	Water balances	Suggestions for level 4 headings are either: inflows, consumptive use and discharge, or a subheading for each water management unit.
2.5.2.1	Reporting unit #1	Number of tables: Three tables will be needed for each spatial reporting unit – one for each of the three time slices. Each will contain results under the baseline, under the CRDP, and the difference. Uncertainty: Within each table, for some outputs, three numbers will be required representing the median, 10th and 90th percentiles from the uncertainty analysis. For some outputs (e.g. rainfall) this will not be required. Table 1 Water balance in [insert reporting unit name] for 2013 to 2042 Table 2 Water balance in [insert reporting unit name] for 2043 to 2072 Table 3 Water balance in [insert reporting unit name] for 2073 to 2102
2.5.2.2	Reporting unit #2	Number of tables: Three tables will be needed for each spatial reporting unit – one for each of the three time slices. Each will contain results under the baseline, under the CRDP, and the difference. Uncertainty: Within each table, for some outputs, three numbers will be required representing the median, 10th and 90th percentiles from the uncertainty analysis. For some outputs (e.g. rainfall) this will not be required. Table 1 Water balance in [insert reporting unit name] for 2013 to 2042 Table 2 Water balance in [insert reporting unit name] for 2043 to 2072 Table 3 Water balance in [insert reporting unit name] for 2073 to 2102
2.5.2.3	Gaps	

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Datasets

Dataset 1 NSW Office of Water (2015) IQQM Model Simulation Regulated Rivers NSW DPI HUN 20150615. Bioregional Assessment Source Dataset. Viewed 24 May 2016, http://data.bioregionalassessments.gov.au/dataset/d6e8c6f0-08bf-4ca6-bbef-6ae0d79c34ce.

Dataset 2 NSW Environment Protection Authority (2012) Hunter River Salinity Scheme Discharge NSW EPA 2006-2012. Bioregional Assessment Source Dataset. Viewed 24 May 2016, http://data.bioregionalassessments.gov.au/dataset/1647c153-5120-4c64-a5e8-6a1b4b0b4e4b.

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

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

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

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

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

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

Bioregional Assessment Data Store: the component of the Bioregional Assessment Repository dedicated to storing datasets, maps and products

Bioregional Assessment Metadata Catalogue: the component of the Bioregional Assessment Repository dedicated to storing metadata

Bioregional Assessment Repository: a collection of systems that together store source and derived datasets, products and maps, accompanying metadata, lineage and supporting material. It consists of the Data Store, Metadata Catalogue and the Repository website. The Repository is not available to the public.

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).

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)

diversion: see extraction

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

ecosystem: a dynamic complex of plant, animal, and micro-organism communities and their non-living environment interacting as a functional unit. Note: ecosystems include those that are human-influenced such as rural and urban ecosystems.

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.

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

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

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

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

Geofabric: a nationally consistent series of interrelated spatial datasets defining hierarchically-nested river basins, stream segments, hydrological networks and associated cartography

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 in an aquifer or other low permeability material), or water occurring at a place below ground that has been pumped, diverted or released to that place for storage there. This does not include water held in underground tanks, pipes or other works.

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

groundwater system: see water system

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

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

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

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

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

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

impact cause: an activity (or aspect of an activity) that initiates a hazardous chain of events

impact mode: the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality 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

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

landscape class: for bioregional assessment (BA) purposes, an ecosystem with characteristics that are expected to respond similarly to changes in groundwater and/or surface water due to coal resource development. 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.

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

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.

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

preliminary assessment extent: the geographic area associated with a subregion or bioregion in which the potential water-related impact of coal resource development on assets is assessed

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

receptor impact variable: a characteristic of the system that, according to the conceptual modelling, potentially changes due to changes in hydrological response variables (for example, condition of the breeding habitat for a given species, or biomass of river red gums)

recharge: see groundwater recharge

risk: the effect of uncertainty on objectives

runoff: rainfall that does not infiltrate the ground or evaporate to the atmosphere. This water flows down a slope and enters surface water systems.

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

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)

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

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

surface water zone of potential hydrological change: outside this extent, changes in surface water hydrological response variables due to additional coal resource development(and hence potential impacts) are very unlikely (less than 5% chance). The area contains those river reaches where a change in any one of nine surface water hydrological response variables exceeds the specified thresholds. For the four flux-based hydrological response variables (AF, P99, IQR and 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 (FD, LFD, LLFS and ZFD), the threshold is a 5% chance of a change of 3 days per year. For the final frequency-based hydrological response variable (LFS), the threshold is a 5% chance of a change of 2 spells per year.

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

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

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

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

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

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’.

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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