Australian Government

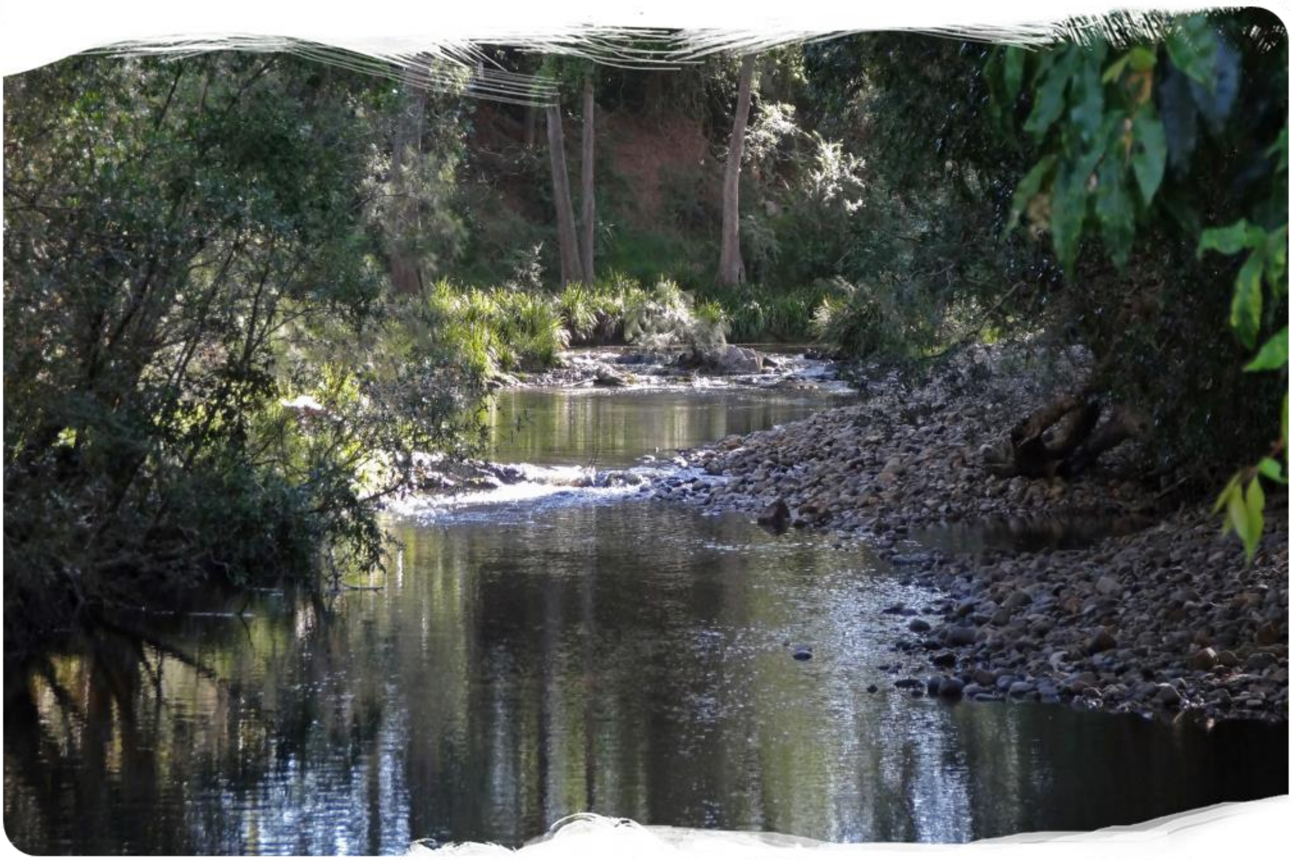
BIOREGIONAL ASSESSMENTS

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

Propagating uncertainty through models

Submethodology M09 from the Bioregional Assessment Technical Programme

4 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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Authorship is listed in relative order of contribution.

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Cover photograph

Wards River, NSW, 10 December 2013

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Executive summary

The surface water and groundwater modelling provides key information for bioregional assessments (BAs), including estimates of the future hydrological regime within the subregion or bioregion, and, in particular, those aspects of the regime subject to hydrological changes due to coal resource development. The robust and comprehensive characterisation of the uncertainty in those models is critical to BA as it underpins the assessment of risk and the likelihood that specific hydrological changes or impacts might occur.

This submethodology gives an overview of the uncertainty analysis and general methods for its implementation in a BA, noting that they may need to be customised for each specific BA. While highlighting linkages with other BA products and submethodologies, this submethodology focuses on the propagation of uncertainty through the chain of numerical models to assess the impact of coal resource development on water and water-dependent assets. The receptor impact modelling submethodology M08 (as listed in Table 1) characterises uncertainty in the system's responses to those hydrological changes.

At the core of this submethodology is the structured characterisation of uncertainty through probability distribution functions, based on measurement data or from expert elicitation. This concentrates in particular on model parameter uncertainty (e.g. hydraulic conductivities of individual model layers or recharge rates) but might also examine other important assumptions such as the presence of unknown subsurface faults or water management rules as appropriate to specific subregions or bioregions. Any aspect of the model that cannot be included in the formal uncertainty analysis (such as discrete choices and model assumptions) will not only be documented, but will also be submitted to a pedigree analysis to assess the quality of the model choice and the potential impact on the prediction. The pivotal aspect of a pedigree analysis is the analysis of the implications and influence of the model assumptions. The main benefit is that it provides a structured way of thinking about and analysing model assumptions which can help in the open and transparent communication of model uncertainty.

This submethodology is structured around a compartmentalisation of the model chain followed by a comprehensive sensitivity analysis to identify the factors that most influence the model prediction of specific hydrological response variables at receptor locations. The subset of factors the prediction is sensitive to will subsequently be used in the uncertainty analysis which propagates the uncertainty in the input factors to the prediction using a Monte Carlo approach. In the event that relevant observational data are available, these will be integrated in the process to constrain the probability distribution of the prediction. In order to keep the computational load manageable and the submethodology amenable to automation, the uncertainty analysis will be carried out with model emulators. The resulting probability distribution functions of the impacts on the hydrological response variables will provide a starting point for the receptor impact modelling.

Examples of the outputs of the sensitivity and uncertainty analysis are included in submethodologies M06 and M07 (as listed in Table 1). Results from the uncertainty analysis are reported in 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling) for each Assessment.

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- Additional reviewers: Emanuelle Frery, Alexander Herr, Yongqiang Zhang.

Valuable comments were also provided by Rod Dann.

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.

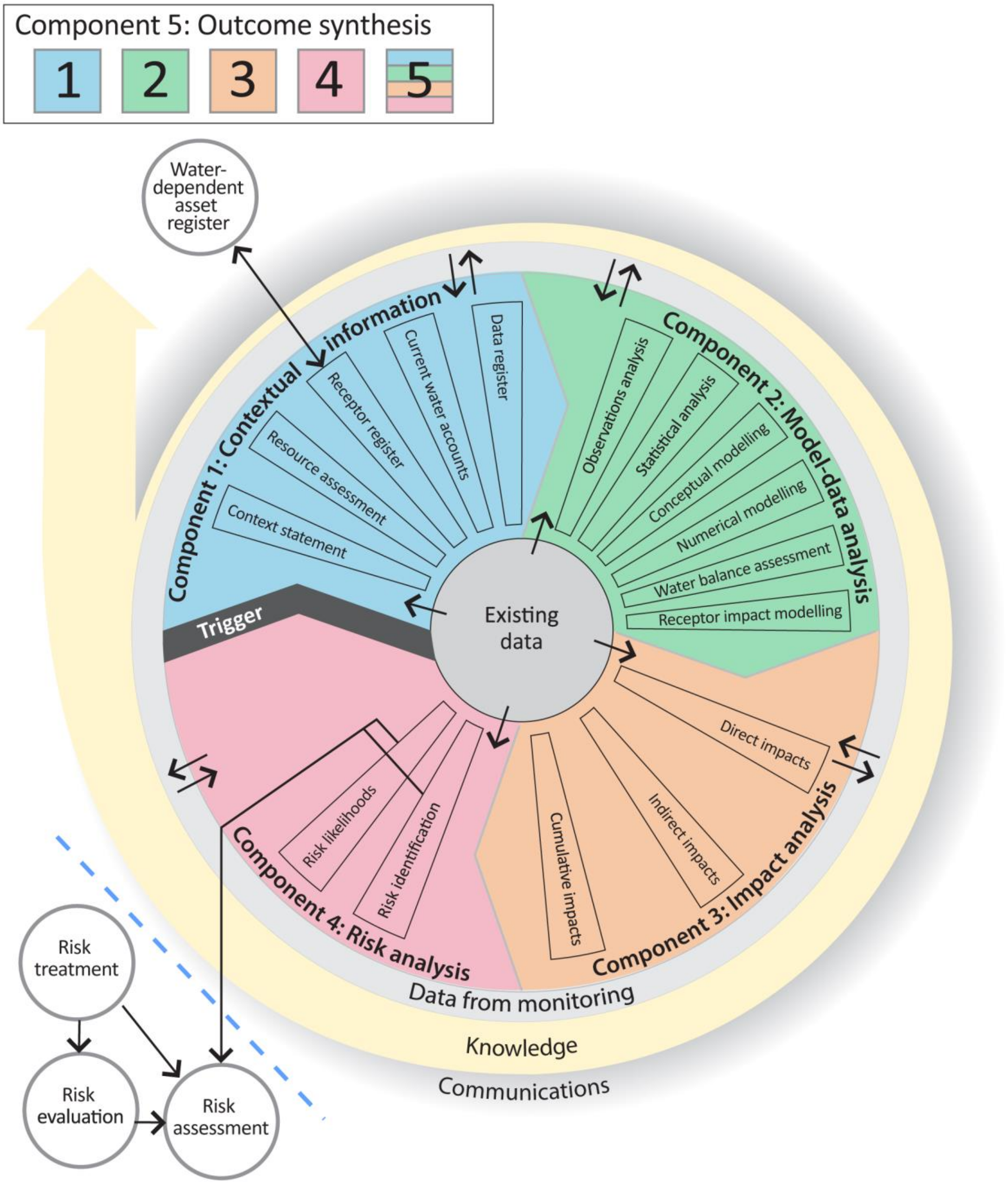

Figure 1 Schematic diagram of the bioregional assessment methodology

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 9, Figure 12. 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

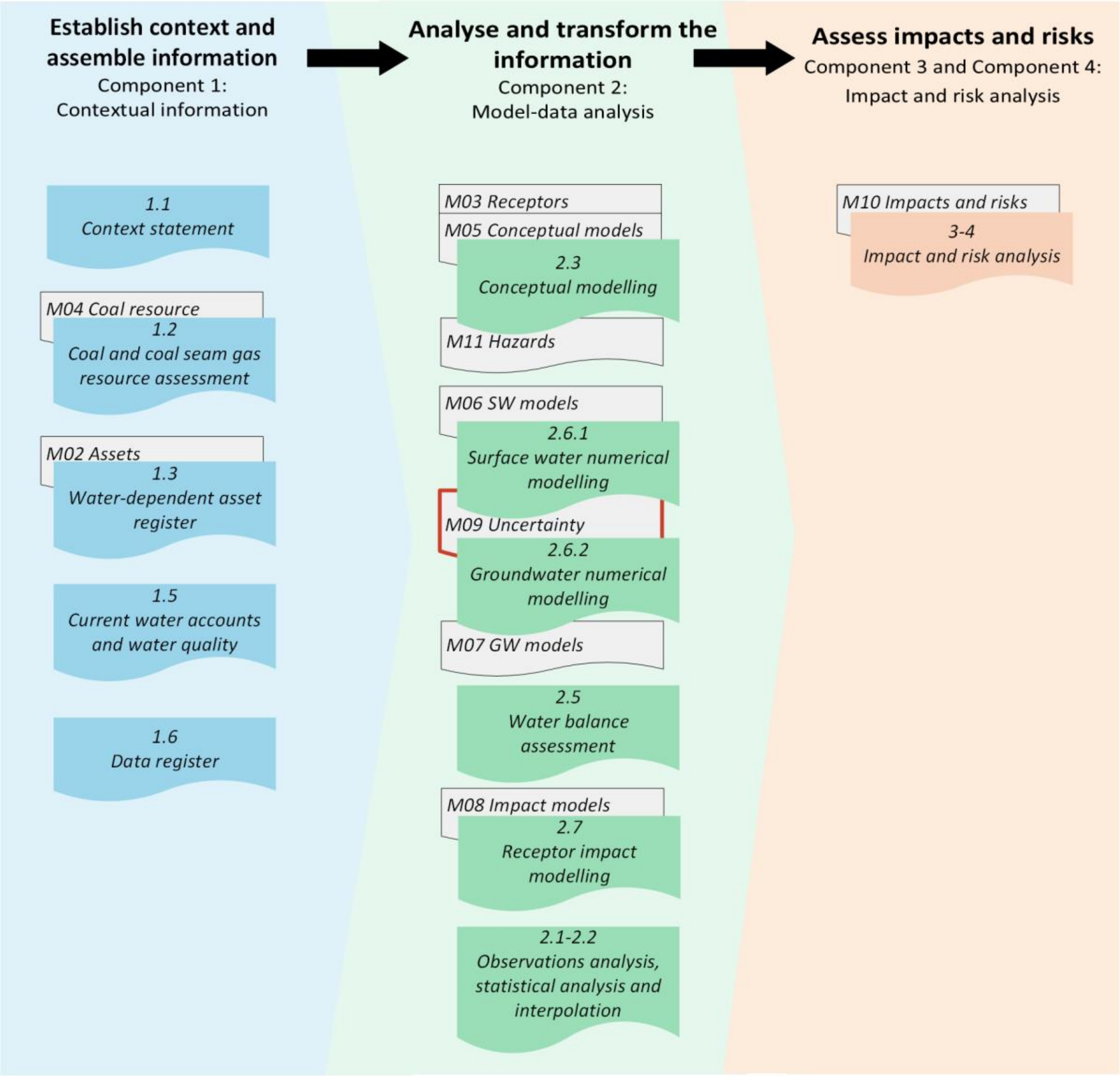

Figure 2 Technical products and submethodologies associated with each component of a bioregional assessment

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)

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Barrett DJ, Couch CA, Metcalfe DJ, Lytton L, Adhikary DP and Schmidt RK (2013) Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources. A report prepared for the Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development through the Department of the Environment. Department of the Environment, Australia. Viewed 30 October 2017, http://data.bioregionalassessments.gov.au/submethodology/bioregional-assessment-methodology.

IESC (2015) Information guidelines for the Independent Expert Scientific Committee advice on coal seam gas and large coal mining development proposals. Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development, Australia. Viewed 30 October 2017, http://www.iesc.environment.gov.au/publications/information-guidelines-independent-expert-scientific-committee-advice-coal-seam-gas.

1 Background and context

A *bioregional assessment* (BA) is a scientific analysis, providing a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential impacts of coal resource development on water and water-dependent assets. The *Methodology for bioregional assessments of the impacts of coal seam gas and coal mining development on water resources* (the BA methodology; Barrett et al., 2013) provides the scientific and intellectual basis for undertaking BAs. It is further supported by a series of submethodologies of which this is one. Together, the submethodologies ensure consistency in approach across the BAs and document how the BA methodology has been implemented. Any deviations from the approach described in the BA methodology and submethodologies are to be noted in any technical products based upon its application.

A critical part of the BA is characterising the uncertainty in the results from the groundwater and surface water models. A robust and comprehensive uncertainty analysis underpins the understanding of risk and the likelihood that certain changes or impacts may occur. The uncertainty analysis is deeply integrated with the rest of the BA methodology and processes, particularly through the groundwater and surface water models, and the receptor impact modelling which depends on the outputs from those models and uncertainty analyses. This submethodology applies overarching principles outlined in the BA methodology to the specifics of quantifying uncertainty in numerical groundwater and surface water models that are reported in products 2.6.1 *(surface water numerical modelling)* and 2.6.2 (*groundwater numerical modelling),* respectively.

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.

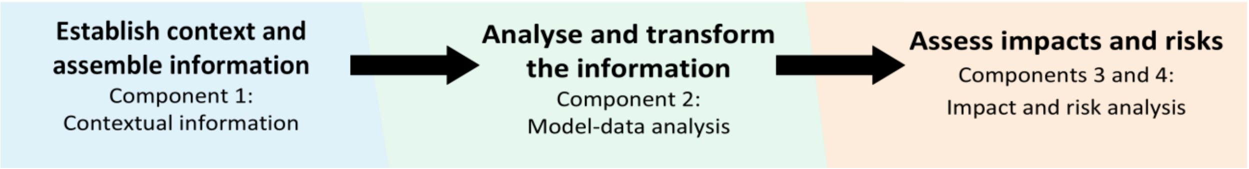

Figure 3 The components in a bioregional assessment

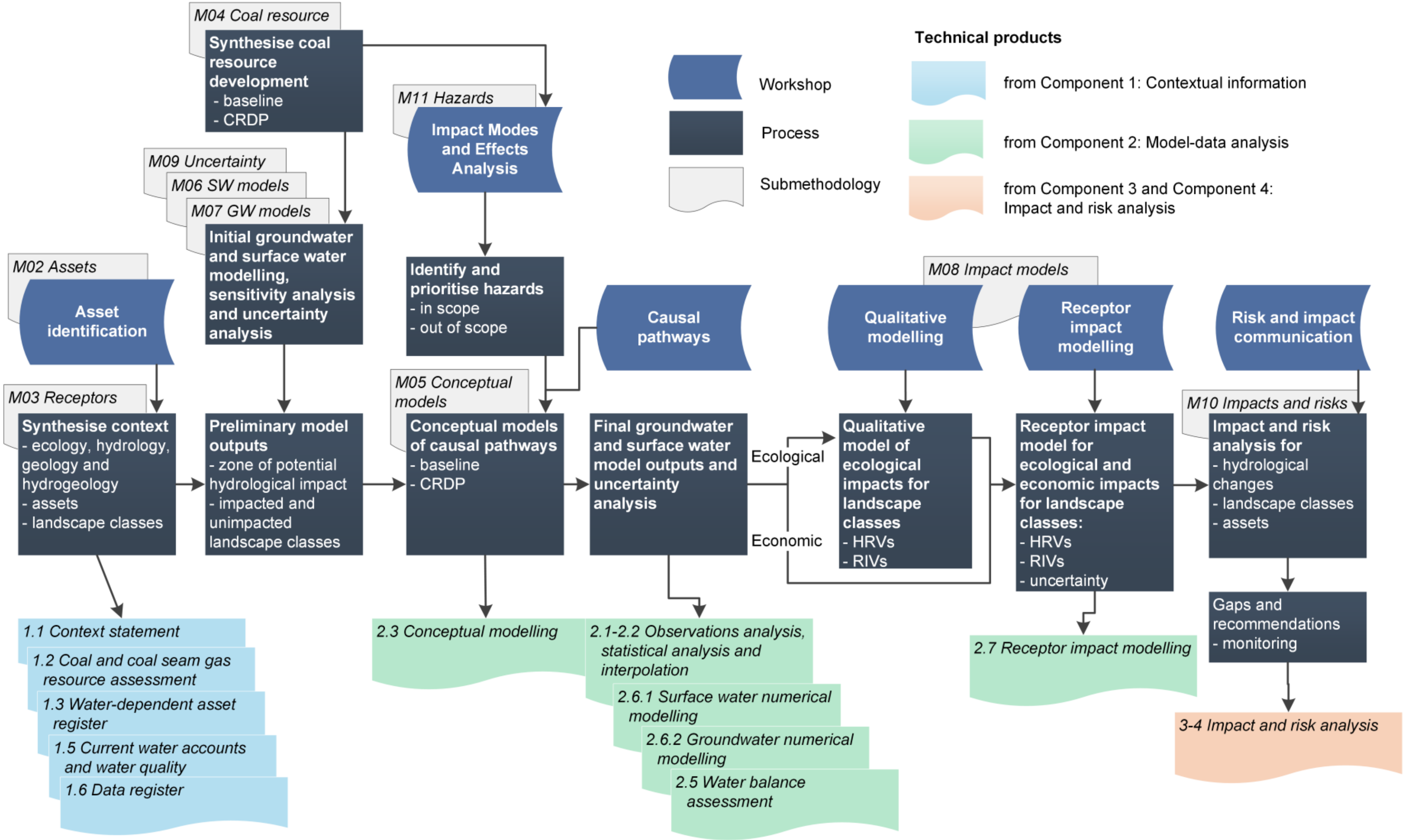

Figure 4 A bioregional assessment from end to end, showing the relationship between the workflow, technical products, submethodologies and workshops

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

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

Highlighting the potential impacts due to the additional coal resource development, and the comparison of these futures, is the fundamental focus of a BA, 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 or landscape class 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 receptor impact variables.

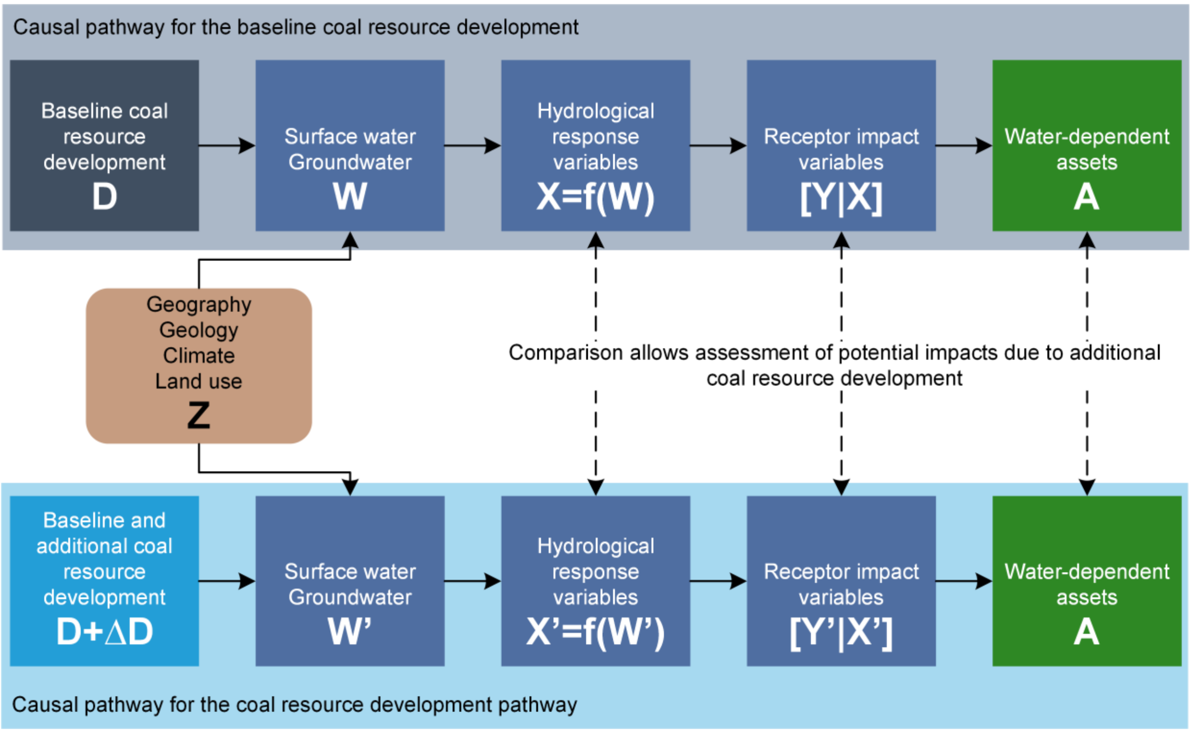

Figure 5 The difference in results under the baseline coal resource development (baseline) and coal resource development pathway (CRDP) provides the potential impacts due to the additional coal resource development (ACRD)

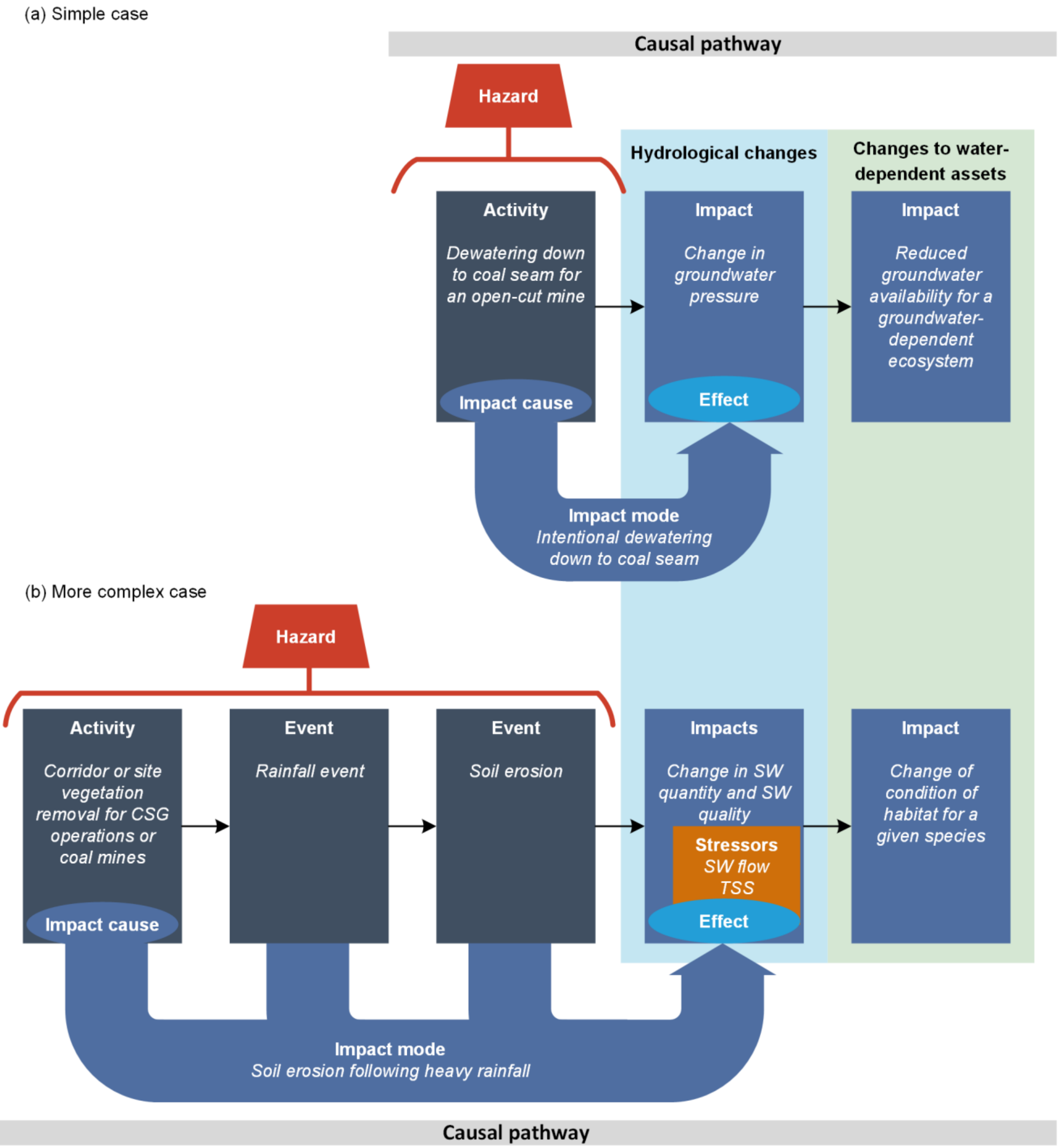

Figure 6 Hazard analysis using the Impact Modes and Effects Analysis

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 and/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 (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-step increase (or decrease) in score indicates a ten-fold increase (or decrease) in the probability of occurrence
- *detection score*: the expected time to discover a hazard, scored in such a way that a one-unit increase (or decrease) in score indicates a ten-fold increase (or decrease) in the expected time (measured in days) to discover it.

Impact modes and *stressors* are identified as they will help to define the causal pathways in Component 2: Model-data analysis. An *impact mode* is the manner in which a hazardous chain of events (initiated by an impact cause) could result in an effect (change in the quality and/or quantity of surface water or groundwater). There might be multiple impact modes for each activity or chain of events. A *stressor* is a chemical or biological agent, environmental condition or external stimulus that might contribute to an impact mode.

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

1.1.2 Component 2: Model-data analysis

Once all of the relevant contextual information about a subregion or bioregion is assembled (Component 1), the focus of Component 2: Model-data analysis is to analyse and transform the information in preparation for Component 3: Impact analysis and Component 4: Risk analysis. The BA methodology is designed to include as much relevant information as possible and retain as many variables in play until they can be positively ruled out of contention. Further, estimates of the certainty, or confidence, of the decisions are provided where possible; again to assist the user of the BA to evaluate the strength of the evidence.

The analysis and transformation in Component 2 depends on a succinct and clear synthesis of the knowledge and information about each subregion or bioregion; this is achieved and documented through *conceptual models* (abstractions or simplifications of reality). A number of conceptual models are developed for each BA, including regional-scale conceptual models that synthesise the geology, groundwater and surface water. Conceptual models of causal pathways are developed to characterise the *causal pathways*, the logical chain of events – either planned or unplanned – that link coal resource development and potential impacts on water resources and water-dependent assets. The conceptual models of causal pathways brings 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 estimate the relationships between meaningful hydrological response variables and the resulting measurable change in a key characteristic of the landscape class or asset (i.e. receptor impact variables). For example, a receptor impact model could be elicited for the relationship between reduced surface water quality and the change in condition of habitat of a given species (as per Figure 6(b)). As only a small number of receptor impact variables (at least one and no more than three) will be identified for each potentially impacted landscape class, the particular receptor impact variables selected for the receptor impact modelling should be considered to be a measure of a critical ecosystem function (e.g. the base of complex food webs) and/or be indicative of the response of the ecosystem to hydrological change more broadly.

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

1.1.3 Component 3: Impact analysis and Component 4: 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 speak to 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 (M09) is intended to assist those conducting a BA to quantify uncertainty in the results from the groundwater and surface water models. It has been written to be generally applicable to all subregions or bioregions. This means that it is pitched at a conceptual level; specific details of the uncertainty analyses and the outputs from those analyses will be written in product 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling) for each Assessment. Those products identify areas of a subregion or bioregion where the hydrological impact of coal resource development are modelled to occur due to changes in surface water or groundwater. The sensitivity analysis identifies the model parameters that most affect predicted hydrological response variables, and that therefore need to feature in the uncertainty analysis. The outputs from the uncertainty analysis play a key role in quantifying the range of hydrological changes that might occur. This is essential input for the receptor impact modelling which assesses how ecological and human-dominated systems (and water-dependent assets) respond to those potential hydrological changes. Interactions between several activities of a BA and the sensitivity and uncertainty analysis are depicted in Figure 7.

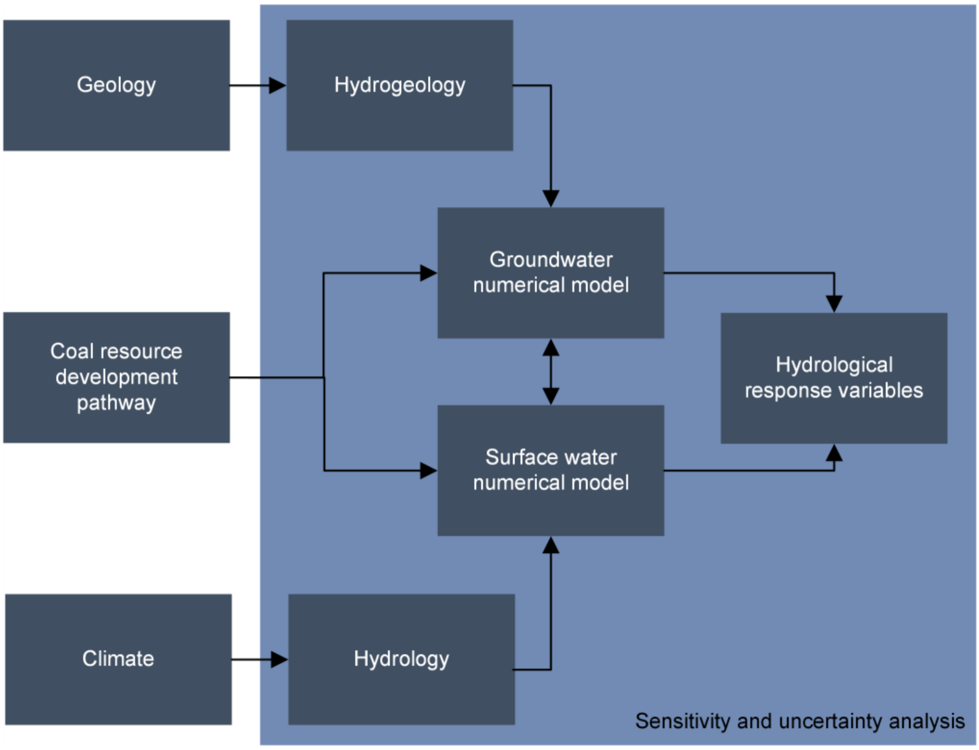

Figure 7 Process for sensitivity and uncertainty analysis (large blue box) and connections to other bioregional assessment activities (grey boxes)

Conceptual representation of the physical system, inputs to and from the groundwater and surface water models, and the sensitivity and uncertainty analysis 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 uncertainty analysis 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)
- groundwater modelling (product 2.6.2).

The estimated uncertainty in hydrological response variables is input for:

- surface water modelling (product 2.6.1)
- groundwater modelling (product 2.6.2)
- receptor impact modelling (product 2.7).

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 BA methodology (M01 as listed in Table 1; Barrett et al., 2013), which remains the foundation reference that describes, at a high level, how BAs should be undertaken. Submethodology M09 is most strongly linked to the following submethodologies:

- submethodology M05 for developing a conceptual model of causal pathways (Henderson et al., 2016)
- submethodology M06 for surface water modelling (Viney, 2016)
- *s*ubmethodology M07 for groundwater modelling (Crosbie et al., 2016)
- submethodology M08 for receptor impact modelling (as listed in Table 1)
- *s*ubmethodology M10 for impacts and risks (as listed in Table 1)
- submethodology M11 for hazard analysis (Ford et al., 2016).

Any deviation in application of, or refinements to, the BA methodology will be submitted for approval and recording by the Programme Science Leadership Group (SLG).

2 Uncertainty analysis

A crucial aspect of the bioregional assessment (BA) methodology is the open and transparent accounting for uncertainty in the predictions. It is this quantification of uncertainty that will feed directly into the risk assessment.

Uncertainty analysis has always been an essential part of any scientific research. In recent decades, however, uncertainty analysis has received increased attention in all disciplines of environmental research. It is not hard to imagine that various environmental science disciplines have adopted and adapted different uncertainty analysis techniques in order to address the key issues relevant to their domain. For example, in geology and hydrogeology emphasis has traditionally been on characterising the spatial heterogeneity of model parameters, while the focus in hydrology is more on characterising the uncertainty in time series of inputs and observations (Gupta et al., 2012).

There are very few studies published in which uncertainty analysis is carried out through a chain of models from different environmental science disciplines at a scale that is comparable to what needs to be achieved in the BA. The 2008 performance assessment of the high-level radioactive waste repository at Yucca Mountain, Nevada, United States is a prime example of a similar uncertainty analysis exercise. The performance assessment is the culmination of over 30 years of multidisciplinary research (Helton et al., 2014) and assesses the dose of radioactivity a reasonably maximally exposed individual would be exposed to after 10^6 years of nuclear waste disposal at the Yucca Mountain site. The performance assessment incorporates a complex model chain in which the uncertainty in 392 physical variables is propagated over a range of scenarios by running the model chain several hundreds of times for each scenario. The model runs provide a probability distribution of the dose of radioactivity after 10^6 years, while post-processing of these enables the identification of the most influential variables. An example for the baseline scenario can be found in Hansen et al. (2014).

Bastin et al. (2013) provide a more general overview of managing uncertainty in integrated environmental models. They argue for probabilistic characterisation of uncertainty as the most quantitative and objective approach, recognising that this will always entail a level of qualitative treatment of model structural uncertainty, mostly based on expert judgement. In order for a framework to be able to manage uncertainty through a chain of interlinked models or components, Bastin et al. (2013) highlight the need for a well-defined protocol for communication of probabilistic uncertainty between model components, an appropriate mechanism to propagate uncertainty, which ideally should require minimal change to the component's model code, and the ability to accommodate different levels of spatial and temporal support among the different components. To make such a framework workable, tools are needed that can aid in expert elicitation (the formal process of capturing expert knowledge) or statistical inference based on observation data of input uncertainties, formal sensitivity and uncertainty analysis techniques, visualisation methods of uncertainty in space and time and finally, tools to validate model chain outputs against observation data.

The methodology for the propagation of uncertainty through models in the bioregional assessment presented in this document will take on board several of these concepts and tailor these to the specific scope of and resources available for bioregional assessments. This submethodology focuses on the propagation of uncertainty in individual, bioregion-specific physical models. The companion submethodology M10 (as listed in Table 1) for identifying and analysing risk outlines and discusses the overarching risks and sources of uncertainty that are shared among bioregions and are inherent to the BA methodology. The companion submethodology M08 (as listed in Table1) about receptor impact modelling also discusses the propagation of uncertainty from the physical models into the receptor impact models.

Chapter 3 provides an overview of the requirements that the methodology will need to fulfil to achieve the goals set out by the BA and, equally important, will establish a number of key assumptions that are needed to have a methodology that is applicable in practice. Chapter 4 discusses the methodology in greater detail. Chapter 5 outlines the outputs of the analysis and where they are used. The last Chapter reiterates and summarises the key points of the methodology.

3 Requirements and assumptions

This chapter summarises the main requirements for a viable and robust uncertainty analysis methodology for bioregional assessments (BAs), and the high-level decisions and assumptions that underpin this methodology.

3.1 Requirements

3.1.1 Transparent and reproducible

Underlying the BA is the requirement that every outcome needs to be reproducible and each step or process that leads to an outcome needs to be documented in a transparent manner so as to allow public scrutiny. These terms are defined in BAs as follows:

- *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
- *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.

These requirements of transparency and reproducibility require researchers in the BA to be diligent in recording in detail the reasoning, the uncertainty associated with any information or model used in BA, and the chain of models that led to a prediction and the source of all the data and information that fed into that chain of models.

Section 3.1 provides guidance on how to characterise and report data and model uncertainty that will feed into the modelling chain. After establishing these uncertainties, it is key that the methodology outlined in this document is adhered to for the propagation of the uncertainty to the prediction of interest (that is the impact on the asset and/or landscape class or the hydrological response variable).

3.1.2 Generic

Due to the nature of the research question, the research in BA inevitably will include various scientific disciplines and work across very different scales. Each scientific discipline has different traditions in handling uncertainty, inspired by the boundary conditions imposed on the statistical techniques applicable to the discipline, by the typical availability of data and by the system linearity and dimensionality.

In order to use the same methodology throughout the BA process, the uncertainty analysis methodology needs to be able to accommodate and integrate various disciplines and different spatial and temporal scales. The methodology therefore will need to be flexible and generic and thus model-independent.

3.1.3 Probabilistic

There are multiple ways of analysing risks associated with future activities. The companion submethodology M11 (as listed in Table 1) for hazard analysis (Ford et al., 2016) opts to apply a risk analysis based upon probabilistic estimates of the uncertainties associated with the predicted impacts of coal mining and coal seam gas development on water and water-dependent assets. This obviously implies that the uncertainty analysis needs to provide probabilistic estimates of the uncertainty of the impact on assets and/or landscape classes or hydrological response variables.

3.1.4 Data and model availability

The quantity and quality of data available to inform the BA is, to say the least, variable. It will not only vary between bioregions, in which for instance the Northern Inland Catchments bioregion has more and more-reliable data than the Lake Eyre Basin bioregion, it will also vary within a bioregion. For example, there might be a high density of observations for shallow groundwater levels, but hardly any data for groundwater pressure in deep aquifers.

The methodology will need to be able to produce an estimate of uncertainty, even if there is no or limited data available. The methodology will also need to accommodate the situation where hard data are only available for parts of the system. While it is essential that all available data are used to constrain the models, care has to be taken not to give overly great weight to small datasets or unrepresentative data in order to avoid bias in the predictions.

Related to the data availability issue is the model availability. The BA project will not be able to create comprehensive, complex models for each aspect of each bioregion. In some regions existing models, created by or for state agencies or mining companies, will be available. As the intellectual property of these models does not reside with the BA partners, it is likely that conditions will be imposed on the BA team as to what extent the model and model results can be used. An example would be that BA is allowed to use the model results, but cannot run the model with changed parameter values or boundary conditions. The methodology will need to accommodate such limitations on the use of models and results.

3.1.5 Practical

The four requirements discussed above condition the science needed to assess uncertainties in the predictions. The reality of time and resources available for the BA, however, require that practical considerations be taken into account as well.

Each researcher in the BA is expected to have a working knowledge of the uncertainty methodology. It is, however, unrealistic to expect every researcher to be across all the mathematical and statistical detail of the methodology, let alone have the software engineering capabilities to apply the methodology to their domain. The methodology therefore needs to be designed so that it can be used, with limited training, by all researchers within the BA.

Additionally, while considerable computing infrastructure is available for the project, resources are not unlimited. The implementation of the uncertainty methodology therefore needs to ensure it is computationally feasible within the time frames agreed in the project plans for individual bioregions.

3.2 Assumptions

3.2.1 Every aspect of the model chain needs scrutiny

The default position when starting to address the question of how coal seam gas extraction and coal mining development will affect an asset is to consider each aspect of the conceptual model and the resulting chain of models as uncertain.

Many of these aspects will be able to be expressed in probabilistic terms. The uncertainty of continuous variables, such as hydraulic conductivity, river discharge or fish biomass, can be directly expressed as a probability density function. In the case of categorical variables, such as fault presence or vegetation type, uncertainty can be expressed as a probability of occurrence. Any aspect that can be expressed in such probabilistic terms will be incorporated formally in the uncertainty analysis process (Section 4.2 and Section 4.3).

However, discrete choices and simplifications are unavoidable in developing conceptual and physical models and it will not always be possible to assign probabilities to competing choices. Section 4.1.1 will discuss in more detail how to assess and document these discrete choices and model assumptions.

3.2.2 Problem can be compartmentalised

The conceptual model will provide causal pathways between coal resource development and impacts on assets. In theory, and as advocated by Voinov and Shugart (2013), it is possible to translate that conceptual model into a chain of physical models and, with the help of a workflow system, carry out an uncertainty analysis of the integrated system.

This will place enormous strain on the logistics of the BA process as it will require all the models that are part of the model chain to be available before the uncertainty analysis can start. Enormous gains in efficiency and tractability can be achieved if the uncertainty analysis can be compartmentalised (i.e. if the model chain can be split up into sub-processes for which the uncertainty analysis can be carried out sequentially but separately).

The main criterion to subdivide the chain of models is the absence of feedback loops. Groundwater models will provide an estimate of baseflow to river models, which in turn affects the river stage, which often is a boundary condition for groundwater models. Such an intimate link between models implies that they cannot be separated, as a change in one model has the potential to affect the other model. A change in hydrology has the potential to change the ecology of that catchment. It is however unlikely that this change in ecology will change the hydrology sufficiently to invalidate the earlier hydrological change simulation. This implies that hydrological models can be isolated from the ecological models where outputs of the former (and associated uncertainty estimates) become inputs for the latter. Note that any external major changes in ecology due to coal resource development, such as land clearance for open-cut mining of coal, are part of the change in stress to the hydrologic models, for instance by specifying a change in runoff in a catchment.

Again, it is paramount to record and document the reasoning and justification for compartmentalising a conceptual model. If there are good reasons to expect important feedback loops between the ecology and the hydrology these should be identified as part of the conceptual modelling. If it is possible to include this feedback in the model chain then that should happen. If not, then it should be, at the very least, acknowledged as something to watch and a potential gap.

3.2.3 Well-defined hydrological response variables

It is important to establish well-defined hydrological response variables, explicitly defined in space and time, for each sub-model, that can: (i) be used to summarise the results of the numerical modelling and (ii) support reasoned explanations for the potential changes in assets or landscape classes (refer to companion submethodology M03 (as listed in Table 1) for assigning receptors to water-dependent assets (O'Grady et al., 2016)) and (iii) be used in the receptor impact modelling (refer to companion submethodology M08 (as listed in Table 1) about receptor impact modelling).

The physical models, hydrogeological and hydrological, will produce both time series and/or maps of change in groundwater level, flux or river flow. From a practical perspective, due to the high dimensionality of the model output, it is not possible to calculate uncertainty estimates for each grid cell and each time step of the model. A limited number of hydrological response variables therefore need to be defined that either summarise the spatial and temporal output of the model or are representative for the spatial and temporal output of the model. An example of this is using the following hydrological response variables to summarise the time series of drawdown at a model node:

- *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
- *tmax*: year of maximum change.

4 Methodology

Figure 8 outlines the methodology for propagation of uncertainty within the BA. The main process, in blue, starts with the compartmentalisation of the conceptual model (i.e. subdividing the conceptual model into a number of sub-models without feedback loops). For each of these sub-models a comprehensive and robust sensitivity analysis is subsequently carried out to identify the model factors (parameters and assumptions) that have the largest impact on the hydrological response variables of interest. From this factor prioritisation, a relatively small number of factors will be selected for inclusion in the actual uncertainty analysis, which will result in a probability distribution function (pdf) for the hydrological response variable (or metric) of interest. When carried out sequentially for each sub-model in the model chain, the process will culminate in the probability distribution function of the hydrological response variable. Since the model chain is compartmentalised, the uncertainty is additive.

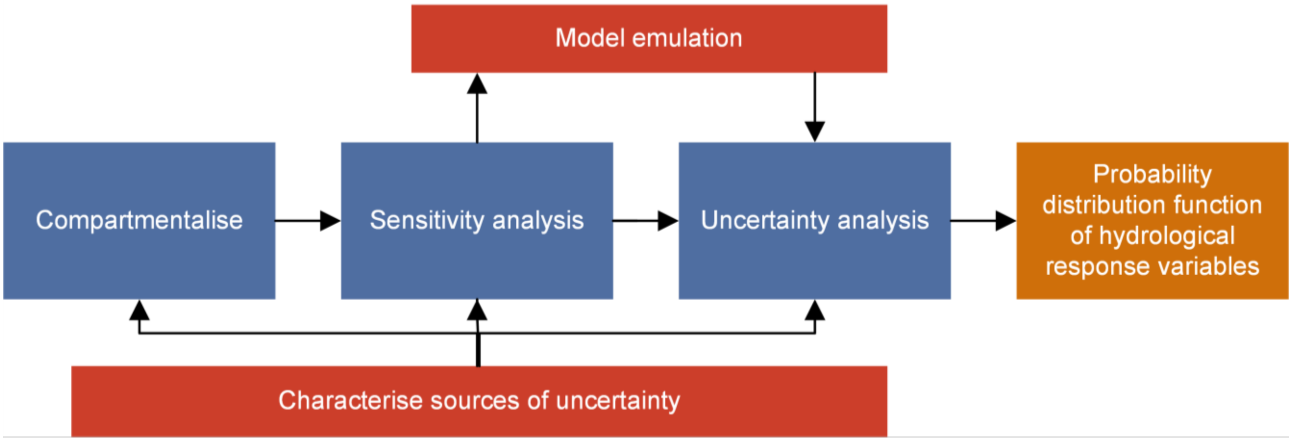

Figure 8 Uncertainty methodology flowchart

Blue boxes indicate the main workflow, the orange box is the result of the workflow and the red boxes indicate concepts and methods that are essential to complete the workflow

At this point it is worthwhile to clearly define and differentiate between the interlinked notions of sensitivity analysis and uncertainty analysis. Saltelli et al. (2008) differentiate between the two as follows:

> Uncertainty analysis is the quantification of uncertainty. Sensitivity analysis is the study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input.

An important goal for a BA is, where possible, to carry out an uncertainty analysis to quantify the uncertainty in the prediction of the effect of coal resource development. Sensitivity analysis will provide insight in how the different sources of uncertainty interact and, at least in this methodology, will primarily be used to focus the effort of the uncertainty analysis on the factors that contribute most to the uncertainty in the prediction.

The two red boxes in Figure 8 represent two crucial aspects of the methodology that will interact with the main process. The first of these is the characterisation of the sources of uncertainty, that is the identification of all possible sources of uncertainty and where possible the quantification of this uncertainty in probabilistic terms from observations or through expert elicitation. The second red interacting box is model emulation. The uncertainty analysis will require a very large number of model runs to arrive at a robust estimate of predictive uncertainty. Integrating each sub-model into uncertainty analysis software is challenging and for some BA models, runtimes will preclude running the model a sufficient number of times to arrive at a robust prediction. The methodology therefore opts to capture the dynamics between the key influential factors, identified through the sensitivity analysis, and the hydrological response variable of interest with a statistical model. It is this statistical model, the model emulator, which will be used for the actual uncertainty analysis. Model emulators are described in more detail in Section 4.5.

The reporting of the propagation of uncertainty through the models will be an integral part of the reporting on the hydrological and hydrogeological models (products 2.6.1 (surface water numerical modelling) and product 2.6.2 (groundwater numerical modelling)).

The following sections discuss in more detail each of the components of the flowchart depicted in Figure 8, beginning with more detail on the characterisation of the sources of uncertainty.

4.1 Characterisation of sources of uncertainty

Uncertainty arises in many aspects of the modelling process and there is a wide variety in the terminology used to describe the source and nature of uncertainty (Walker et al., 2003). Hayes (2011) summarises this varied terminology in the Venn diagram shown in Figure 9.

Decision uncertainty relates to the uncertainty that enters policy analysis after risks have been estimated. As such, this lies outside the scope for the BA. Linguistic uncertainty, however, is an aspect of uncertainty analysis that needs attention. It arises through communication about uncertainty using language that is not precise. Important aspects are vagueness, context dependence, ambiguity, indeterminacy and under-specificity (Hayes, 2011). Even when adopting clear mapping between numerical probabilities and linguistic terms, such as that used by the International Panel for Climate Change (IPPC) where for instance a probability between 90 and 100% is expressed as ‘Very Likely’ (see Mastrandrea et al., 2010), it has been shown that interpretation by policy makers and the general public is still very individual and context-specific (Spiegelhalter et al., 2011). Linguistic uncertainty will especially come into play when communicating the results of the uncertainty analysis (Patt, 2009) and during expert elicitation workshops (O’Hagan et al., 2006).

The focus of this submethodology report, however, is on variability and on epistemic uncertainty. Variability is the variation in a quantity or process that is caused by natural fluctuations or heterogeneities. Variability can be described in probabilistic terms, but cannot be reduced. Epistemic uncertainty lumps all uncertainty together that stems from incomplete knowledge, understanding or representation of the system under study. In theory, this form of uncertainty is reducible by gathering additional data and a more exact representation of the system in models. It is seldom possible to attribute uncertainty of a value solely to one or both types of uncertainty.

The uncertainty in the hydraulic properties of an aquifer for instance is largely attributable to epistemic uncertainty, as generally there are only a few measurements of these properties. Even with unlimited resources, it would not be possible to deterministically describe the hydraulic properties due to natural heterogeneity of the subsurface (de Marsily et al., 2005; Caers, 2011) and so, part of the uncertainty in the hydraulic properties will remain due to variability.

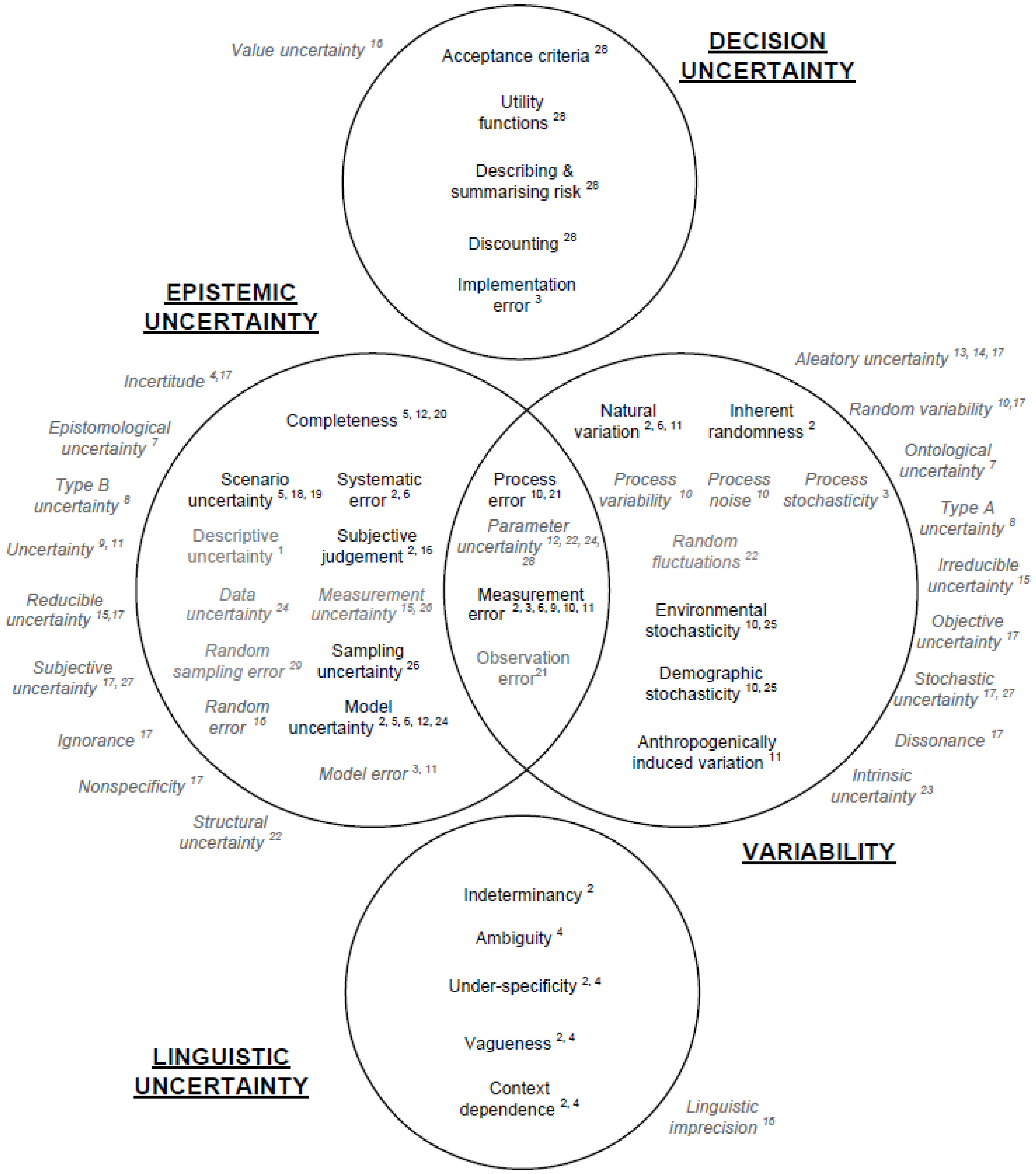

Figure 9 Venn diagram illustrating four broad categories of uncertainty with more specific types of uncertainty (black) and different nomenclature (grey italic).

Source: Figure 2.3 in Hayes (2011). This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of CSIRO. The numbers in superscript refer to references in that report.

Regardless of the source of uncertainty, the quality of the uncertainty propagation, such as presented in Figure 8, hinges on the characterisation of the uncertainty to be propagated. An adequate characterisation of an uncertain factor not only entails a quantitative aspect, in which the value, the units and the spread or variation are described, but it also needs to have a qualitative aspect (van der Sluijs et al., 2005). This qualitative aspect assesses both the quality of the information (e.g. the significance level of a statistical test) and whether the estimate is pessimistic or optimistic. The latter will generally be based on expert judgement, such as through a peer review.

The next three sections provide some guidance on how to characterise uncertainty in view of the above-mentioned philosophy. The discussion is differentiated based on two important practicalities:

- Can the source of uncertainty be incorporated in an automated sensitivity/uncertainty analysis? (Section 4.1.1)
- Are there sufficient and relevant observations available of the factor of interest? (Section 4.1.2 if data are available, Section 4.1.3 if not).

4.1.1 Model assumptions

It is widely recognised that the assumptions and conceptual model choices that form the basis of any environmental model are crucial, albeit often overlooked, components of the uncertainty analysis (Saltelli and Funtowicz, 2014). In the field of hydrogeological modelling this is vividly illustrated in the classic paper by Bredehoeft (2005), where post-audits of several groundwater models revealed major shortcomings in conceptualisation.

Section 3.2.1 postulates that in this methodology every aspect of the model will be scrutinised while Section 3.1.3 states the requirement for the uncertainty analysis to be fully probabilistic. In a very practical sense, for a model aspect to be amenable for sensitivity analysis and uncertainty analysis, it needs to be able to be varied in an automated fashion through some sort of computer script. This obviously implies that all model aspects that cannot be varied automatically due to technical issues or other operational constraints cannot be part of the probabilistic uncertainty analysis.

Refsgaard et al. (2006) and Kloprogge et al. (2011) provide examples of methods to formally account for the uncertainty introduced by these kind of model assumptions. The pivotal aspects of these methodologies are the structured listing of model assumptions, and the analysis of the implications and influence of those assumptions (a pedigree analysis) through peer review or a workshop with experts and stakeholders. Finding and listing all key assumptions requires, as argued by Saltelli et al. (2013), an assumption-hunting attitude in order to ‘find important assumptions before they find you’. The pedigree analysis in Kloprogge et al. (2011) for instance suggests scoring each assumption on aspects such as the practical motivation, plausibility, availability of alternatives, agreement among peers and stakeholders and, most importantly, the perceived influence on the final prediction. While it is recognised that these scoring systems are prone to subjectivity and their results can be heavily influenced by the numerical scoring system used, such methods are very useful for a BA. The main benefit is that they provide a structured way of thinking about and analysing model assumptions which can help in the open and transparent communication of model uncertainty.

Section 2.6.2.8.2 (qualitative uncertainty analysis) in the Gloucester subregion groundwater model product (product 2.6.2, Table 2) shows an example of such a structured listing and discussion of model assumptions (Table 3).

Table 3 Qualitative uncertainty analysis as used for the Gloucester subregion

CSG = coal seam gas

Number	Assumption / model choice	Data	Resources	Technical	Effect on predictions
1	Hybrid analytic element – MODFLOW model methodology	high	high	low	low
2	Principle of superposition [includes no recharge, no surface water – groundwater interaction]	low	low	low	low
3	Horizontally spatially uniform hydraulic properties	low	low	low	low
4	Hydraulic properties vary with depth, not with stratigraphy	high	low	low	medium
5	Stochastic representation of coal seams and faults	high	high	medium	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	low	medium	medium
8	Open-cut mines as prescribed pumping rate	high	low	low	high
9	Specification of prior distributions	high	low	low	low

The major assumptions and model choices underpinning the Gloucester groundwater models are listed in Table 3. The goal of the table is to provide a non-technical audience with a systematic overview of the model assumptions, their justification and effect on predictions, as judged by the modelling team. This table is aimed to assist in an open and transparent review of the modelling.

In the table each assumption is scored on four attributes using three levels; high, medium and low. Beneath the table, each of the assumptions are discussed in detail, including the rationale for the scoring. The data column is the degree to which the question ‘if more or different data were available, would this assumption/choice still have been made?’ would be answered positively. A ‘low’ score means that the assumption is not influenced by data availability while a ‘high’ code would indicate that this choice would be revisited if more data were available. Closely related is the resources attribute. This column captures the extent to which resources available for the modelling, such as computing resources, personnel and time, influenced this assumption or model choice. Again, a ‘low’ score indicates the same assumption would have been made with unlimited resources, while a ‘high’ value indicates the assumption is driven by resource constraints. The third attribute deals with the technical and computational issues. ‘High’ is assigned to assumptions and model choices that are dominantly driven by computational or technical limitations of the model code. These include issues related to spatial and temporal resolution of the models.

The final, and most important column, is the effect of the assumption or model choice on the predictions. This is a qualitative assessment of the modelling team of the extent to which a model choice will affect the model predictions, with ‘low’ indicating a minimal effect and ‘high’ a large effect. Especially for the assumptions with a large potential impact on the predictions, it will be discussed that the precautionary principle is applied; that is, the hydrological change is over- rather than underestimated.

4.1.2 Observation data

In a BA, a large amount of resources is invested in gathering and analysing existing data. These data will be used to inform the conceptual model. Some of these data will become part of the model chain as they inform models on initial conditions, boundary conditions and parameters. Section 4.4 will elaborate upon how observation data can be used to constrain the models.

The probability density for numerical, continuous variables can be described via the parameters of a probability density function. The most well-known is the normal distribution which is fully described by the mean and standard deviation. There is a wide variety of other types of distributions that can be used to describe a dataset. Uncertainty of categorical data can be expressed as a probability of occurrence of each category, where the total probability of all possibilities needs to sum to one.

Observations will always have a measurement uncertainty. The precision and accuracy of measurement devices is generally well-known and therefore straightforward to incorporate in the probability distribution. Larger contributors to measurement uncertainty are the location and time of measurement. For historical data and for subsurface data, the date of the measurement is often not recorded accurately and the elevation or the depth of the measurements are sometimes not available. Even when these are available, they can be of questionable accuracy. Another contributor to measurement error is the observation model used. River discharge for instance is mostly inferred from river stage elevation through a rating curve. The shape of this curve can contribute markedly to measurement uncertainty (Tomkins, 2014).

The data that will inform environmental models, however, will always have spatial and temporal support. This implies that point measurements of parameters and driving forces need to be upscaled to the scale relevant to the model, whilst model simulation results often need to be downscaled to be able to be compared with observations at a point scale. The spatial and temporal variability of data therefore also need to be described. Traditional techniques such as the variogram for spatial data and autoregressive–moving-average time series models for temporal data can be used to capture the spatio-temporal variability for stationary systems. Describing more complex variability is beyond the limitations of these simple hydrological response variables. In those cases, there is a need to resort to explicitly describing the variability through stochastic realisations of the spatial or temporal field. An example for rainfall grids is given in Shao et al. (2012).

Van Loon and Refsgaard (2005) provide an extensive overview of and guidance on assessing data uncertainty, with a focus on water resources management. It provides a good reference document for BAs as it provides detailed discussions on characterising uncertainty for meteorological, soil physical and geochemical, geological and hydrogeological, land cover, river discharge, surface water quality, ecology and socio-economic data.

4.1.3 Expert elicitation

In many cases there will be insufficient relevant data available to directly inform the uncertainty characterisation of a factor of interest. These cases need to rely on expert elicitation. Expert elicitation aims at capturing the scientific understanding of a process or a quantity in a probability distribution by questioning experts. In order for the obtained probability distribution to be reliable, the elicitation method needs to be transparent and reflect a consensus of the opinion of the scientific experts (O’Hagan et al., 2006).

Consider the scenario where expert elicitation is required to estimate the change in depth to watertable from a water extraction scenario at several locations and times. In direct elicitation, the panel of experts are asked to directly estimate the change in watertable. The response in depth to watertable, however, will depend on many site- and time-specific factors. Such direct elicitation will pose a high cognitive load on the expert. An alternative elicitation method is elaboration (O’Hagan, 2012) in which the elicitation focuses on a set of quantities that govern the process. An essential step in elaboration is to break down the process that leads to a quantity of interest in cognitively manageable chunks. In this example, rather than estimating the change in watertable at a location directly, focus can shift to quantities such as the distance to extraction, the hydraulic properties and hydrostratigraphy of the aquifer, proximity to surface water features or faults. As such this is not too different from the way piezometric surfaces traditionally have been created in data-poor areas, as recently illustrated in the updated watertable map for the Great Artesian Basin (Ransley and Smerdon, 2012). A more formal way is to use these elicited quantities in a groundwater model (i.e. eliciting the probability distribution functions of parameters of a groundwater model).

In indirect elicitation, the priors for the parameters of a linear model (Kadane et al., 1980) or generalised linear model (Bedrick et al., 1996; Garthwaite et al., 2013) are based on expert opinion of the predicted response at various combinations of the covariates. In ecology, this approach is used to elicit expert opinion on the spatial distribution of a species given a set of physical attributes, which may be spatially distributed, and thereby specify priors for a generalised linear model (Al-Awadhi and Garthwaite, 2006; Denham and Mengersen, 2007; Murray et al., 2009).

Even after elaboration and reduction of the elicitation problem to a manageable set of parameters or other quantities of interest, a number of possible cognitive biases can influence the elicitation process. For example, probabilities elicited from experts may suffer from overconfidence, anchoring to arbitrary starting values and the availability of the frequency of events in the memory of the expert. These cognitive restrictions and recommended remedies are discussed by Kadane and Wolfson (1998) and Kynn (2008), who document some rules of thumb for an analyst to adopt when eliciting expert opinion, such as eliciting percentiles or quantiles from an expert (e.g. as in O'Hagan, 1998, for a hydrogeological model). Elicitation methods based on an expert's opinion of statistical moments have been found to be less reliable (Garthwaite et al., 2005). The quantile or percentile method is adopted by available elicitation software (Low-Choy et al., 2009). Web-based, direct elicitation tools for univariate priors are available, such as ‘The Elicitator’ (Bastin et al.,

2013) and ‘MATCH’ (Morris et al., 2014). The former focuses on documenting the elicitation process, whereas the latter provides a web-based interface to the SHELF software (Oakley and O'Hagan, 2010) and focuses on direct prior elicitation.

A consensus on how to mathematically accommodate expert opinion in a group setting has not yet been achieved. In fact, it is not altogether clear what it means to assimilate group expert opinion in a decision-making context (see Garthwaite et al., 2005). An alternative to model-based approaches for assimilating group opinion is to instead use behavioural approaches (Clemen and Winkler, 1999). A formal method of behavioural aggregation can be used, such as the Delphi-method that is commonly used in ecology (Kuhnert et al., 2010). Alternatively, a consensus prior may be developed through interaction among the individuals within a group of experts (O'Hagan and Oakley, 2004). The behavioural aggregation through interaction may be applicable where the opportunity for feedback and discussion among experts is allowed and encouraged.

4.2 Compartmentalisation of the conceptual model

A number of conceptual models are developed for each BA, including regional-scale conceptual models that synthesise the geology, groundwater, surface water and surface ecosystems. The conceptual model of causal pathways (the conceptual model) brings together a number of these conceptual models and describe the potential links between coal resource development and impacts to water resources and water-dependent assets. Ultimately, it is the goal of the BA to translate the conceptual model into a chain of numerical models to predict potential impacts to water resources and water-dependent asset at particular points in space and time with quantified uncertainty.

At a high level, a conceptual model will include the aspects shown in Figure 10; the development will affect the physical system which subsequently influences the ecological system which finally results in an impact to water-dependent assets. As long as the arrows in Figure 10 can be considered as one-way interactions, the conceptual model can be subdivided into isolated subsystems. Conceptual modelling should identify any important potential feedback loops between subsystems. If they exist then they either need to be incorporated into the model or noted as a watchpoint and a gap.

Even within these subsystems, there is potential to further subdivide, as shown in Figure 11 for the physical system.

The compartmentalisation of a system consists of delineating the subsystems and, especially important, identifying the point of interaction. This point of interaction is an observable quantity or model outcome that forms the output of one model and will be input to the linked model. The change in flow rate due to coal resource development for example can be the point of interaction between the physical system and the ecological system. It will be the outcome of the hydrological model and form the input for an ecological response function. Note that the ecological response function can combine several hydrological response variables. Similarly, the geological model can provide an estimate of fault probability at a location, which will feed into the hydrogeological conceptual model and ultimately into the groundwater model.

Figure 10 High-level compartmentalisation of conceptual model

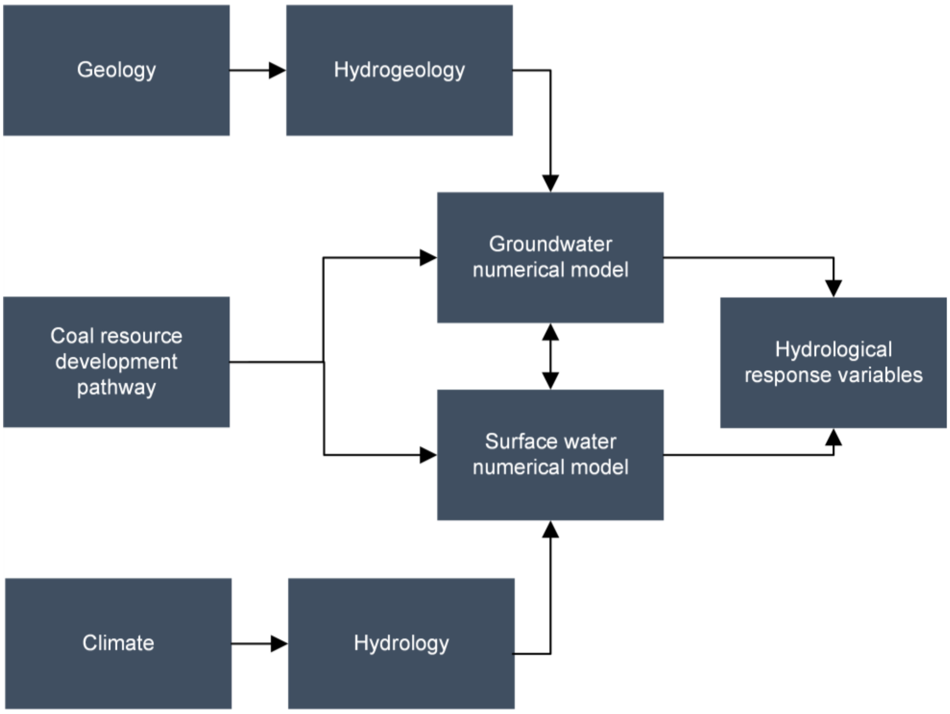

Figure 11 Example of compartmentalisation of the physical system

Conceptual representation of the physical system and inputs to and from the groundwater and surface water models. Surface water modelling uses the Australian Water Resources Assessment (AWRA) model suite, while the groundwater model varies between subregions and bioregions.

4.3 Sensitivity analysis for factor prioritisation

Sensitivity analysis (SA) methods can be broadly categorised into two groups, based on their strategy to explore parameter space: local SA and global SA. Local SA methods are usually based on the estimation of partial derivatives and provide measures of importance within a small interval around the 'baseline' or 'nominal value' point (Hill and Tiedeman, 2007; Doherty and Hunt, 2009; Nossent, 2012). Most local SA methods involve varying one model input factor at a time while keeping all others fixed, so they are special cases of 'one-factor-at-a-time' (OAT) approaches. An extensive review of these methods is provided in Turanyi and Rabitz (2000). Local SA methods are usually easy to implement and computationally cheap (require only a limited number of model evaluations), but are only suitable for linear or additive models. When these conditions are not satisfied, OAT approaches result in a sub-optimal SA due to the ignoring of the effect of interactions between input factors, since they do not take into account the simultaneous variation of input factors (Saltelli and Annoni, 2010).

Global SA overcomes the aforementioned drawbacks by exploring the full multivariate space of a model simultaneously. Since the 1990s, several global SA methods have been developed (Plischke et al., 2013): screening methods (Morris, 1991; Bettonvil and Kleijnen, 1997), non-parametric methods (Saltelli and Marivoet, 1990; Young, 2000), variance-based methods (Sobol, 2001; Saltelli et al., 2010; Nossent et al., 2011), density-based methods (Liu and Homma, 2009; Plischke et al., 2013), and expected-value-of-information based methods (Oakley et al., 2010). The last three categories require a larger investment in computer time, but they are more accurate and robust (Gan et al., 2014).

The main purpose of the sensitivity analysis in this methodology is to identify the subset of potential sources of uncertainty to which the hydrological response variables of interest are the most sensitive. This will allow for rationalising the uncertainty analysis and limiting its scope.

As outlined in Section 4.1.1, all factors of the model that can be changed automatically will be included in the sensitivity analysis and plausible ranges will need to be formulated for them. These are the ranges within which the factor will be varied to assess its influence on the outcome hydrological response variables. At this stage it is not essential that this range is the best estimate of the uncertainty of the factor; it is sufficient for the range to be plausible and realistic.

The ranges of each variable will be sampled in a quasi-random fashion using techniques such as Latin Hypercube sampling (Helton and Davis, 2003) or Sobol sampling (Sobol, 1976). Such sampling techniques generate random combinations of parameter values in an efficient way that maximises coverage of the range of each parameter and combination of parameters with a minimal number of samples.

Each of these samples (i.e. parameter combinations) is then evaluated using the original model and the model outcome is recorded. The number of model runs that will be carried out, however, will be equal to the number of model runs that are possible within the time allocated to this aspect of the project. It will depend on the model and the circumstances. As a rule of thumb, for a problem with a limited number of factors, less than 20, 1000 model runs are considered a minimum to ensure a minimal coverage of parameter space.

The analysis of the sensitivity analysis model runs will be done both qualitatively through visual inspection of scatter plots and quantitatively through sensitivity indices, where the sensitivity indices are preferably derived from a global SA method. The visual inspection of scatter plots of the variation of a factor against the model outcome hydrological response variable provides insight into the relationship between the factor and the hydrological response variable. Scatter plots are especially relevant to understand complex and non-linear model behaviour.

To objectively rank the factors, a quantitative measure of sensitivity is needed. Most of the above mentioned SA techniques provide such an objective measure.

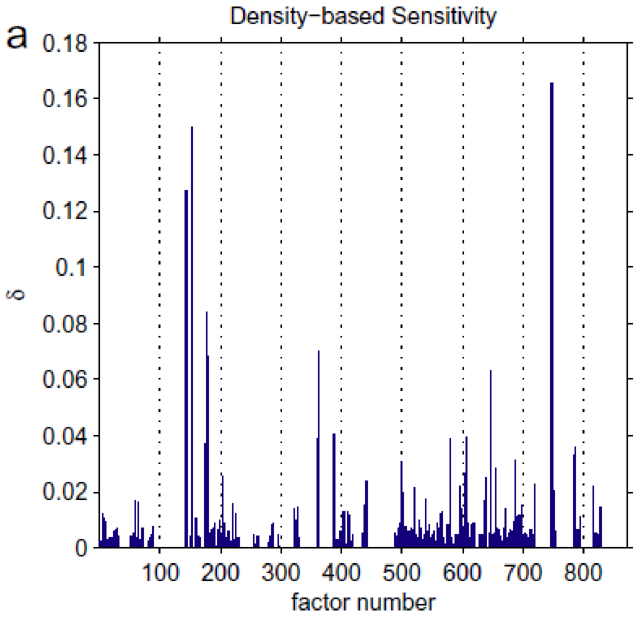

Figure 12 Sensitivity indices computed for a problem with 872 factors based on 65,000 model runs

Source: Figure 11a in Plischke et al., 2013. This figure is not covered by a Creative Commons Attribution licence. It has been reproduced with the permission of Elsevier.

As an example of the use of sensitivity indices, Figure 12 shows the result of an application of a density-based SA method, applied to a NASA space mission model (Plischke et al., 2013). The model has 872 uncertain factors and a single outcome. The model was run 65,000 times to assess the sensitivity of each factor. It becomes immediately apparent that there are only a limited number of factors that have a sizeable influence on the model outcome. This case study also illustrates that robust sensitivity estimates can be achieved for models with very high dimensionality with a limited number of model runs per parameter (~75 model runs per parameter in this case).

4.4 Uncertainty analysis is a function of data availability

The choice of uncertainty analysis methodology will be determined by the availability of relevant observation data. If no relevant observation data are available, the uncertainty analysis will be limited to a Monte Carlo simulation or propagation of the prior estimates of uncertainty of the important factors through the model chain. If relevant and sufficient data are available, the uncertainty analysis will be a Bayesian inference based on a Markov Chain Monte Carlo in which the observations will constrain the prior pdfs of the important factors to result in posterior pdfs of both the factors and the prediction.

Within the context of uncertainty analysis for BA, relevant observation data are data that are able to constrain the key influential factors that affect the model outcome hydrological response variable, as identified through the sensitivity analysis. A second condition is that the size of the dataset is sufficiently large to reliably constrain these factors. The evaluation of potential data starts with quality assessment to estimate the uncertainty of the observation data. From the sensitivity analysis described in the previous section, not only the effect of the factors on the prediction needs to be assessed, but also the effect of the factors on the model-simulated equivalents to the observation data. Observation data can only be considered relevant if its simulated equivalent is sensitive to parameters that are part of the subset of influential factors for the prediction of interest. Part of the evaluation of the observation dataset is to assess if the observation data are representative of the system or they are overly influenced by a local phenomenon. Related to this is the size of the dataset. Are there enough observations available to have a reliable estimate of the natural variability of the observations? If an observation dataset is considered not relevant for the uncertainty analysis, it does not mean that the data cannot be used within the BA uncertainty analysis. These data can still have potential to guide the expert elicitation of prior uncertainties of factors.

In the absence of sufficient relevant data, the prior probability distribution of each influential factor will be described, either from data or from expert elicitation. A Monte Carlo process will randomly sample these probability distributions and run these through the model. As such, this is the same as the sensitivity analysis process with the main difference being that the factors are no longer sampled uniformly from a plausible range, but from a distribution that reflects and incorporates the current knowledge on that factor. The resulting distribution of the prediction is then considered to be the estimate of uncertainty of the hydrological response variable.

When relevant data are available, the prior probability distribution of each influential factor will be described similar to the previous case. Rather than regular Monte Carlo simulation, Markov Chain Monte Carlo sampling will be applied. This sampling scheme favours parameter combinations that agree with the observation data. Several implementations of this scheme are available. A very promising tool is the LibBi software (Murray, 2013) developed by CSIRO, which is designed to maximally utilise the high-performance computing hardware available to BA.

4.5 Model emulation

The bottleneck in any Monte Carlo estimation is the large number of model runs required. Even for problems with moderate dimensionality, the number of simulations needed to arrive at robust estimates of the probability distribution function of the prediction will be in the order of 10,000 or even 100,000. For more complex models with higher dimensionality, millions of model runs might be required. Such large numbers of model runs are only feasible when the model run time is in the order of seconds. Most environmental models, however, take minutes, and in the case of groundwater models even hours, to converge to a solution.

Another potential bottleneck specific for BA is that each environmental model needs to be integrated into a software package or script that can carry out the Monte Carlo or Markov Chain Monte Carlo efficiently. The software implementation of environmental models likely to be used in BA can vary from straightforward spreadsheet calculations to custom-made scripts to third-party closed-source software. Implementing such a variety of software tools poses a significant challenge to the modellers and software engineers.

Both of these problems can be overcome using a technique called ‘model emulation’. The principle behind model emulation, sometimes referred to as surrogate modelling or meta-modelling, is to use a computationally efficient statistical approximation of the slower process-based model. Several techniques are available to create surrogate models (see Razavi et al., 2012). For BA, response surface models offer a relatively simple and well-studied solution to performing model emulation. In this technique, the response of a model to variations in the inputs and parameters is approximated with a mathematical function, such as a Gaussian Process (GP) model (O'Hagan, 2006) or Kriging (Kleijnen, 2009). The emulator is often implemented based on the output obtained from limited runs of the process-based model.

Of the statistical procedures used in model emulation, GP models are the most commonly utilised (see Kennedy and O'Hagan, 2001; Oakley and O'Hagan, 2002; Higdon et al., 2008). This is most likely because of their mathematical simplicity, low computational overheads, ability to fit complex surfaces and successful application in a range of disciplines. The ease with which such emulators can be constructed is also aided by a number of freely available tools developed specifically for these purposes (Hankin, 2013a, 2013b).

The GP is a distribution for a function where each evaluated point $\boldsymbol{y} = f(\boldsymbol{x})$, where $\boldsymbol{x}$ is a vector of inputs, is assumed to have a multivariate normal distribution (O'Hagan, 2006). Like all approximations, GPs introduce an error in regions other than the design points, often referred to as 'code uncertainty' (O'Hagan, 2006). Fortunately, the error associated with a statistical emulator can be readily quantified and incorporated into any assessment of uncertainty. For GP emulation, this relies on a number of assumptions to be made regarding the laws governing the covariance of model outputs over the parameter space. In addition, GP emulation assumes that model outputs vary smoothly across the parameter space and do not accommodate discontinuities (O'Hagan, 2006). Careful sampling from the process-based model input domain is required to effectively and efficiently generate the model output required for building the emulator. Appropriate design of input configurations need to be implemented for this, such as might be achieved through Latin-hypercube or Quasi-Monte Carlo sampling.

A further challenge that may be encountered in emulation of groundwater models is how to construct an emulator that is able to model multi-dimensional and potentially high-dimensional outputs (raster outputs for example). A common way in which to deal with this is through the use of dimension reduction techniques such as the singular value decomposition, which emulate the model outputs using a smaller set of eigenvectors. This is a strategy that has been applied with success for GP emulation by Higdon et al. (2008) and with other types of emulators such as random forests by others (see Hooten et al., 2011; Leeds et al., 2013). The practical implementation of these methods is not yet at the same level of robustness as univariate emulators and cannot be considered as a routine methodology. It is beyond the scope of BA to further develop and fine-tune this methodology, hence the requirement for a limited number of individual hydrological response variables to summarise the spatio-temporal model output. For communication and illustrative purposes, it is possible to sample the posterior parameter distribution and run a limited number of model runs after the uncertainty analysis to show the spatial and temporal distribution of uncertainty. This, however, is part of the post-processing and cannot be considered a main objective or task in the uncertainty analysis.

4.6 Implementation

The uncertainty analysis workflow (Figure 13) implemented in BA consists of the following steps:

1. design of experiment

2. sensitivity analysis
3. emulator development
4. obtaining posterior parameter distributions through Approximate Bayesian Computation Monte Carlo analysis
5. generating the predictive posterior distributions through evaluation of the posterior parameter distributions with the emulators.

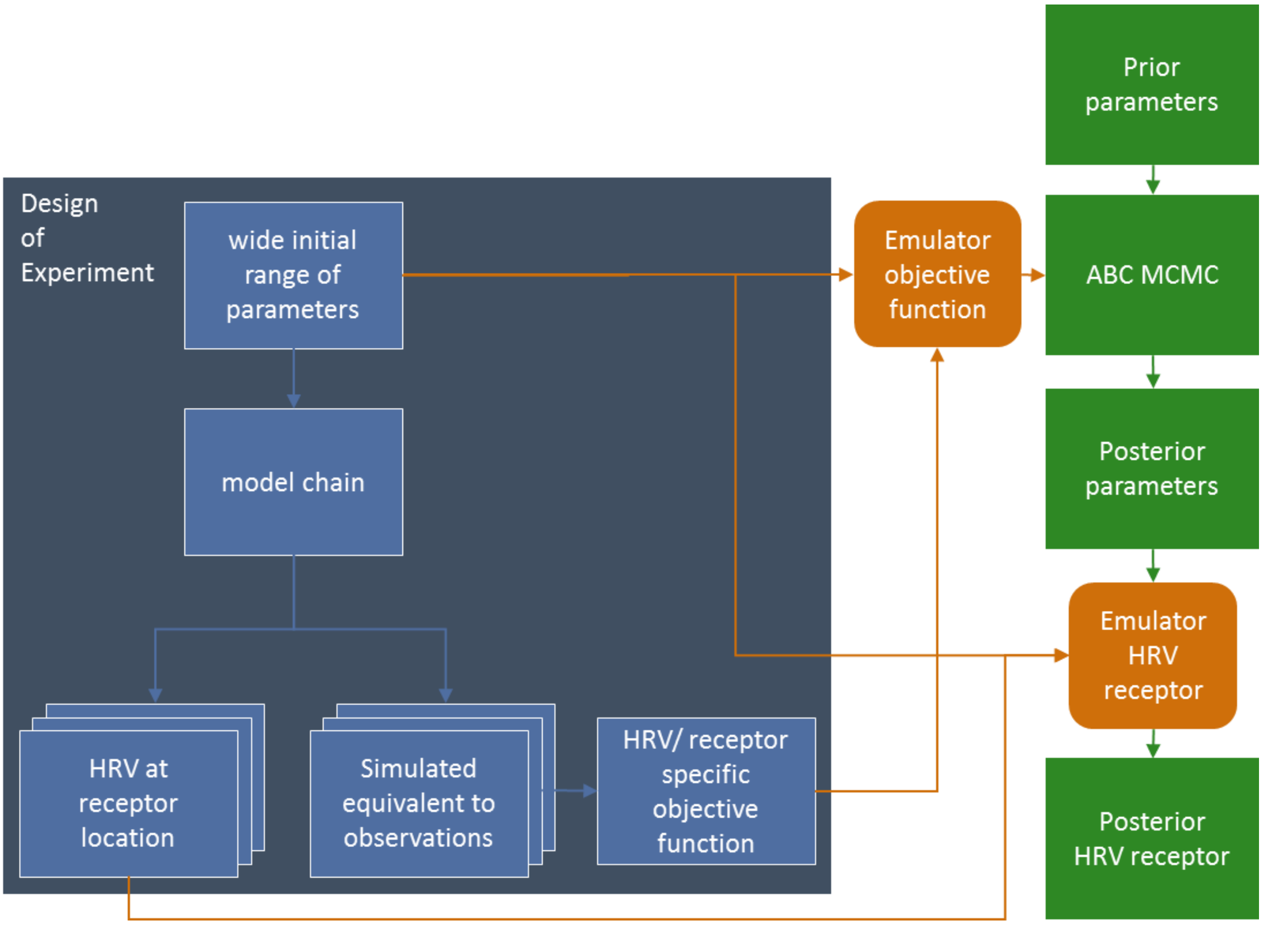

Figure 13 Uncertainty analysis workflow

HRV = hydrological response variable; ABC MCMC = Approximate Bayesian Computation Markov Chain Monte Carlo

In the design of experiment, a large number of parameter combinations are generated for the complete model sequence. The number of the parameter combinations is primarily determined by the number of model evaluations that can be afforded within the computational budget for that subregion. The parameters are generated through a Latin Hypercube sampling (Helton and Davis, 2003) that optimises the coverage of the parameter space. This results in a quasi-random but uniform sample across the range of each parameter. The ranges of parameters are chosen such that they are wide enough to encompass the prior parameter distributions, but sufficiently narrow to avoid numerical instability due to unrealistic parameter values. The ranges are defined based on the results of a stress test and the experience of the model team. A stress test consists of running the model a limited number of times with extreme parameter combinations. If the model proves to be stable for these extreme parameter combinations and provides results consistent with the conceptualisation, it inspires confidence that the model can be successfully evaluated for the parameter combinations of the design of experiment. The stress test also serves as a tool to identify and remediate any errors or inconsistencies in the implementation of the conceptual model in the numerical model.

The chain of numerical models generates the quantity of interest, the hydrological response variable, at a predefined set of points in space and time. These points in space can be used to directly assess potential changes or impacts, or they can provide the basis for an interpolation that may be able to assess potential impacts. In addition to those predictions, the model outputs corresponding to observations are stored as well. For a groundwater model this can be the simulated value of groundwater level at the time and place a head observation is available. A single model sequence run will result in multiple hydrological response variables at several locations and times in the subregion or bioregion.

The most computationally intensive step in the workflow is evaluating the original model sequence for all parameter combinations. This results in a dataset of parameter combinations and their corresponding simulated equivalents to observations and the predictions. For each prediction an emulator will be trained with the design of experiment results. The emulator chosen is a local Gaussian process approximation (laGP) (Gramacy, 2013; Gramacy and Apley, 2015).

Observations are not emulated directly. The observations are combined in a summary statistic for the Approximate Bayesian Computation process and the summary statistic is emulated.

In Approximate Bayesian Computation a summary statistic is defined to assess the quality of the model, together with an acceptance threshold for this statistic. During the Monte Carlo sampling of the prior parameter distributions, only parameter combinations that meet the acceptance threshold are accepted into the posterior parameter distributions. The Approximate Bayesian Computation methodology allows the tailoring of the summary statistic to individual predictions. For example, to predict change in annual flow, the summary statistic only contains the observations of annual flow. For a groundwater level prediction, the summary statistic can be a weighted sum of the head observations in that aquifer, with higher weights for observations close to the prediction location, together with constraints on the overall model balance. This type of summary statistic optimises the use of local information, while ensuring the overall water balance is respected.

For each prediction a tailored summary statistic is defined and the Approximate Bayesian Computation Monte Carlo sampling is carried out until the posterior parameter distribution has a predefined large number of samples. These posterior parameter distributions are evaluated with the emulator for the prediction to arrive at the posterior predictive probability distribution.

As there is no guarantee that for each prediction an emulator can be created that will adequately capture the relationship between the model parameters and the predictions, each emulator is systematically tested using cross-validation. Emulators that do not satisfy predefined performance criteria are not used in the analysis. For these predictions, the predictive posterior probability distribution cannot be obtained and only the median of the design of experiment runs is reported.

5 Outputs from the sensitivity analysis and uncertainty analysis

Product 2.6.1 (surface water numerical modelling) and 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 surface water and groundwater model domains respectively. This is done by comparing model simulations that account for the coal resource development pathway (CRDP) with those that only consider the baseline. A critical part of both of these products is the representation of the uncertainty in numerical model predictions. This is achieved in various ways, including by demonstrating the distribution of model outputs (i.e. hydrological response variables) at specific model nodes or illustrating the probability of exceeding certain drawdown thresholds.

Examples are not presented as part of this submethodology but the reader is referred to submethodology M06 (as listed in Table 1) for surface water modelling (Viney, 2016) and submethodology M07 (as listed in Table 1) for groundwater modelling (Crosbie et al., 2016) which contain specific examples of uncertainty outputs for product 2.6.1 (surface water numerical modelling) and Product 2.6.2 (groundwater numerical modelling).

6 Conclusions

This submethodology provides guidance on how to propagate uncertainty through the chain of environmental models to assess the impact of coal resource development on water and water-dependent assets. The methodology is devised to allow for maximum transparency in the modelling process. At the core of the submethodology is the structured characterisation of uncertainty through probability distribution functions, based on measurement data or from expert elicitation. Any aspect of the model that cannot be included in the formal uncertainty analysis (such as discrete choices and model assumptions) will not only be documented, but will also be submitted to a pedigree analysis to assess the quality of the model choice and the potential impact on the prediction.

This submethodology is structured around a compartmentalisation of the model chain followed by a comprehensive sensitivity analysis to identify the crucial factors that the model prediction is most sensitive to. The model prediction relates the model output to a model node via a hydrological response variable. The subset of factors the prediction is sensitive to will subsequently be used in the uncertainty analysis which propagates the uncertainty in the input factors to the prediction using a Monte Carlo approach. In the event that relevant data are available, these will be integrated in the process to constrain the probability distribution of the prediction. In order to keep the computational load manageable and the methodology amenable to automation, the uncertainty analysis will be carried out with model emulators. The resulting probability distribution functions of the impacts on the hydrological response variables will provide a starting point for the receptor impact modelling, as specified by submethodology M08 (as listed in Table 1) and reported in product 2.7 (receptor impact modelling).

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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

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

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

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

conceptual model: abstraction or simplification of reality

consequence: synonym of impact

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

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.

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

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

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

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

likelihood: probability that something might happen

material: pertinent or relevant

model chain: a series of linked models where the output of one model becomes an input to another

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.

Monte Carlo simulation: a simulation technique involving random sampling of each probability distribution within the model to produce large number of plausible scenarios. Each probability distribution is sampled in a manner that reproduces the distribution's shape. The distribution of the values calculated for the model outcome therefore reflects the probability of the values that could occur.

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)

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.

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)

stationary system: a system in which the hydrological regime or other conditions do not vary through time

stratigraphy: stratified (layered) rocks

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

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

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

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.

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

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

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

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

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