Australian Government

BIOREGIONAL ASSESSMENTS

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

Groundwater modelling

Submethodology M07 from the Bioregional Assessment Technical Programme

3 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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Wards River, NSW, 10 December 2013

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Executive summary

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

This submethodology gives a high-level overview of how groundwater modelling is undertaken in BAs and highlights linkages with other components of the BAs. It is not prescriptive in terms of model codes or approaches as there are substantial differences in data availability and potential coal resource development across the subregions and bioregions, which results in different model types and model codes in different BAs. Therefore this submethodology has been written at a conceptual level to be independent of any specific model code to remain generally applicable to all subregions or bioregions. Specific details for the chosen groundwater models will be included in product 2.6.2 (groundwater numerical modelling) for each Assessment.

An important distinction between the models used for BA and most groundwater models is that the BA models are designed around giving probabilistic predictions, this ensures that as much uncertainty as can be quantified is provided in the predictions. Generally, the type of modelling undertaken will be trajectory modelling. Two potential futures are considered in a BA:

- *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 CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference in results between CRDP and baseline is the change that is primarily reported in a BA. This change is due to the additional coal resource development– all coal mines and CSG fields, including expansions of baseline operations, that are expected to begin commercial production after December 2012. This manner of using groundwater models is different to the typical use for which many existing groundwater flow models were developed. Therefore, the use of existing models in BAs are evaluated in terms of their suitability for this purpose.

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

- *dmax*: maximum difference in drawdown for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures, with units of metres (m)
- *tmax*: year of maximum change, with units of years.

The groundwater model results are used to refine the surface water 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 groundwater modelling also interacts with the BA process for placing receptors across the landscape.

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 groundwater modelling are reported in product 2.6.2 (groundwater 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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- Additional reviewers: Praveen Kumar Rachakonda.

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.

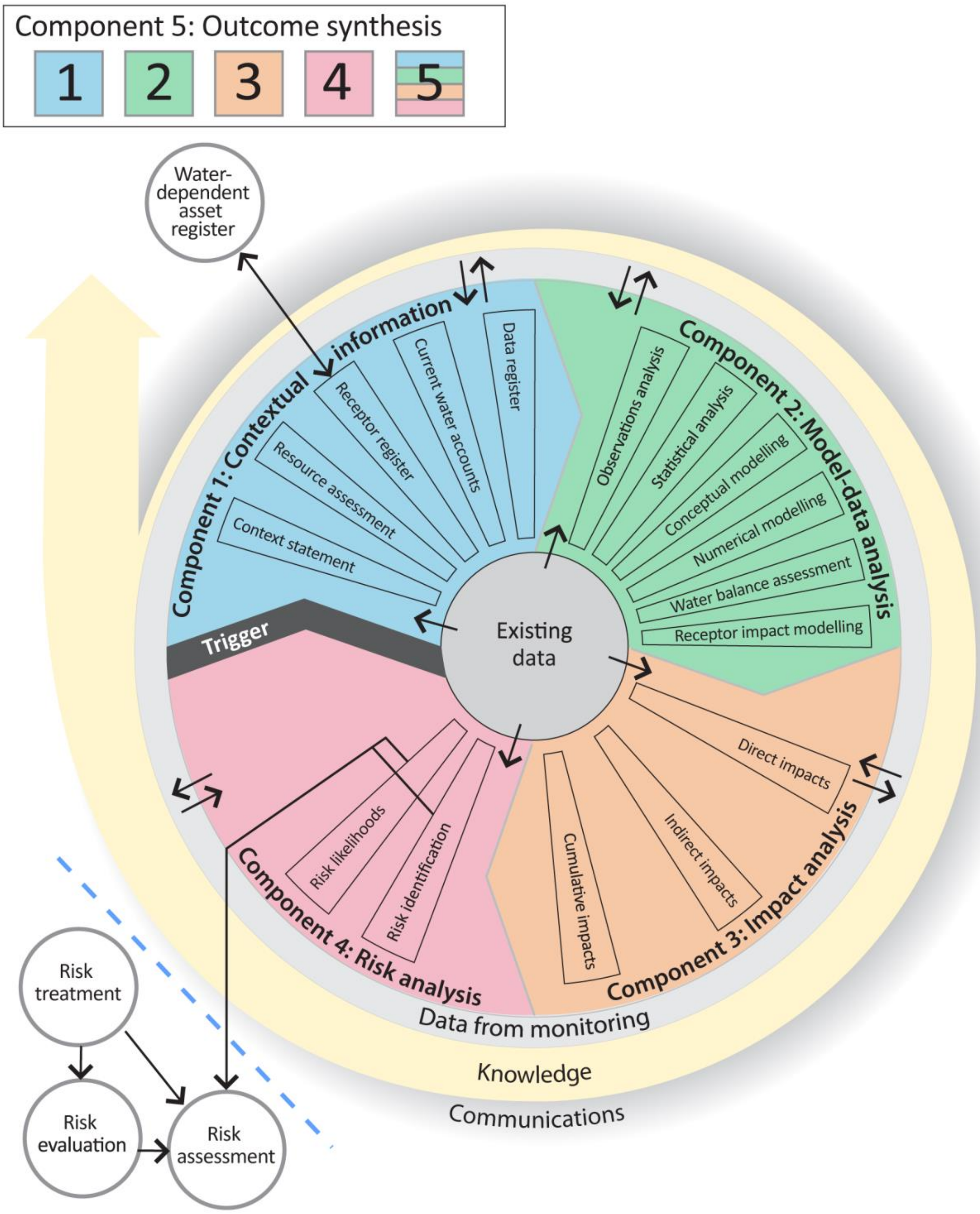


Figure 1 Schematic diagram of the bioregional assessment methodology

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 13. 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

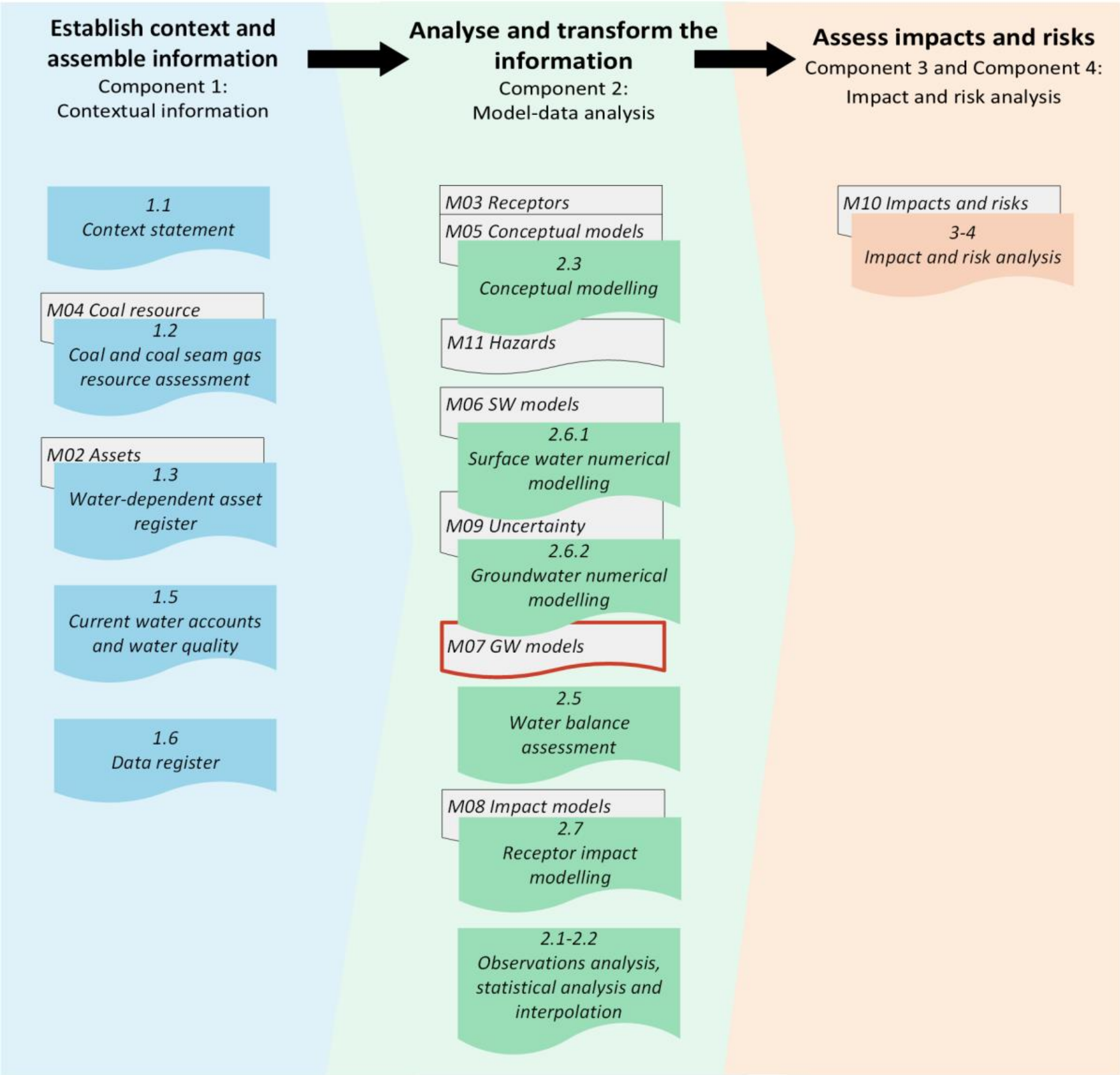


Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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 9 December 2016, 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 9 December 2016, 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 the BA is implementing a groundwater model that estimates fluxes and stores of groundwater. The groundwater model must integrate with other BA models and processes, particularly the surface water modelling, uncertainty analysis and receptor impact modelling. This submethodology applies overarching principles outlined in the BA methodology to the specifics of developing and running groundwater models and writing product 2.6.2 (groundwater numerical modelling) and product 2.5 (water 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.

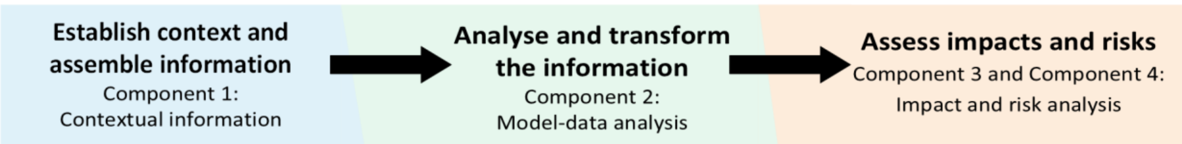


Figure 3 The components in a bioregional assessment

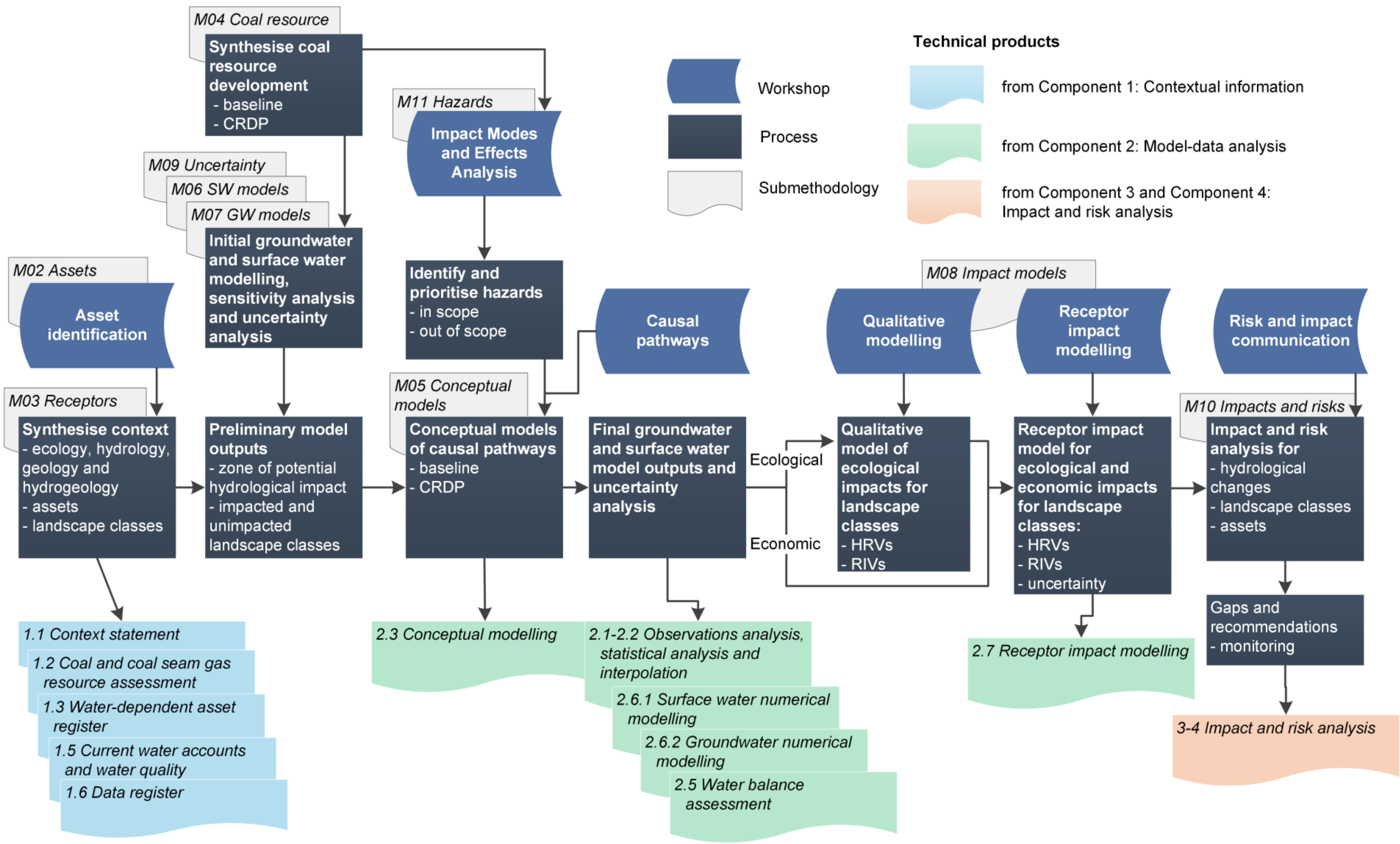


Figure 4 A bioregional assessment from end to end, showing the relationship between the workflow, technical products, submethodologies and workshops

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. 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 – 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.

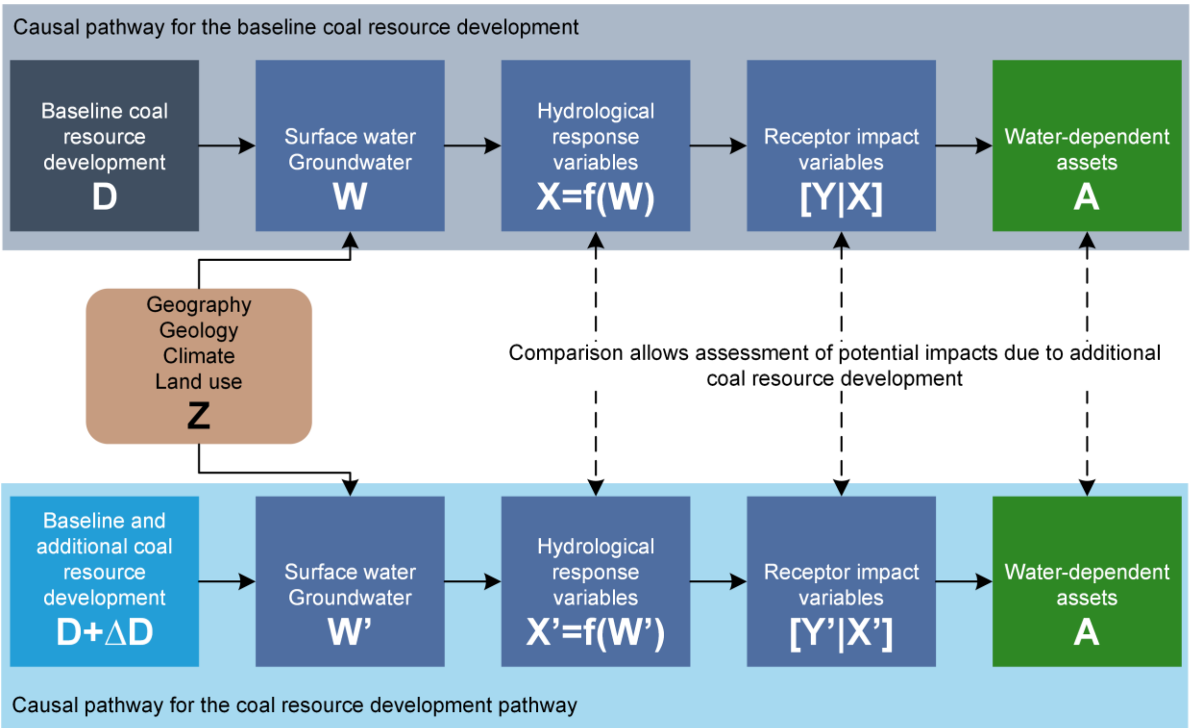


Figure 5 The difference in results for the coal resource development pathway (CRDP) and the baseline coal resource development (baseline) provides the potential impacts due to the additional coal resource development (ACRD)

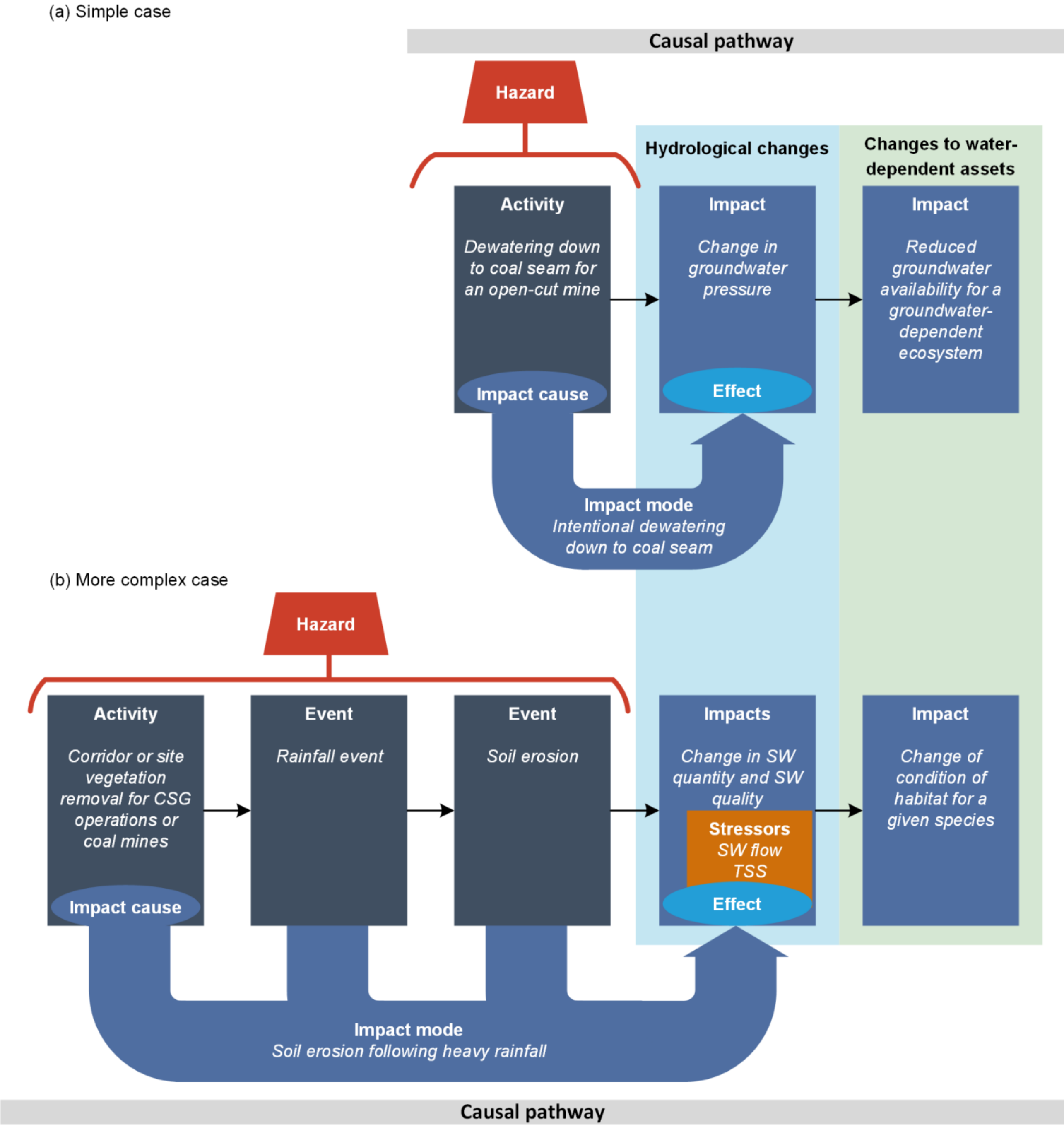


Figure 6 Hazard analysis using the Impact Modes and Effects Analysis (IMEA). This figure shows how hazards identified using IMEA are linked to changes in hydrology and water-dependent assets via causal pathways

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 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 at each receptor within a 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.

1.2 Role of this submethodology in a bioregional assessment

This submethodology (M07) is intended to assist those conducting a BA to model groundwater. 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 groundwater fluxes or stores (for example, changes in drawdown).

Different model types and model codes have been chosen to be used in different subregions or bioregions due to the differing requirements in each subregion or bioregion; therefore this submethodology has been written at a conceptual level to be independent of any specific model code to remain generally applicable to all subregions or bioregions. Specific details for groundwater models will be written in product 2.6.2 (groundwater numerical modelling) for each Assessment.

The model delivers spatially explicit model outputs that are used as inputs to other BA models, including the surface water 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 groundwater modelling (Figure 7).

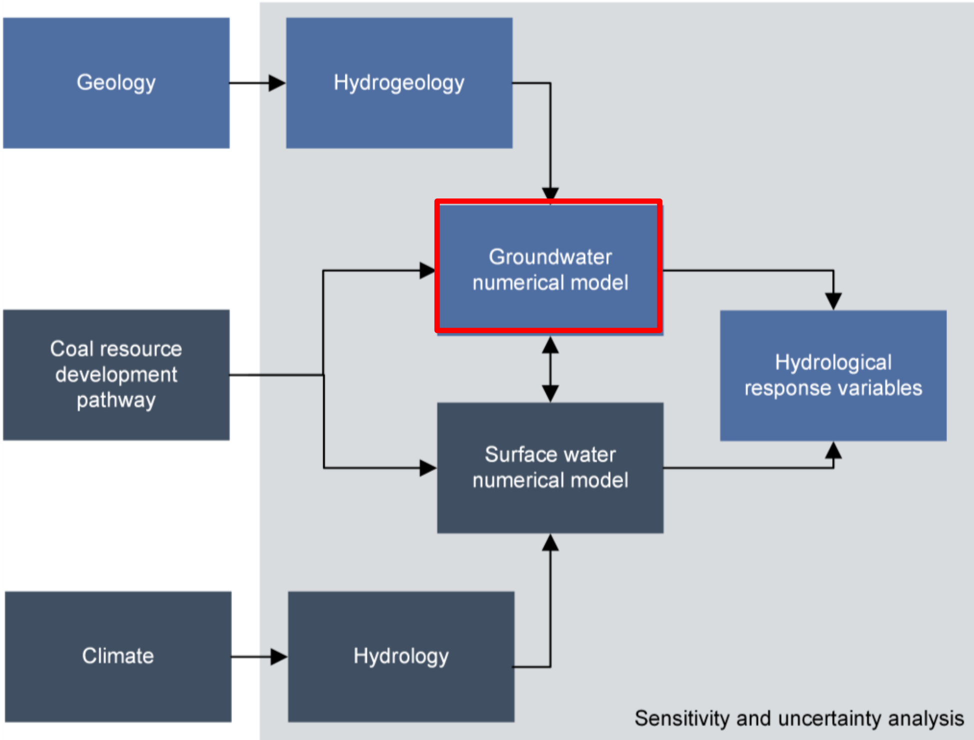


Figure 7 Data flows for groundwater modelling (red outline) showing connections to closely related bioregional assessment activities including the sensitivity and uncertainty analysis (light grey box)

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.

The model will provide the basis for product 2.6.2 (groundwater numerical modelling) (see Table 2 for BA product details).

The development of the groundwater 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)
- surface water modelling (product 2.6.1).

The groundwater model outputs hydrological response variables which are inputs for:

- surface water modelling, particularly regarding surface water – groundwater interactions
- model node placement
- uncertainty analysis
- receptor impact modelling.

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 M07 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 M06 for surface water modelling (Viney, 2016)
- submethodology M08 for receptor impact modelling (as listed in Table 1)
- submethodology M11 for hazard analysis (Ford et al., 2016).

2 Modelling philosophy

The objective of groundwater modelling undertaken as part of a bioregional assessment (BA) is to assess the potential impact of coal resource development on water and water-dependent assets.

Generally, the type of modelling undertaken will be trajectory modelling. Two potential futures are considered in a BA:

- *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 CSG fields that are in the baseline as well as those that are expected to begin commercial production after December 2012.

The difference between CRDP and baseline (known as the *additional coal resource development*) is the change that is primarily reported in a BA. This manner of using groundwater models is different to the typical use for which many existing groundwater flow models were developed. Therefore, the use of existing models in BAs will need to be evaluated in terms of their suitability for this purpose.

As outlined in the BA methodology (Barrett et al., 2013), one of the overarching goals of the Bioregional Assessment Programme is for results to be transparent and reproducible. Transparency will require that the models and related scripts used in BA analyses are subsequently made publicly available. Reproducibility requires that model runs are undertaken using a documented workflow.

There is an explicit acknowledgement that in all cases not all of the information required to build an ideal groundwater flow model will be available; therefore assumptions will need to be made with regards to model conceptualisation and parameterisation. The uncertainties associated with these assumptions are to be quantified and then propagated from conceptual modelling to receptor impact modelling wherever possible. This will require that models are run probabilistically and not deterministically; consequently, this means that modelling outputs will not be scalar values but probability distributions.

Mismatches in scale between the regional nature of the modelling and the point-scale nature of the model nodes mean that the modelling will not be able to capture fine-scale complexities of impacts upon assets and/or landscape classes. For this reason, results will not be reported in absolute terms but instead as differences between the baseline and CRDP (see Figure 15).

All of the models used in BAs will be 'Class 1' models as defined by the *Australian groundwater modelling guidelines* (Barnett et al., 2012). This is the lowest level of certainty within the classification and is a reflection of the data available and predictions required, rather than the quality of the models. Key indicators of Class 1 models include that model predictive time frames are more than ten times longer than the length of the transient model calibration period, and that the magnitude of stresses featured in prediction scenarios is more than five times larger than simulated in the calibration period (Barnett et al., 2012).

2.1 The principle of superposition

In BA we are interested in the difference between two future model runs, it is the drawdown that we are focused on rather than the absolutes. The principle of superposition is a mathematical concept that applies to linear systems governed by linear differential equations. This is often invoked in groundwater modelling and can be illustrated at its simplest as a doubling of a stress (e.g. pumping) will result in a doubling of the response (drawdown). The principle of superposition is used in BA through reporting of results as the difference between the baseline and CRDP.

The principle of superposition can be demonstrated mathematically for transient groundwater flow in a confined aquifer (Reilly et al., 1987):

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial h}{\partial y}\right)+W=S\frac{\partial h}{\partial t} \tag{1}$$

Where T is transmissivity in the x and y directions, W is the applied stress (e.g. pumping or recharge) and S is the storage coefficient. For a particular set of stresses (pumping) in space and time W(x,y,t), simplified to W_1, we get a particular groundwater level distribution h(x,y,t), simplified to h_1:

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial h_1}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial h_1}{\partial y}\right)+W_1=S\frac{\partial h_1}{\partial t} \tag{2}$$

If we now impose an additional stress on the system (additional pumping) $W_1 + \Delta W$, we get a different distribution of groundwater levels, $h_1 + \Delta h$:

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial (h_1+\Delta h)}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial (h_1+\Delta h)}{\partial y}\right)+(W_1+\Delta W)=S\frac{\partial (h_1+\Delta h)}{\partial t} \tag{3}$$

As the derivative of a sum is equal to the sum of the individual derivatives, we get:

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial h_1}{\partial x}\right)+\frac{\partial}{\partial x}\left(T_x\frac{\partial \Delta h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial h_1}{\partial y}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial \Delta h}{\partial y}\right)+W_1+\Delta W=S\frac{\partial h_1}{\partial t}+S\frac{\partial \Delta h}{\partial t} \tag{4}$$

If the second equation is subtracted from the fourth equation, then we have:

$$\frac{\partial}{\partial x}\left(T_x\frac{\partial \Delta h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_y\frac{\partial \Delta h}{\partial y}\right)+\Delta W=S\frac{\partial \Delta h}{\partial t} \tag{5}$$

The resulting equation shows that the change in groundwater level distribution (drawdown, Δh) is only dependent on the change in stress (additional pumping, ΔW). In this way the initial groundwater level distribution (dependent on recharge and boundary conditions) and the initial stresses (e.g. agricultural extraction) become irrelevant to the solution. This principle is used explicitly in the analytical element modelling (Gloucester and Galilee) where the initial groundwater levels are all at 0 and the agricultural pumping and recharge are not simulated.

In cases where non-linear differential equations are used, such as in unconfined aquifers, Reilly et al. (1987) suggest that less than 10% change in saturated thickness probably results in negligible errors if the principle of superposition is used. To minimise these errors we cannot ignore the recharge or agricultural pumping in the models that use unconfined aquifers (such as Namoi and Hunter), however getting the recharge and agricultural extraction absolutely correct is not essential for BA purposes (this limits the applicability of these models for water resource planning).

2.2 The precautionary principle

In the groundwater modelling, the precautionary principle is adopted: impacts are over estimated rather than under estimated. There are many assumptions necessary in building a groundwater model, as long as it can be shown that an assumption over estimates – not under estimates – impacts, the assumption is considered valid for the specific purpose of this modelling. An example is the vertical hydraulic conductivity of aquitards; in the absence of definitive measurements, the full plausible range of this parameter is used in BA modelling.

However, an overly conservative estimate of impact is not desirable either. If there are sound reasons to believe that predicted impacts are deemed unrealistically high (e.g. in comparison to earlier modelling efforts in the bioregion) or in excess of legally defined thresholds (such as the specified drawdown thresholds in the NSW aquifer interference policy), the magnitude of the over-estimation needs to be quantified or assessed more closely.

3 Choice of model

3.1 A fit-for-purpose model

Many regions have existing groundwater models but that does not necessarily mean that they are suitable for use in BA. Any existing models need to be evaluated to ensure that they are fit for purpose for use in BA. Table 3 lists the criteria a groundwater model in BA needs to satisfy to be considered fit for purpose for BA. If an existing model cannot be used in BA then a new model would need to be developed that does comply with the criteria in Table 3.

Table 3 Assessment of groundwater numerical modelling approach in bioregional assessments

Fit-for-purpose assessment criteria	Components
1. Prediction of hydrological response variables	Probabilistic estimates of hydrological change at model nodes
	Integration with receptor impact modelling
	Integration with surface water numerical models
2. Design and construction	Modelling objectives stated
	Model confidence level
	Modelling approach
3. Integration with sensitivity and uncertainty analysis workflow	Formally address uncertainty
	Parameterisation
	Convergence
4. Water balance components	Conceptual model agreement
5. Transparent and reproducible model outputs	Model data repository
	Model code and executables
	Pre- and post-processing scripts

Each of the criteria in Table 3 should be discussed in product 2.6.2 (groundwater numerical modelling) and the assumptions inherent in them. A discussion of these criteria forms part of the qualitative uncertainty analysis that is further described in the companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016).

3.2 Model code

The transparency requirements of the Bioregional Assessment Programme mean that the models used need to be made publicly available. This will ensure that the experts outside of the Assessment team can run the models and obtain the same results. This requires that the models are developed using public domain software and are independent of proprietary graphical user interfaces.

There are many different model types available that have been used for modelling the groundwater impacts of coal seam gas (CSG) and/or coal mining development; these include analytical, axisymmetric and numerical models. A useful summary of these is provided in Coffey Geotechnics (2014). Different model types and model codes have been chosen to be used in different subregions or bioregions due to the differing requirements in each subregion or bioregion. These include considerations such as data availability, intensity of development and the scheduling of extraction of coal resources. Model codes chosen for each subregion or bioregion to date include:

- hybrid analytical element-numerical model using TTim (Bakker, 2013) and MODFLOW (Harbaugh and McDonald, 1996) (Gloucester subregion)
- analytical element model using TTim (Bakker, 2013) (Galilee subregion)
- numerical model developed in MODFLOW (Harbaugh and McDonald, 1996) (Clarence-Moreton bioregion and Namoi subregion)
- numerical model developed in MOOSE (Wilkins, 2015) (Hunter subregion)
- existing jurisdictional MODFLOW (Harbaugh and McDonald, 1996) model (Maranoa-Balonne-Condamine subregion).

A deterministic MODFLOW groundwater model was also developed as a related product for Galilee subregion.

In the Bioregional Assessment Technical Programme, no groundwater modelling was undertaken for Gwydir, Central West, Arckaringa, Pedirka and Cooper subregions. State jurisdiction models exist for Arckaringa, Pedirka and Cooper subregions and the Gippsland Basin bioregion.

This submethodology has been written to be independent of any specific model code to remain generally applicable to all subregions or bioregions. This means that it is pitched at a conceptual level; specific details will be written in product 2.6.2 (groundwater numerical modelling) for each Assessment.

The *Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (Barrett et al., 2013) discusses the requirements for dual-phase flow, geomechanical deformation and solute transport modelling in a BA. This modelling will not be performed in the current round of BAs due to operational constraints. The implication of only using single-phase flow modelling is that impacts due to CSG developments could be overestimated (Herckenrath et al., 2015). Geomechanical deformation modelling will not be conducted in this round of BAs but the impact of subsidence on the hydraulic properties of the aquifers and aquitards will be incorporated in the modelling (where possible) through an increase in hydraulic conductivity above and below longwall mining areas. It is not possible to vary hydraulic properties for the analytical element models, thus this is only done where the Programme has developed numerical groundwater models.

4 Boundary conditions

4.1 Model extent

Ideally the model domain should extend to geological boundaries so that boundary effects on model predictions can be minimised. This is especially the case in those subregions or bioregions that have an off-shore component to the geological basin, such as the Hunter subregion.

4.2 Recharge

Temporal distributions of diffuse recharge to groundwater will be obtained from the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) that is used for the surface water modelling in BA (Viney, 2016). Since AWRA-L is calibrated to streamflow observations, recharge outputs will most likely be of different magnitudes to those determined using hydraulic and hydrochemical methods (e.g. chloride mass balance, water balance, tracers, etc.). For this reason, these recharge outputs will require scaling before use. In addition, AWRA-L outputs are produced over a 0.05 degree grid at a daily time step. These will need to be aggregated temporally to match the monthly time steps used in the groundwater models. Similarly, AWRA-L outputs will need to be aggregated spatially to a single temporal sequence to be applied to all recharge grid cells in the groundwater models. This simplification to a single temporal pattern for a subregion was shown to be appropriate for Clarence-Moreton bioregion in Crosbie et al. (2015).

The landscape model will be run under historical conditions for the 30-year period from 1 January 1983 to 31 December 2012. Climate forcing data for the forward modelling will be constructed from the historical climate time series repeated three times to create a 90-year time series and modified to be consistent with a median future climate projection. Further details of the future climate time series is given in the companion submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016).

Localised recharge due to river losses, overbank flooding and irrigation will be modelled in the AWRA river model (AWRA-R). The overbank flooding and irrigation recharge are used directly and the river losses are calculated by the groundwater model using the river stage from the AWRA-R model (see Chapter 6). These outputs from the river model will be provided as daily time series and will need to be aggregated temporally to match the monthly time steps used in the groundwater models and matched spatially from the river reach to the irrigated or flooded portion of that river reach in the groundwater model.

4.3 Extraction

Rates of groundwater extraction for stock, domestic, irrigation, industry and town water supplies will be treated as constant and equal to the rates specified in the water sharing plan (or other equivalent instrument) that was enacted for the last quarter of 2012 (unless actual metered data are available). Any future developments associated with agriculture or other industries have been excluded from the scope of the BAs and so these extractions will be consistent between the baseline and coal resource development pathway (CRDP).

Groundwater extractions associated with coal seam gas (CSG) and large coal mining development are determined based on target groundwater levels rather than extraction rates. For example, the target groundwater level for a CSG operation could be specified as the elevation located approximately 35 m above the top of the target coal seam. Similarly, the target groundwater level for large coal mining operations would be the pit floor for open-cut operations and atmospheric pressure for longwall mining operations. Using this approach, the rate of groundwater extracted is a function of hydraulic properties of the aquifers and aquitards involved (which are uncertain) and will be estimated as a probability distribution rather than as a discrete value.

4.4 Evapotranspiration

In areas featuring shallow watertables, or where shallow watertables might develop due to irrigation developments (associated with co-produced water), the parameterisation of evapotranspiration will require use of a depth-dependent boundary condition in the groundwater models in order to account for the loss of groundwater via evapotranspiration. In MODFLOW this is implemented as the EVT package (Harbaugh et al., 2000) with other model codes having something similar. In this manner, terrestrial groundwater-dependent ecosystems have been incorporated into the groundwater models.

5 Model time steps and predictive time frame

The length of model time steps (i.e. stress periods) will be a compromise between (i) the temporal resolution of the outputs required and (ii) achieving feasible model run times while minimising data storage requirements. Laminar groundwater flow is generally a relatively slow process; therefore the use of a daily time step length would be a waste of computational resources. However, in ecological terms, seasonal (i.e. quarterly) variations in baseflow are important; therefore, for BA purposes, this provides an upper limit on the acceptable time step frequency. It has therefore been decided to use a monthly time step length wherever practical for the 90 years of simulation.

It is assumed that after 90 years of simulation the coal seam gas (CSG) and large coal mining development that is simulated has ceased operation. The further into the future we project the impacts of large coal mines and coal seam gas developments the more uncertainty there is in future conditions. These future conditions include the degree to which post-operational conditions have stabilised, the future climate, land use and water sharing rules.

As the modelling is only progressing until 2102 there will be situations where *dmax* (maximum difference in drawdown for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures) has not been reached within this time. After the pumping associated with coal resource development has ceased, *dmax* at the well will have been reached but the cone of depression can still expand while the pressure is recovering at the well location. This can lead to *dmax* at a point away from the pumping occurring well after the pumping has ceased. The analytical solution of Yeh and Wang (2009) allows us to investigate the impact of not running the model until *dmax* is reached:

$$s(r,t_2) = \frac{s_0}{W\left(\frac{Sr_w^2}{4Tt_h}\right)}\left[W\left(\frac{Sr^2}{4T(t_h+t_2)}\right) - W\left(\frac{Sr^2}{4Tt_2}\right)\right] ,r \gg r_w \qquad (6)$$

where s(r,t) is the drawdown at a radial distance from the well r at time t, S is the storativity, T is the transmissivity, r_w is the radius of the well and W is the Theis well function. Figure 8 shows a solution of *dmax* and time to *dmax* as a function of distance from the extraction well for a case with a T/S of 254 m^2/d (this is an example, not related to a specific bioregion). This is showing that close to the well *dmax* is much greater than when further from the well but time to *dmax* occurs close to when the pumps are switched off for locations close to the well but time to *dmax* increases with increasing distance from the pumping well. There is a very clear negative correlation between *dmax* and time to *dmax*. For any model node where *dmax* has not occurred within the temporal domain of the model, *dmax* must be smaller than every point closer to the pumping well.

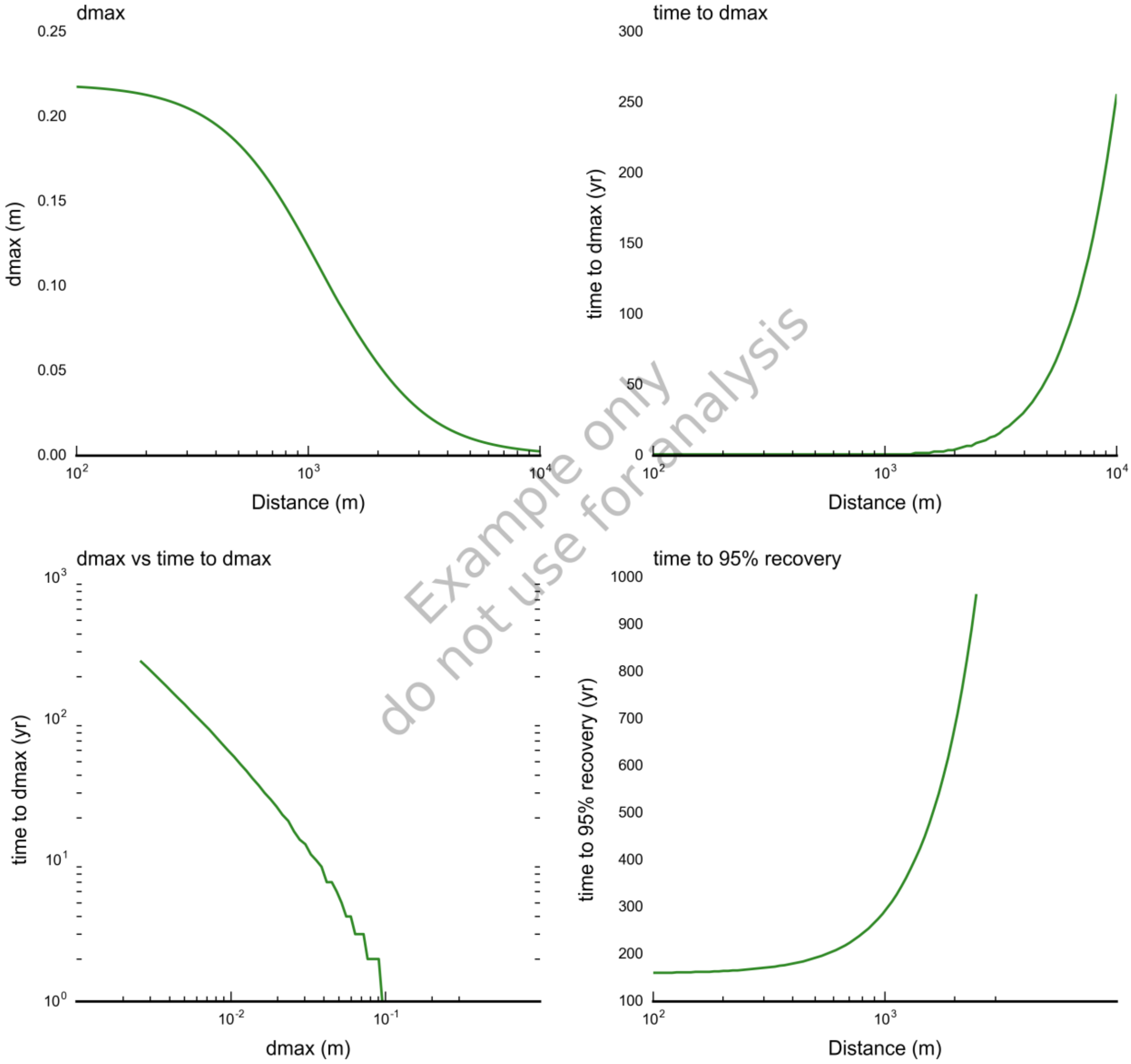


Figure 8 Calculation of *dmax* and time to *dmax* as a function of distance from the pumping well for T/S = 254 m^2/d using the analytical solution of Yeh and Wang (2009)

Example only; do not use for analysis

dmax refers to maximum difference in drawdown for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures

6 Integration with surface water modelling

There are several points at which the surface water modelling (Viney, 2016) and groundwater modelling need to be integrated. These include the fate of co-produced CSG water and mine water make, stream depletion due to watertable drawdown, and losing streams.

6.1 Co-produced water and mine water make

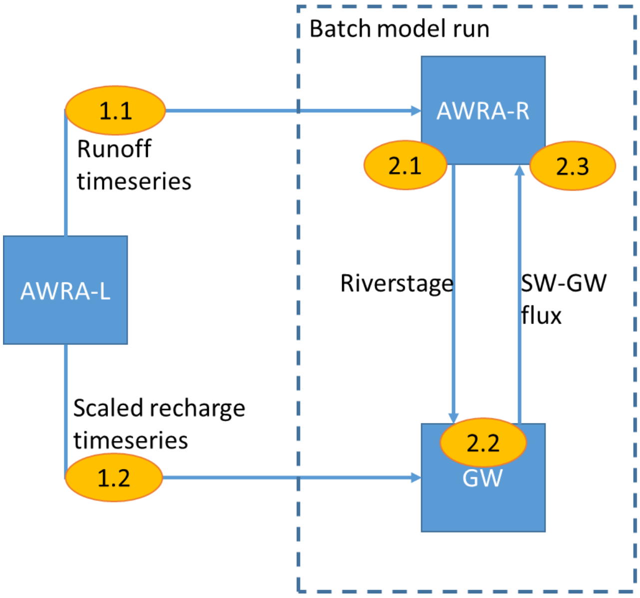
The groundwater extracted for dewatering coal mines (water make) or de-pressurising coal seams (co-produced water) needs to be routed somewhere; this will occur through the surface water modelling (Viney, 2016). The water make or co-produced water will be disposed of in a number of ways, including (i) process water on site, (ii) water use for irrigation, (iii) route water along stream channels or (iv) truck water off site.

6.2 Surface water – groundwater integration with a river model

Some of the considerations necessary are that the river and groundwater models need to be developed concurrently and ideally have a common development time frame. River models are calibrated using stream gauges without considering constraints related to groundwater. While previous generations of river models have lumped groundwater interactions into unallocated losses, the Australian Water Resources Assessment (AWRA) river model (AWRA-R) is capable of attributing river losses to various places but the groundwater losses are not constrained by groundwater data. In most semi-arid areas, river losses to groundwater are a substantial part of the groundwater balance and the groundwater model performance is very sensitive to errors. In other areas river losses to groundwater are often a small part of the river reach water balance, so the calibration is not sensitive to errors in the losses to groundwater.

A series of recommendations were made by Rassam et al. (2008) on improving the way that river models and groundwater models were coupled during the Murray-Darling Basin Sustainable Yields Project (CSIRO, 2008). The lessons learnt during that project will need to be incorporated into the modelling for BA. The general methodology is a three-stage process (Figure 9):

1. A river model is used to provide river stages to a groundwater model.
2. A groundwater model is run using the river stages to calculate exchange fluxes between groundwater and the river.
3. The river model is run again with the updated exchange fluxes calculated by the groundwater model. It is assumed that the change in baseflow fed back to the river has a very small impact on the river stage and so the proceeding steps do not need to be repeated.



1. Run AWRA-L to provide
    1. runoff to AWRA-R
    2. (scaled) recharge to GW
2. Start Batch model run
    1. Run AWRA-R to
        1. get riverstages for GW
    2. Run GW to
        1. Make predictions at GW receptors
        2. Provide SW-GW flux to AWRA-R
    3. Run AWRA-R with updated SW-GW flux
        1. Make predictions at SW receptors

This model sequence needs to be run for

1. Historical -> Baseline
2. Historical -> CRDP

Figure 9 Schematic of model run sequencing between the landscape, river and groundwater models

6.3 Surface water – groundwater integration without a river model

In bioregional assessment (BA) subregions or bioregions that will not include the development of a river model, the modelling of surface water – groundwater interactions will be limited. The AWRA-L landscape model outputs will be used to generate runoff rates for all BA subregions or bioregions, which will subsequently be aggregated to model nodes. However, the river stage variable (which is the boundary condition of interest for groundwater models) will not be calculated and so changes in river flow will not result in variations in surface water – groundwater fluxes.

For gaining streams and rivers, watertable declines due to groundwater extraction can result in reductions in baseflow. This requires that the stream network is built into groundwater models where there is a model node located on that stream segment. Differences in baseflow calculated by the groundwater model, between the baseline and coal resource development pathway (CRDP), will need to be subtracted from the runoff rates obtained from the Australian Water Resources Assessment (AWRA) landscape model (AWRA-L) for the baseline so that the impact on the model nodes associated with surface water can be determined in the CRDP.

For losing-connected streams and rivers the impacts of a falling watertable will result in increased river losses. These changes in river losses can be calculated by the groundwater model and subtracted from the aggregated runoff at the model node.

7 Parameterisation

The groundwater models used in the Bioregional Assessment Programme have a relatively simple parameterisation. That is the hydrostratigraphic layers are generally assumed to be homogeneous with the properties having a depth dependence and are modified due to geomechanical deformation following longwall mining.

7.1 Assumption of homogeneity of aquifer parameters

In most groundwater models developed for BA purposes, spatial heterogeneity of hydraulic properties is not represented explicitly. Most hydrostratigraphic units are assigned a spatially uniform hydraulic property.

This section illustrates that by stochastically varying this uniform hydraulic property, the variation in predicted groundwater levels is at least as large as the variability that would arise from simulating spatial heterogeneity explicitly. This means that the stochastic predictions will be conservative (i.e. the range of the ensemble prediction will be larger compared to the range based on modelling heterogeneous hydraulic properties).

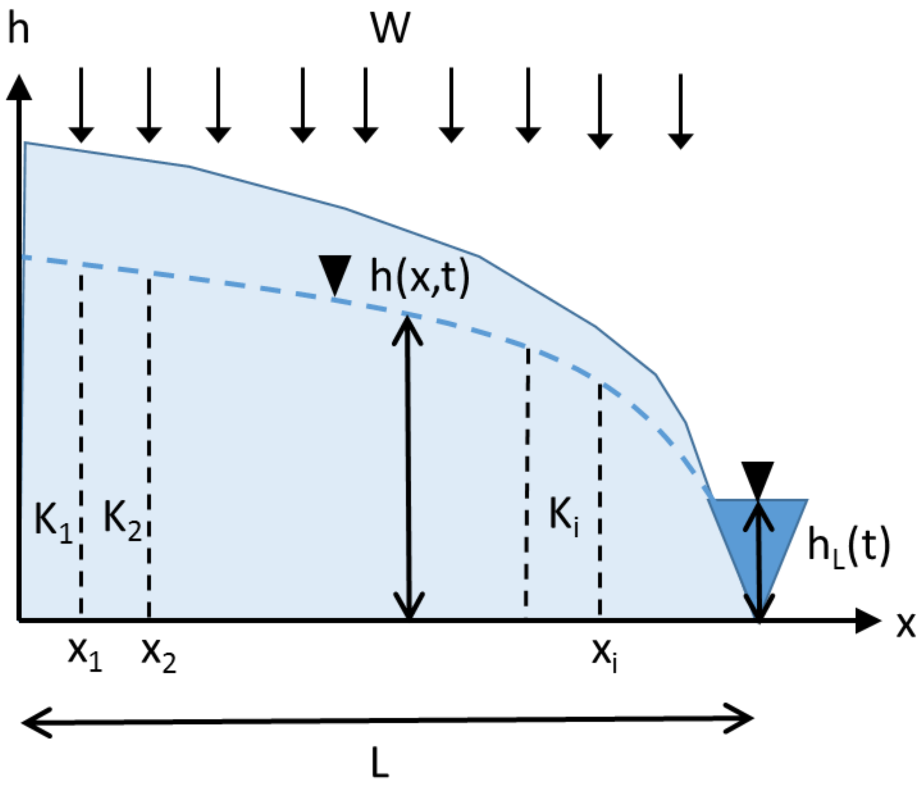


Figure 10 Conceptualisation of groundwater flow example (after Liang and Zhang, 2013)

The steady state solution for the groundwater level at a distance x from a no flow boundary, with a constant head boundary at x_N with constant head h_L , a spatially uniform diffuse recharge W and piecewise constant, spatially varying hydraulic conductivity $K(x) = K_i$ for $x_{i-1} < x < x_i$ $(i = 1,2, \dots, N)$ can be expressed as (Figure 10 and equations 4 and 5 in Liang and Zhang, 2013):

$$h_x^2 = h_L^2 + \frac{W}{K_i}(C_i - x^2), \qquad x \in [x_{i-1}, x_i], i = 1,2, \dots, N \tag{7}$$

$$C_i = \frac{K_i}{K_N} x_N^2 + \Theta(N-i) \sum_{j=i}^{N-1} \left(\frac{K_i}{K_j} - \frac{K_i}{K_{j+1}} \right) x_j^2 , \qquad \Theta(\vartheta) = \begin{cases} 1 & \vartheta \neq 0 \\ 0 & \vartheta = 0 \end{cases} \tag{8}$$

These equations present a linear approximation to groundwater flow in a spatially variable field and yields the same results as a numerical model that is discretised in N grid cells. While this is a simplification of any field conditions, this general conceptual model resembles situations that are relevant to BA, such as groundwater mounding away from a river or groundwater level variation away from a mine that is drained to a fixed level.

Equations 7 and 8 are straightforward to implement numerically and are solved very quickly, which allows the exploration of the effects of spatial heterogeneity on groundwater level predictions.

Consider the log of hydraulic conductivity is normally distributed with a mean of 1 m/d and a standard deviation of 1:

$$\ln(K) = N(\mu, \sigma^2) = N(0,1) \tag{9}$$

The spatial correlation can be described with an exponential variogram with correlation length λ so that the variance between two locations a distance d apart is:

$$\sigma_d^2 = \sigma^2 \exp(-\lambda d) \tag{10}$$

Figure 11 shows the results of a comparison of groundwater levels predicted at a distance of 9000 m from the constant head boundary (x=1000 m). For the heterogeneous case, 1000 samples of ln(K) are generated from a multivariate normal distribution with mean equal to zero and a covariance governed by equation 10 with three different correlation lengths (100 m, 1000 m and 10,000 m). For the uniform K case, 1000 samples of ln(K) are taken from the normal distribution specified in equation 9. The latter approach is the approach that is taken in the stochastic sampling in the uncertainty analysis of BA groundwater models.

From Figure 11 it becomes clear that the resulting ensembles of groundwater level predictions are nearly identical between the heterogeneous and the uniform hydraulic conductivity fields for the three different correlation lengths.

Figure 12 shows the same analysis for groundwater level predictions 1000 m from the constant head boundary (x=9000 m). It is apparent that the uniform hydraulic conductivity field results in ensembles that have a similar mean and median to the heterogeneous case, but the spread in the distribution is underestimated. This effect is more pronounced for short correlation length.

While this is by no means a comprehensive study of the effects of spatial heterogeneity on groundwater level predictions, some general findings are:

1. At regional scale, i.e. distances larger than a few kilometres, from a stress or boundary condition, spatial heterogeneity has little influence on groundwater level predictions. The uncertainty in groundwater level predictions can be captured by stochastically varying a spatially uniform hydraulic conductivity
2. At a local scale, i.e. distance smaller than a few kilometres from a stress or boundary condition, spatial heterogeneity will have a distinct effect on groundwater level predictions. The differences between simulating spatial heterogeneity and varying a spatially uniform hydraulic conductivity increase for decreasing correlation length (i.e. higher spatial variability).

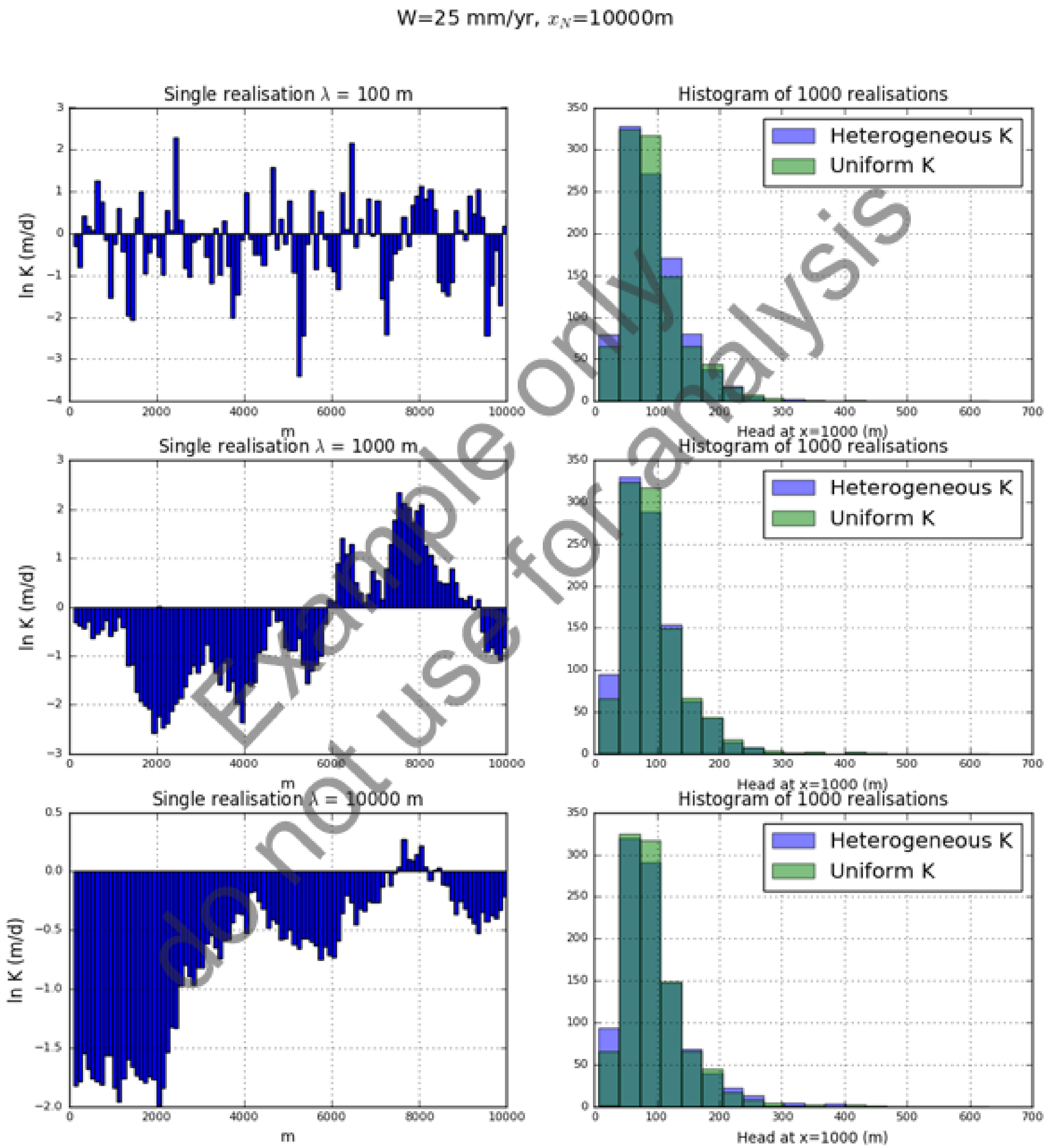


Figure 11 Single realisations of spatial variation in hydraulic conductivities (left column) for varying correlation lengths with the corresponding groundwater level predictions at x = 1000 m for 1000 realisations of the spatial varying field (heterogeneous K) and 1000 samples of spatially uniform hydraulic conductivity (uniform K) for a system with recharge W = 25 mm/year and xN = 10,000 m

Example only; do not use for analysis

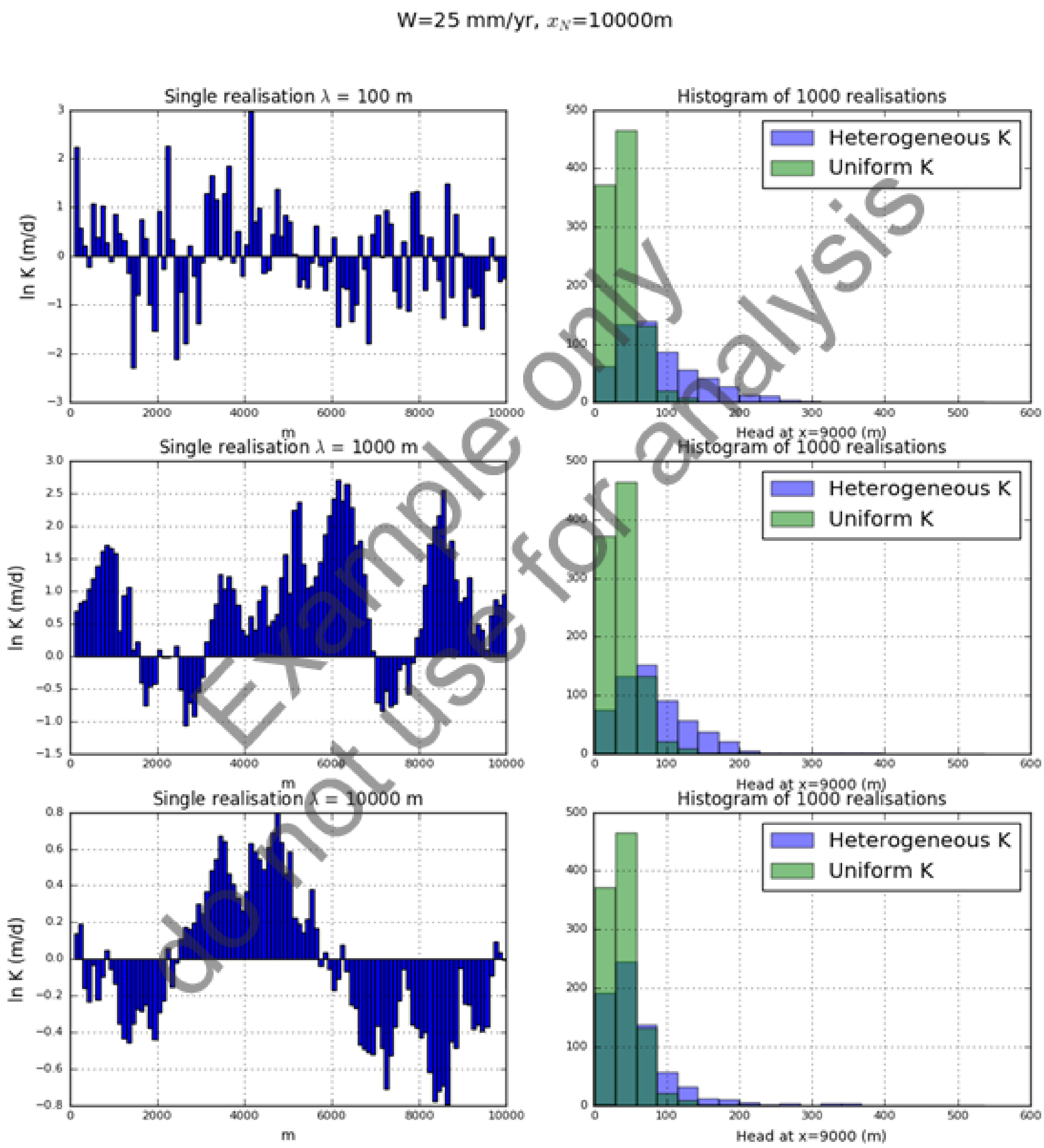


Figure 12 Single realisations of spatial variation in hydraulic conductivities (left column) for varying correlation lengths with the corresponding groundwater level predictions at x = 9000 m for 1000 realisations of the spatial varying field (heterogeneous K) and 1000 samples of spatially uniform hydraulic conductivity (uniform K) for a system with recharge W = 25 mm/year and xN = 10,000 m

Example only; do not use for analysis

7.2 Depth dependence of hydraulic properties

Even though a simple parameterisation of the models is used that will generally see hydrostratigraphic layers treated as homogeneous, the hydraulic properties used in the groundwater modelling have a depth dependence that has been observed in many coal basins. An example is shown in Figure 13 for data from the Hunter subregion, Gloucester subregion and Sydney Basin bioregion (Parsons Brinkerhoff, 2015).

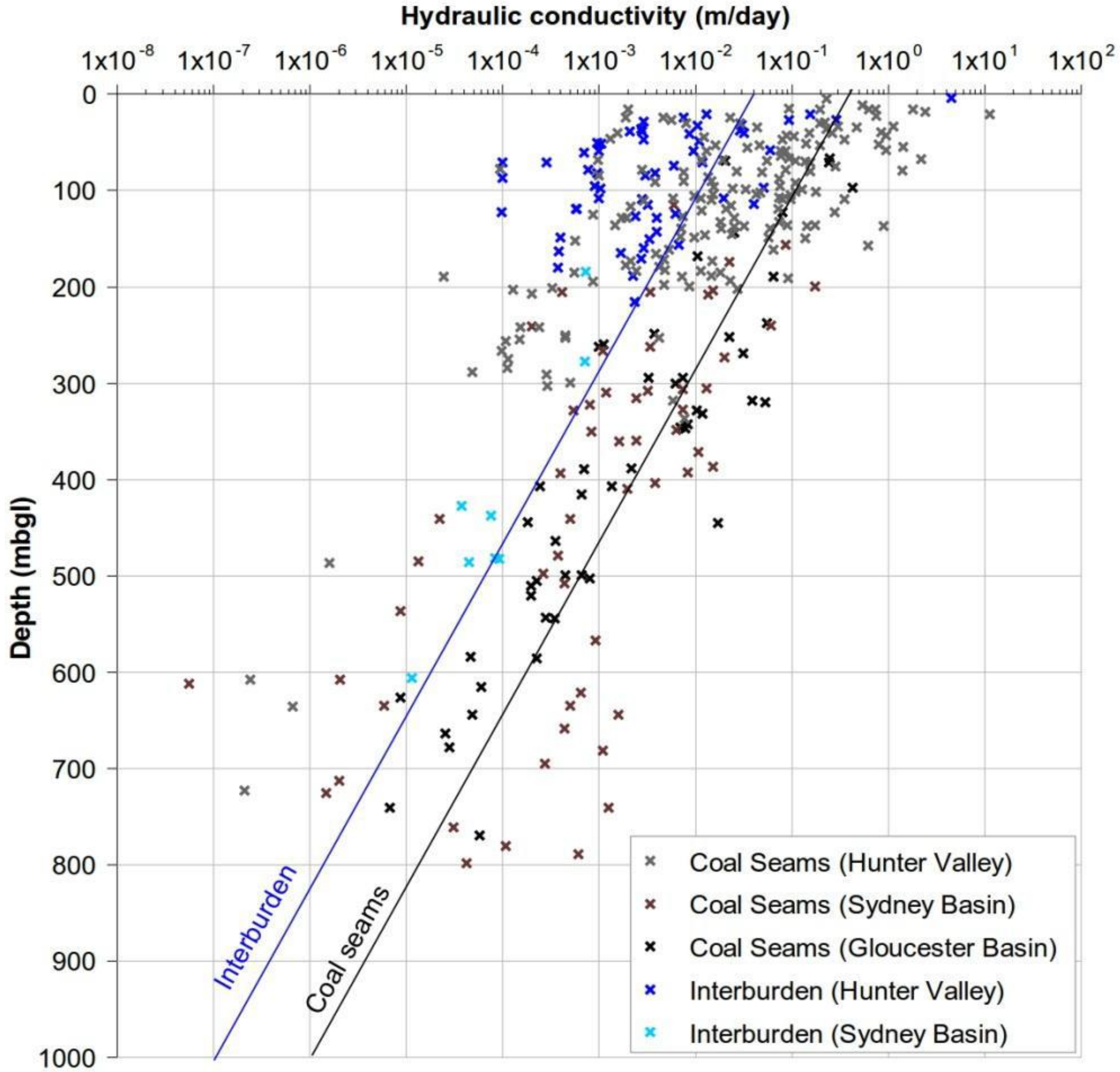


Figure 13 Relationship between depth and hydraulic conductivity for coal seams and interburden

Source: Figure 7.3 in Parsons Brinckerhoff (2015). This figure is not covered by a Creative Commons Attribution Licence, it has been reproduced with the permission of AGL.

7.3 Changes in hydraulic properties post-mining

Following longwall mining there are often changes in hydraulic properties observed due to geomechanical deformation. This can be represented in the groundwater models by enhancing the hydraulic conductivity after longwall mining. The hydraulic conductivity, *K*, above and below each mine working, is enhanced according to:

$$K(x,y,z,t) = 10^{\Delta} K_0(x,y,z) \quad (11)$$

where K_0 is the base conductivity (both horizontal and vertical components), and Δ parameterises the conductivity change. $\Delta=0$ before mining of the seam commences, and $\Delta=\Delta(h)$ at height, *h,* above the seam after mining commences. Δ is calculated using the following piecewise-linear function of the height above the mining seam, *h*:

$$\Delta = 0 \text{ for } h > Z >= 0 \quad (12)$$

$$\Delta = 0 \text{ for } h < z < 0 \quad (13)$$

$$\Delta = M(Z-h)/Z \text{ for } 0 <= h <= Z \quad (14)$$

$$\Delta = m(h-z)/z \text{ for } z < h < 0 \quad (15)$$

The general form of the relationship is illustrated in Figure 14 where it is clear that conductivity change is *M* orders of magnitude directly above the seam, and *m* orders of magnitude directly below the seam, and that the conductivity changes occur between -*z* below the seam and *Z* above the seam.

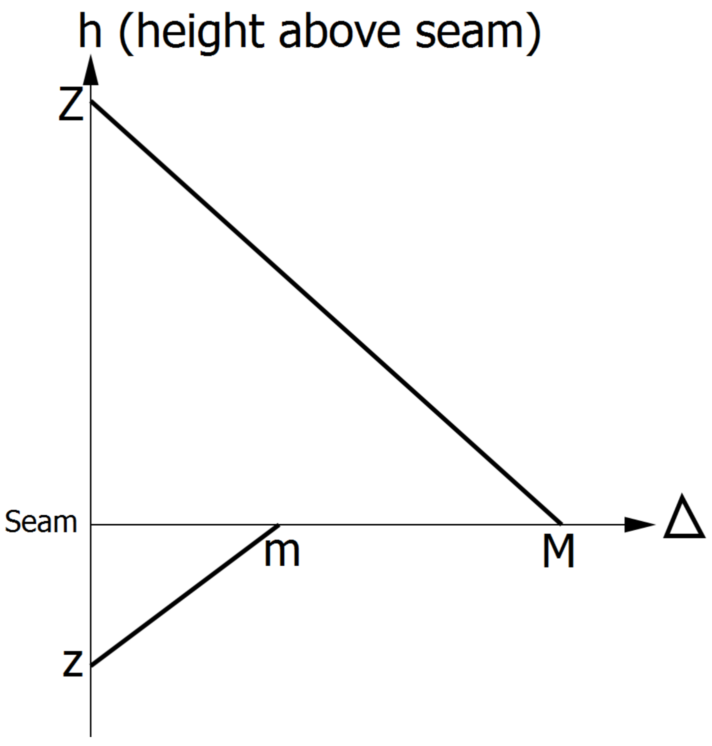


Figure 14 Assumed relationship between the conductivity-change parameter, Δ, and the height above the mining seam, *h*

As discussed in Adhikary and Wilkins (2012), the effective conductivity in the immediate roof of longwall mines can be enhanced by up to 10 orders of magnitude. The enhancement of hydraulic conductivity can extend up to 500 m above and 250 m below the longwall panel.

8 Calibration, sensitivity analysis and uncertainty analysis

Due to the bioregional assessment (BA) requirement that groundwater modelling should take as many forms of uncertainty as possible into account, a ‘conventional’ (i.e. deterministic) calibration process will not be followed in the bioregional assessments. A global sensitivity analysis will be conducted on each model prediction using as many parameters as possible within the model. The sensitivity analysis will determine which parameters each model prediction is most sensitive to. The uncertainty analysis will be conducted using plausible ranges of values for each of the sensitive parameters using (i) a Monte Carlo procedure if there are no constraining data available or (ii) a Markov Chain Monte Carlo procedure when there are data to constrain the prediction. As the computational cost of a thorough uncertainty analysis using groundwater models is generally prohibitive, a limited number of model runs (i.e. in the order of thousands) will be conducted to train a statistical model emulator. For each prediction of interest, a Gaussian Process emulator will be built which can be run more efficiently (and enable model runs in the order of tens of thousands) to quantify the probability distribution function of the required output. The details of the uncertainty analysis can be found in the companion submethodology M09 (as listed in Table 1) for propagating uncertainty through models (Peeters et al., 2016).

Constraining data to be used for model predictions will ideally include hydraulic heads in various aquifers as well as fluxes such as baseflow and volumes of co-produced water. The location of these data points will need to be evaluated thoroughly to ensure they are responding to regional stressors rather than local effects (which are not captured by the regional model).

The sensitivity and uncertainty analyses undertaken for BAs require that groundwater models are built with this use in mind. This will require robust models that are capable of converging for a broad range of parameter values. This will likely require model grid simplifications to aid convergence and reduce run times. These requirements have been defined before a groundwater model can be passed to the risk team:

1. Coal resource development pathway (CRDP)
   a. the final CRDP is implemented in the model.
2. Model nodes
   a. a preliminary list of model nodes is identified (90% final)
   b. model output for these locations is generated through the observation functionality of MODFLOW or via ZONEBUDGET (not via post processing the heads or budget file in a graphical user interface (GUI)).

3. Parameterisation
   a. an exhaustive list of parameters is compiled. For each parameter it describes:
      1. name
      2. units
      3. description (in case of parameter zones, reference needs to be made to maps and cross-sections)
      4. preferred value
      5. minimum plausible value
      6. maximum plausible value (the plausible range of hydraulic properties is expected to vary over at least two orders of magnitude).
   b. The value of each parameter can be changed via a script in an automated way, either via the native parameter functionality of MODFLOW or via a custom script.
   c. The parameterisation and model run can be executed as a single batch-file from command line, independent of the GUI used for development.
4. Convergence
   a. The model converges for the steady state, baseline transient and CRDP transient for the preferred parameter values. The model convergence criteria for these runs are not to be changed in the subsequent stress testing runs.
   b. The model also converges for the extreme parameter combinations (e.g. minimum plausible recharge with maximum plausible hydraulic conductivity with minimum specific storage).
   c. Non-converging parameter combinations can be acceptable if a sound hydrogeological reason is provided for the non-convergence.
   d. In case of acceptable non-convergence parameter combinations, the most extreme parameter combination of that type for which the model converges needs to be established.
5. Head and flux observations
   a. An objective function is formulated, combining and weighting all historical observations, both heads and fluxes.
   b. The objective function is part of the model output, either via the native parameterisation and observation functionality of MODFLOW or customised scripting.

9 Meeting the requirement for transparency

The bioregional assessment (BA) requirement for the model results to be reproducible means that the models need to be run as part of a documented workflow that records the provenance of the input data, executables and outputs. This has been achieved through the use of scripting. All pre-processing, model runs and post-processing is done using scripts that will be made available along with the products; this ensures that all model inputs, parameters, executables and outputs are traceable.

10 Outputs from groundwater modelling

10.1 Outputs for product 2.6.2 (groundwater numerical modelling)

Product 2.6.2 (groundwater numerical modelling) reports the potential impacts of coal resource development on water resources at the selected model nodes within the groundwater model domain. This is done by comparing model simulations that account for the coal resource development pathway (CRDP) with those that only consider the baseline.

10.1.1 Hydrological response variables

The groundwater modelling outputs *hydrological response variables*, the hydrological characteristics of the system or landscape class that potentially change due to coal resource development. These outputs from the groundwater modelling can be either fluxes or stores. They need to be decided before the sensitivity analysis begins and also need to be defined precisely – for example, drawdown at location (*x, y, z*) at time *t*.

The primary hydrological response variables for groundwater are shown in Table 4.

Table 4 Primary hydrological response variables for groundwater

Shortened form	Description of hydrological response variable	Units
tmax	year of maximum change	year
dmax	maximum difference in drawdown for one realisation within an ensemble of groundwater modelling runs, obtained by choosing the maximum of the time series of differences between two futures	metres

Figure 15 shows an example of output for hydrological response variables for the Clarence-Moreton bioregion (see Cui et al. (2016) for full explanation and interpretation of these results). Uncertainty analysis has been undertaken for these results as well (as per Chapter 8).

Other outputs from groundwater modelling include:

- groundwater fluxes to or from the stream network, which are fed back to the surface water modelling (Viney, 2016) and are reported as surface water hydrological response variables in product 2.6.1 (surface water numerical modelling)
- the volume of co-produced water and mine water make, which is reported in product 2.5 (water balance assessment)
- interpolated surfaces of percentiles of drawdown and probability of exceeding thresholds of 0.2 and 2 m for the baseline, CRDP and additional coal resource development.

Some groundwater models will be capable of generating many gigabytes of output data from a single model run. When such models are run thousands of times, the storage space required may become infeasible and file transfers may become prohibitive or impossible. For this reason, only the model outputs that will actually be used in evaluating the potential impacts of coal resource development on assets and landscape classes will be stored.

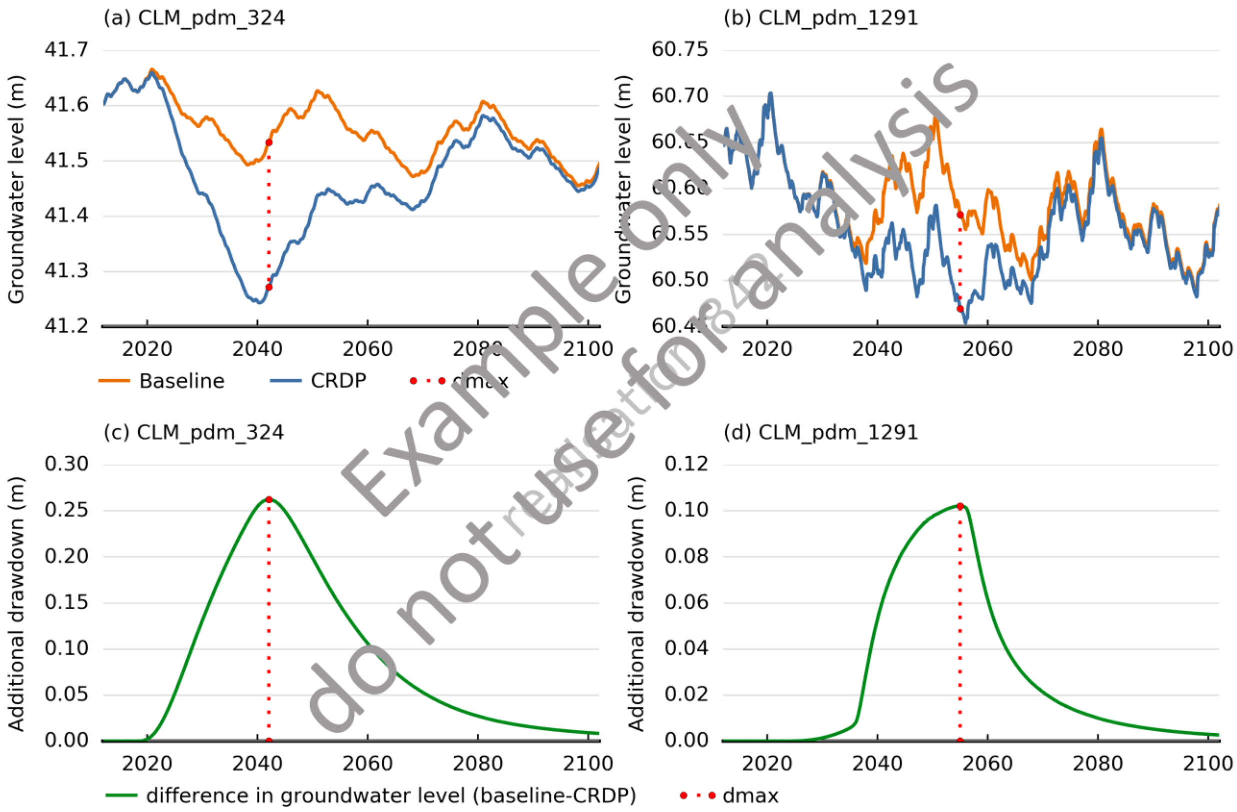


Figure 15 Example of the groundwater model output time series of model nodes pdm_324 (a) and (c) and pdm_1291 (b) and (d)

Example only; do not use for analysis. This is an early draft of a figure published in Cui et al. (2016). See Cui et al. (2016) for full explanation and interpretation of these results.
Additional drawdown is the maximum difference in drawdown (*dmax*) between the coal resource development pathway (CRDP) and baseline, that is due to additional coal resource development.
Coal resource development pathway = baseline + additional coal resource development

10.1.2 Content for product 2.6.2 (groundwater numerical modelling)

Table 5 shows the recommended content for product 2.6.2 (groundwater numerical modelling).

The outline for product 2.6.2 (groundwater numerical modelling) can be flexibly adapted where there are multiple groundwater models. There are several reasons why there could be multiple groundwater models within a subregion or bioregion including:

- where the development occurs in two distinct geographical regions without overlap
- a hybrid approach with models feeding in to one another, or
- if child models are used for detail in an area of a regional model.

In the Bioregional Assessment Technical Programme only the Gloucester subregion has multiple groundwater models. Two models were built for the Galilee subregion, although only one is used directly for the Bioregional Assessment Technical Programme analysis.

Table 5 Recommended content for product 2.6.2 (groundwater numerical modelling) when there is one groundwater model

Section number	Title of section	Main content to include in section
2.6.2.1	Methods	**Summary** This section identifies the models used, the interactions between the different models, the sequence in which they need to be run and for which model nodes they simulate the impact of coal resource development.
2.6.2.2	Review of existing models	**Summary** This section reviews the previous groundwater models developed for coal resource development in the subregion or bioregion. Level 5 headings can cover individual projects.
2.6.2.3	Model development	**Summary** This section describes how the model was developed. The following Level 5 headings are recommended but not mandatory. **2.6.2.3.1 Objectives** **2.6.2.3.2 Hydrogeological conceptual model** **2.6.2.3.3 Design and implementation** **2.6.2.3.4 Model code and solver** **2.6.2.3.5 Modelling approach**
2.6.2.4	Boundary and initial conditions	**Summary** This section characterises the boundary and initial conditions. The following Level 5 headings are recommended but not mandatory. **2.6.2.4.1 Lateral** **2.6.2.4.2 Recharge** **2.6.2.4.3 Surface water – groundwater interactions**
2.6.2.5	Implementation of coal resource development pathway	**Summary** This section describes how the coal resource development pathway (as specified in product 2.3 (conceptual modelling)) is implemented in the groundwater model. The following Level 5 headings are recommended but not mandatory. **2.6.2.5.1 Open-cut mines** **2.6.2.5.2 Underground mines** **2.6.2.5.3 Coal seam gas wells**
2.6.2.6	Parameterisation	**Summary** Table 6 (in this submethodology) provides an exemplar table for listing parameters in this section.
2.6.2.7	Observations and predictions	**Summary** This section provides the results, namely predictions of the hydrological response variables and the sensitivity of the results to the parameters used. The following Level 5 headings are recommended but not mandatory. **2.6.2.5.1 Predictions** **2.6.2.4.2 Sensitivity analysis**

Section number	Title of section	Main content to include in section
2.6.2.8	Uncertainty analysis	**Summary** Both qualitative and quantitative uncertainty is presented. **2.6.2.6.1 Qualitative uncertainty analysis** The qualitative uncertainty analysis lists the main model assumptions and choices and discusses their potential effect on the predictions. Table 7 (in this submethodology) provides an exemplar table. **2.6.2.6.2 Quantitative uncertainty analysis** For the quantitative uncertainty analysis, prior distributions, including covariance, are specified for all parameters from expert elicitation; constraining these prior distributions with the maximum coal seam gas (CSG) and coal mine water production rate results as well as head and flux observations in posterior probability distributions for dmax and tmax. The potential effect on the predictions are discussed along with a comparison to previous model results. Figure 16 and Figure 17 (in this submethodology) provide exemplar figures.
2.6.2.9	Limitations and conclusions	**Summary** This section describes the use for which the groundwater model was developed, and limitations on its application to other uses.

Table 6 Example table to include in Section 2.6.2.6: parameters of the Avon and Karuah models for the Gloucester subregion

Example only; do not use for analysis

Parameter name	Value	Description	Unit	Minimum	Maximum
Kha	1.0	Saturated hydraulic conductivity of top alluvial layer	m/d	0.1	10.0
Khw	0.003	Saturated hydraulic conductivity of lower weathered layer	m/d	0.01	0.0001
Sy	0.15	Specific yield of the top alluvial layer	na	0.25	0.05
Dc	100.0	Hydraulic conductance of lower boundary of drain bed	m^2/d	10.0	1000.0
Rmult	1.0	Multiplier for monthly recharge	na	0.1	2.0
dh	2.0	Depth to water in the lower weathered layer	m	0.0	5.0

The 'value' column lists the initial parameter value simulation, while the 'minimum' and 'maximum' columns show the range sampled for the design of experiment. The last two lines list non-variable parameters used in the simulations.
na = not applicable
See Peeters et al. (2016) for full explanation and interpretation of these results.

Table 7 Example table to include in Section 2.6.2.8: qualitative uncertainty analysis as used for the Gloucester subregion

Example only; do not use for analysis.

Number	Assumption / model choice	Data	Resources	Technical	Effect on predictions
1	Hybrid analytic element – MODFLOW model methodology	high	medium	high	low
2	Principle of superposition	medium	low	low	low
3	Horizontally spatially uniform hydraulic properties	high	medium	medium	low
4	Hydraulic properties vary with depth, not with stratigraphy	high	low	low	medium
5	Stochastic representation of coal seams and faults	high	low	low	low
6	Random location of CSG wells and assigning pumping interval to random coal seams	high	low	low	low
7	CSG wells as constant head wells	high	medium	high	medium
8	Open-cut mines as prescribed pumping rate	high	low	low	high
9	Specification of prior distributions	high	medium	low	low
10	River network implemented as drainage boundary	medium	low	low	low
11	Constrain model with flux estimates rather than head observations	high	low	low	low
12	Simulation period from 2012 to 2102	low	high	medium	low

CSG = coal seam gas
See Peeters et al. (2016) for full explanation and interpretation of these results.

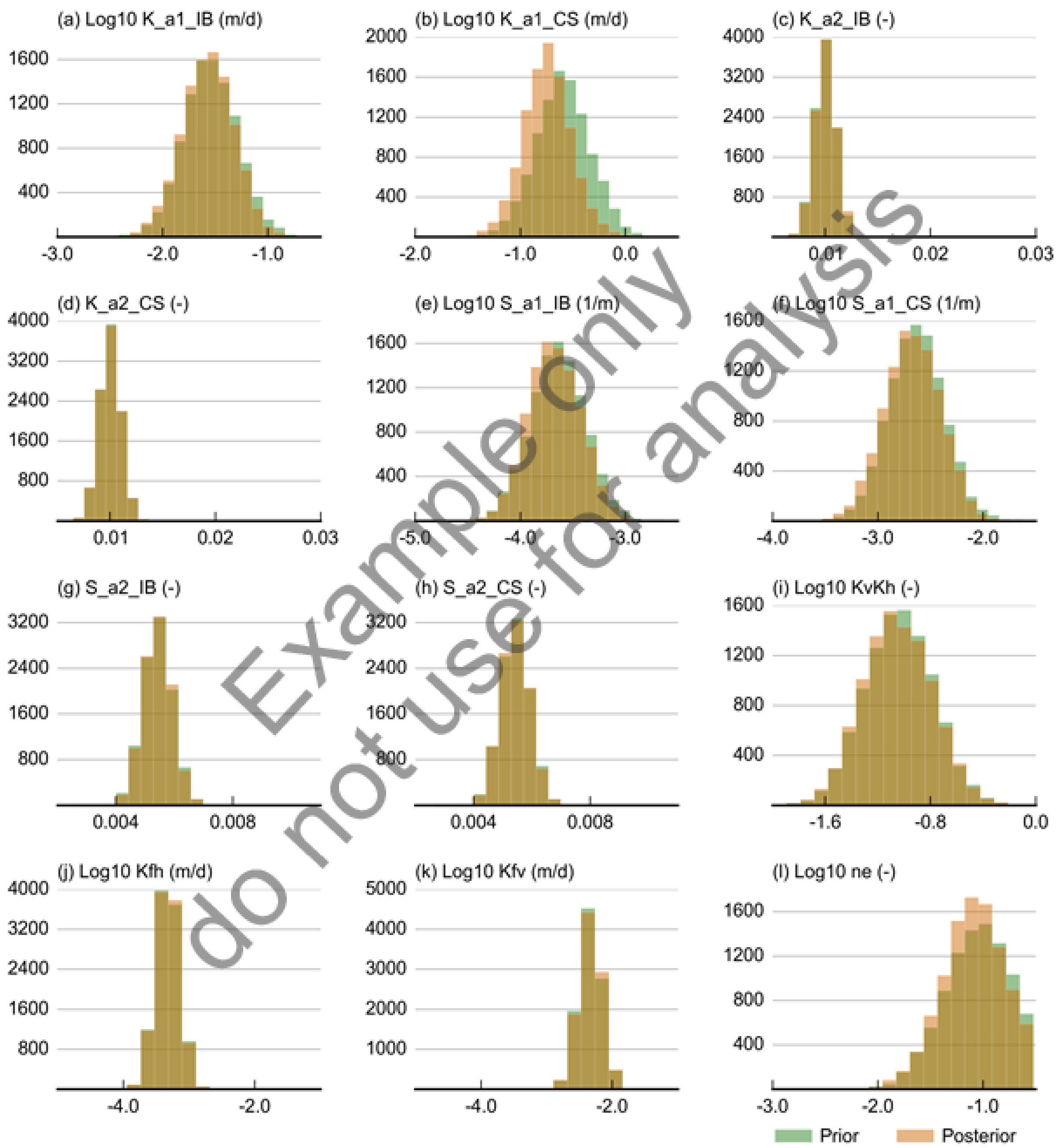


Figure 16 Example figure to include in Section 2.6.2.8 *Uncertainty analysis*: histograms of prior and posterior distributions of the regional analytic element model for the Markov chain Monte Carlo analysis for the Gloucester subregion

Example only; do not use for analysis.
The extent of the x-axis in each plot corresponds to the range of parameters sampled during the design of experiment. Refer to Table 3 in Section 2.6.2.3.4 for definitions of terms.
See Peeters et al. (2016) for full explanation and interpretation of these results.

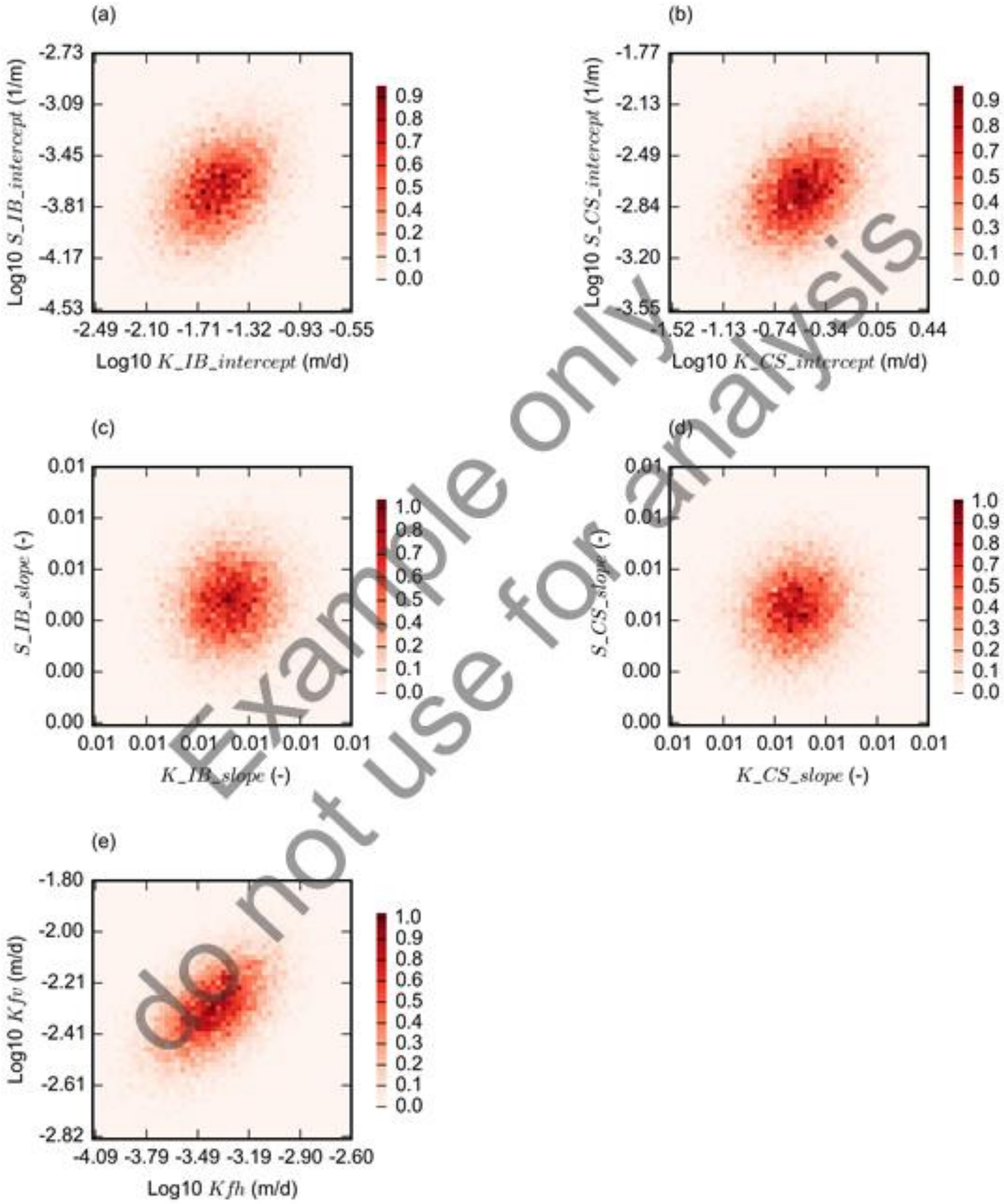


Figure 17 Example figure to include in Section 2.6.2.8 *Uncertainty analysis*: covariance of the posterior parameter distributions for the regional analytic element groundwater model for the Gloucester subregion

Example only; do not use for analysis.
The colour scale is proportional to the density of points. Refer to Table 5 in Section 2.6.2.6 of Peeters et al. (2016) for definition of terms. See Peeters et al. (2016) for full explanation and interpretation of these results.

10.2 Outputs for product 2.5 (water balance assessment)

Product 2.5 (water balance assessment) presents a quantitative water balance for the subregion. The groundwater components of this water balance are typically derived from the outputs of the groundwater modelling. Other approaches for determining groundwater balance components may be required (e.g. SKM, 2006) if the groundwater modelling undertaken for a subregion does not provide the necessary information for reporting in the water balance. Table 9 shows the recommended content for product 2.5 (water balance assessment).

The water balance will represent a defined control volume. The nature of this control volume may vary between subregions or bioregions. However, it is likely to involve a subarea of the surface water model 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. In product 2.5 a map will be provided that shows the location of the control volumes used for the water balance.

The following groundwater components will be reported in the water balance:

- recharge
- evapotranspiration
- baseflow (discharge to stream)
- upward flow from deeper groundwater
- change in storage.

An exemplar for a water balance table is shown in Table 8 (see Herron et al. (2016) for full explanation and interpretation of these results).

Table 8 Example water balance table: mean annual groundwater balance for the alluvial groundwater model extent in the Avon River for 2013 to 2042 in the Gloucester subregion (ML/year)

Example only; do not use for analysis.

	Water balance term	Under the baseline	Under the coal resource development pathway	Difference
Groundwater	Recharge	6893 (6067; 8191)	6893 (6067; 8191)	0
	Evapotranspiration	289 (46; 866)	285 (46; 808)	–4
	Baseflow (discharge to stream)	6929 (6441; 7353)	6848 (5659; 7296)	–81
	Upward flow from deeper groundwater	392 (–44; 533)	340 (–368; 512)	–52
	Change in storage	–11 (–180; 3)	–5 (–138; 101)	6

The first number is the median, and the 10th and 90th percentile numbers follow in brackets.
See Herron et al. (2016) for full explanation and interpretation of these results.

Table 9 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 coal resource development pathway (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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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

aquitard: a saturated geological unit that is less permeable than an aquifer, and incapable of transmitting useful quantities of water. Aquitards often form a confining layer over an artesian aquifer.

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.

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

Clarence-Moreton bioregion: The Clarence-Moreton bioregion is located in north-east NSW and south-east Queensland and adjoins the Northern Inland Catchments bioregion. Along with the towns of Casino, Lismore and Grafton, it contains the outskirts of the Queensland cities of Brisbane, Ipswich, Logan and Toowoomba. The bioregion contains large river systems (including the Clarence, Richmond and Logan-Albert rivers) and extensive wetlands, some of which are nationally important. Many of these wetlands are home to water-dependent plants and animals that are listed as rare or threatened under Queensland and Commonwealth legislation. The bioregion contains numerous national parks and forest reserves and includes sites of international importance for bird conservation. A large area of the bioregion is used for dryland farming and plantations and as grazing land for livestock. Irrigated agriculture takes up a comparatively small area. Groundwater is extracted for various uses but most commonly for livestock and agricultural purposes. The largest water reservoir in this bioregion is Lake Wivenhoe on the Brisbane River, which supplies Brisbane and its surrounds. The NSW part of the bioregion has smaller dams located in the upper Richmond river basin.

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

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

conceptual model: abstraction or simplification of reality

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

consequence: synonym of impact

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

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

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

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.

likelihood: probability that something might happen

model emulator: a computationally efficient statistical approximation of a process model that mimics the effect of parameter values on a model prediction. In uncertainty analysis a slow, complex process model is replaced by an emulator, which, for a given parameter combination, will provide a prediction that is very close to the prediction that would be obtained by running the process model.

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.

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

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

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

receptor impact 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

reproducibility: the extent to which materially consistent results are obtained when experts outside of the Assessment teams redo part or all of a bioregional assessment using the same methods, models, data and software, but different computer systems

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.

scalar value: a single real number that describes a measurable quantity, such as temperature, length or groundwater level

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

sustainable yield: the level of water extraction from a particular system that, if exceeded, would compromise the productive base of the water resource and important environmental assets or ecosystem functions

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

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

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

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 make: the groundwater extracted for dewatering mines

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

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

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

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